Abstract No: A-147

SOURCES OF ANTHROPOGENIC FIRE IGNITIONS ON THE PEAT-SWAMP LANDSCAPE IN KALIMANTAN, INDONESIA

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SUMMARY

Fire disturbance in Southeast Asian tropical peat swamps have become more frequent and extensive in recent decades. These fires compromise a variety of ecosystem services, notably mitigating global climate change through carbon storage, and cause severe health, ecological, and economic impacts. Key to understanding and managing fire in the region is identifying the land use / land cover (LULC) classes associated with fire ignitions. We assess the oft-asserted claim that industrial-scale oil palm concessions and smallholder farms near settlements are the primary ignition sources in a peat-swamp forest area in Central Kalimantan, Indonesia, equivalent to around a third of Kalimantan's total peat area. We use the MODIS Active Fire product from 2000-2010 to evaluate fire origin and spread on the LULC classes of legal oil palm concessions, non-forest (a relatively heterogeneous mixture that includes fern-dominated, shrub/bushland, bare peat, plantations including smallholder and very young oil palm outside legal concession boundaries, and degraded forest), and forest, as well as in relation to settlement proximity. Most fires (70%) originate in non-forest, compared to legal, industrial oil palm concessions (18%), and relatively few (5%) are within 5 km of settlements. Moreover, most fires started within oil palm concessions and close to settlements stay within those boundaries (90% and 88%, respectively). Similarly, a small proportion of fire detections in forest originate from oil palm concessions (2%) and within close proximity to settlements (2%). However, fire ignition density in oil palm (0.055 ignitions km^{-2}) is comparable to that in non-forest (0.060 ignitions km^{-2}), which is approximately ten times that in forest (0.006 ignitions km^{-2}). Ignition density within 5 km of settlements is the highest at 0.125 ignitions km^{-2}. Thus, although fire in oil palm is important, these results refute the claims that most fires originate in oil palm concessions and that fires escaping from oil palm concessions and settlements constitute a major proportion of fires in this study region. However, there is a potential for these land use types to contribute more substantially to the fire landscape if their area expands as projected. Effective fire management in this area should target not just legal oil palm concessions, but also non-forested, degraded areas where ignitions are most likely to occur.

Keywords: *disturbance, fire, human-environment coupled system, ignitions, Indonesia*

INTRODUCTION

Peatland fires in Indonesia have been following pantropical trends of increased frequency and severity in recent decades (Meijaard and Dennis, 1997). During El Niño phases, there is increased likelihood of drought in Southeast Asia and, thus, an increased incidence of fire (e.g., Page *et al.,* 2002; Wooster *et al.,* 2012). Extreme fire events would not exist without anthropogenic influence on the landscape, as fire is increasing in tandem with land use change and increased population density (Field *et al.,* 2009). Carbon emissions from fires in peatlands are particularly high, as peat is extremely rich in belowground organic carbon. An estimated 0.81-2.57 Gt C were released from Indonesia's peatlands during the 1997/98 fire season alone due to peat and vegetation combustion (Page *et al.,* 2002), equivalent to 13-40% of the mean annual global carbon emission from fossil fuels (van der Werf *et al.,* 2004). Fires in the 2015 dry season were the most severe since 1997/98. Peat fires in Indonesia are consequently a major cause of smog and particulate air pollution (Hayasaka *et al.,* 2014; Reddington *et al.,* 2014), with serious consequences for human health (Marlier *et al.,* 2013). In addition, peatland fires are responsible for habitat loss and degradation, driving wildlife declines (Jaafar and Loh, 2014; Yule, 2010), as well as high economic costs (Varma, 2003). Given the variety and severity of the consequences of tropical peatland fires, particularly those in Indonesia, it is of global interest to understand this disturbance regime and reduce fire occurrence.

Ignitions in Indonesia, as in many parts of the tropics, are primarily of anthropogenic origin (Bowen *et al.,* 2000), through either accidental or deliberate fires. Thus, a key component to understand changing fire regimes is to identify the sources of fire ignitions and the land use / land cover (LULC) classes associated with fire ignitions. Who is responsible for ignitions in Indonesia is highly contested, and reports of the ignition sources are many and varied (Dennis *et al.,* 2005; Page *et al.*, 2009). Although some large-holders do clear land mechanically, most land is cleared in Indonesia through use of fire (Stolle *et al.,* 2003), and people use fire as a management tool to clear debris and reduce pests. Because fires set for clearing can 'escape' beyond their intended boundaries, both large and small holders have been held responsible (e.g., Page *et al.,* 2009; Stolle *et al.,* 2003), as is often the case in rainforest fires more generally (Goldammer, 1991). In this study, for what we believe to be the first time, we disentangle fire detections from individual fire ignitions to discern the origin of fires in a peat-swamp forest landscape in Central Kalimantan, Indonesia. In so doing, we assess the oft-asserted claim that escaped fires from oil palm concessions and from smallholder farms near settlements are the primary sources of fire, through addressing the following questions:

1) In which LULC classes do fires, in particular the longest and hottest fires, originate and to which LULC classes do they spread?,
2) What proportion of fires, in particular the longest and hottest fires, escape from oil palm concessions and settlements into other surrounding LULC classes?, and
3) Do fire ignitions occur disproportionately in proximity to oil palm concessions and settlements? Are these fires longer in duration or hotter than fires occurring away from oil palm concessions and settlements?

METHODS

Study Site

We analyze fire ignitions in an area of lowland tropical peat-swamp forest in Central Kalimantan, Indonesia (Figure 1). The study area consists of the Sabangau-Katingan Forest and the recently degraded failed agricultural development called the Mega Rice Project (MRP), representing a combined total of ~2.5 Mha of the total 6.8 Mha of lowland peatland in Kalimantan. Currently, tens of thousands of families live along the Katingan, Sabangau Kahayan, Kapuas, and Barito Rivers that border the area. There are several oil palm concessions located throughout.

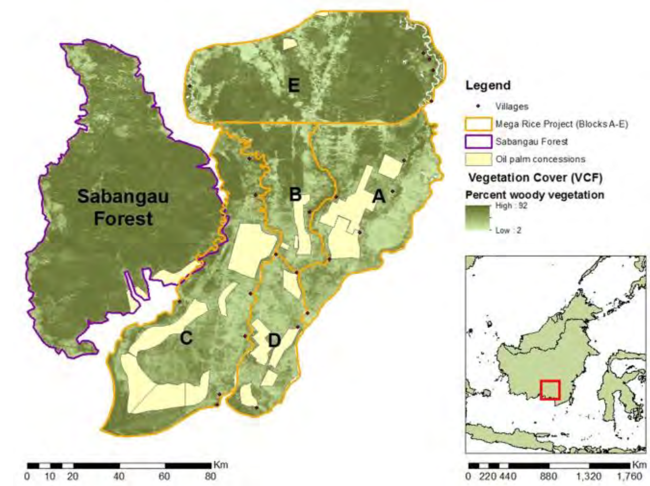

Figure 1: The study area: lowland peat-swamp forest in Central Kalimantan, Indonesia, consisting of the failed Mega Rice Project (pink borders; letters indicate administrative zones) and the adjacent Sabangau Forest (yellow border), including the percent woody vegetation, legal oil palm concession boundaries, and major villages and settlement locations. Inset: Location within Indonesia.

Data

Fire detections at the 1 km^2 resolution across the study area from 2000-2010 are obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) Active Fire Detections, extracted from MCD14ML. We create a LULC layer at the annual temporal resolution consisting of oil palm concessions, forest, and non-forest classes. Oil palm concession boundaries for this LULC layer according to the Indonesian Ministry of Forestry are obtained from the Global Forest Watch portal. The forest and non-forest classes for this LULC layer are based upon tree cover derived from the MODIS Vegetation Continuous Fields (VCF) Collection 5 product, which contains proportional estimates of woody vegetation at the 250 m^2 resolution. VCF is aggregated to the 1 km^2 resolution, and a forest binary layer is created by thresholding VCF at 55 percent woody vegetation to designate tree cover based upon the range of VCF values of areas known to be tree cover in the study area. Classification accuracy of the forest binary layer is assessed using GPS points collected in the field in forest (50 points) and non-forest (50 points) in 2009, and accuracy is over 95%. Finally, settlement locations, or points indicating the center of major villages and cities, obtained from Simon Husson of OuTrop, are used to calculate distance from settlement across the study area.

Analysis

Data analysis covers the period from 2000-2010. The MODIS Active Fire Product indicates the presence of a fire within a 1 km^2 area, but not the exact location or size of a particular fire. Thus, it is challenging to determine if proximal fire detections are spatially contiguous or if they represent isolated fires. We assign all fire detections to a particular fire event using two methods: the single-pixel technique, in which fire detections from successive days that occur within a given pixel are assigned to the same fire and thus fires are restricted to a 1km^2 area, and the neighborhood-pixel technique, in which fire detections from successive days that occur within a given pixel or the eight adjacent pixels are assigned to the same fire using hierarchical clustering. We consider the earliest fire detection in each fire event to be the ignition for that fire event. Fire events with a duration and/or maximum heat (fire radiative power (FRP)) within the top decile of fires are considered "high-impact," because these factors affect the fires' potential environmental damage.

1) In which LULC classes do fires, in particular the longest and hottest fires, originate and to which LULC classes do they spread?

For each fire event, we identify the LULC class in which the ignition occurs and calculate how many fire detections are associated with fires started on each LULC class. We determine the density of ignitions per LULC class by normalizing the number of ignitions in each LULC class to the area of that class in the entire study region for each year.

2) What proportion of fires escape from oil palm concessions and settlements into other surrounding LULC classes?

We identify fires that escape from oil palm concessions by isolating fires that start within oil palm concessions and burn outside the concession boundaries at some point during the burn. Similarly, we identify fires that escape from settlements by isolating fires that start near settlements (5km threshold) and burn outside that boundary at some point during the burn.

3) Do fire ignitions occur disproportionately in proximity to oil palm concessions and settlements?

To analyze the influence of increased anthropogenic activity around settlements and outside of oil palm concessions on fire activity, we evaluate if the number of ignitions and the severity of fires (i.e., fire duration or the maximum FRP) varies as a function of the fire ignitions' distance from oil palm concessions or from settlements. After assessing exploratory plots, we fit models of the number of fire ignitions as a function of distance from oil palm concessions and from settlements (binned into 50m increments). We fit exponential regression models for distance from oil palm concessions because we expect anthropogenic ignitions to be highest near concession borders (due to expansion of the concession itself, clearing for smallholder plots, or accidental fires where workers are regularly frequenting) and then decrease as distance from concession increases (due to increased cost of travel from the concession). For distance from settlements, we fit Ricker functions of the form $y \sim ax \exp(-bx)$, where y is the number of ignitions and x is the distance from settlements. We select a Ricker model because we expect the number of ignitions to start at zero due to an aversion to burn very close to the village, increase to a peak, and then decrease back to zero as the cost of travelling from the settlement increases with distance. We estimate the parameter b and calculate $1/b$, the distance from settlements at which ignitions peak.

RESULTS

1) In which LULC classes do fires, in particular the longest and hottest fires, originate and to which LULC classes do they spread?

Non-forest and oil palm concessions have a comparable density of ignitions, which is about ten times the density of ignitions in forest (Table 1). However, by far the majority of fire detections are associated with fires that start on non-forest (70.0% for all fires and 70.3% for high-impact fires). Non-forest is also the primary LULC class on which ignitions occur for fires that burn forest (46.4%). Fire detections associated with fires started on oil palm constitute 17.5% of all detections (17.9% for high-impact fires), and most fires that burn oil palm concessions are started on the concessions themselves. The density of fire ignitions in forest is low, and fire detections associated with fires starting on forest constitute only 7.3% of all detections (6.5% for high-impact fires). The percent of detections associated with fires that are started close to settlements, which could occur on oil palm concessions, non-forest, or forest, is negligible (0.2-5.0% for all fires and 0.1-3.4% for high-impact fires). However, although the overall contribution of ignitions near settlements is low, the density of ignitions near settlements is high - just over twice that of non-forest and oil palm for all fires, and approximately 1.5 times that of non-forest and oil palm for high-impact fires.

Table 1: The percent of fire detections associated with fires that start on each land use / land cover (LULC) class and density of fire ignitions (ignitions km^{-2}) that are located in each LULC class. Numbers for high impact fires are in parentheses.

Land use / land cover class	Non-forest	Oil palm concession	Forest	Within 5km	Within 4km	Within 3km	Within 2km	Within 1km
Density of ignitions (ignitions km^{-2})	0.060 (0.010)	0.055 (0.010)	0.006 (0.001)	0.125 (0.015)	0.096 (0.011)	0.077 (0.008)	0.058 (0.006)	0.051 (0.008)
Percent of detections	70.0 (70.3)	17.5 (17.9)	7.3 (6.5)	5.0 (3.4)	2.9 (1.8)	1.8 (1.2)	0.6 (0.2)	0.2 (0.1)

2) What proportion of fires escape from oil palm concessions and settlements into other surrounding LULC classes?

A minority of fires (10.5% of all fires, 37.3% of high-impact fires) that are started within oil palm concessions escape the concession into other LULC classes, and a minority of fires (12.2% of all fires, 44.1% of high-impact fires) that are started near settlements escape. Although some fires, and particularly high-impact fires, do escape from oil palm concessions and from settlements, they constitute only a small percent of total fires in the study area (1.8% of all fires, 6.8% of high-impact fires and 1.2% of all fires, 3.0% of high-impact fires, respectively). Furthermore, these escaped fires do not serve as a notable ignition source for forest fires; only 1.5% of forest fire detections are associated with fires that were ignited in oil palm concessions and 2.4% with fires that were ignited close to settlements.

3) Do fire ignitions occur disproportionately in proximity to oil palm concessions and settlements?

The number of ignitions of all fires and high-impact fires decreases exponentially with increasing distance from oil palm concessions (adjusted R^2= 0.59, $p<0.001$). When we explore the relationship between the number of ignitions and distance from settlements, we find that the Ricker model fits the data well, including at the extremes, and that the number of ignitions increases farther from settlements, peaks at 7.2 (±0.2) km from settlements, and then decreases. Fire duration and maximum FRP do not have a clear relationship with either distance from oil palm concessions or from settlements.

DISCUSSION

Our results provide only limited support to the claim that fires occurring on or escaping from industrial-scale oil palm concessions and settlements are major contributors to fire in this study region during our study period. The vast majority of fire detections is associated with ignitions that occur in non-forested areas, a relatively heterogeneous mixture that includes fern-dominated, shrub/bushland, bare peat, plantations including smallholder and very young oil palm outside legal concession boundaries, and degraded forest. A relatively low but still substantial percentage of detections are associated with ignitions that occur on oil palm concessions, and very few with ignitions that occur in close proximity to settlements. The majority of fires started within concessions or near settlements is confined to those boundaries, and ignitions in these land use classes contribute very little to fires that burn in forest.

While there is potential for oil palm concessions from converted degraded land to reduce fire prevalence on the landscape if ignitions on oil palm concessions can be reduced relative to degraded areas, this is not currently the case; ignition density in oil palm was on par with that in degraded areas, both of which were substantially higher than in forests. Although fires that have escaped from oil palm concessions currently constitute a small percentage of fires in the study area relative to fires on degraded non-forest areas, our findings nevertheless support concerns about the contribution of oil palm companies to emissions and hazardous smog in the region (e.g., Marlier *et al.,* 2015; Stuart, 2012). Furthermore, our results likely underestimate the number of ignitions attributable to oil palm companies and overestimate the contribution from other LULC classes, as our oil palm category includes only those plantations found within the reported boundaries of legal oil palm concessions.

Our findings that there is a detectable pattern in the number of fire ignitions as a function of distance from oil palm concessions and settlements suggest that these LULC classes influence the fire regime through increased anthropogenic activity around them, plus escaped fires from these LULC classes. The extent to which these ignitions will result in high-impact fires depends upon both the flammability of the landscape and the capacity for management interventions. If the peat is relatively undrained and inundated close to the surface, the forest is intact, and fire-fighting resources are available, an ignition is much less likely to turn into a high-impact fire than if the land is degraded from canal development and unmanaged. Our results indicate that fire reduction efforts are needed in these degraded areas, through both capacity building and awareness raising, to increase the success of management interventions, plus landscape restoration to reduce the predisposition of the landscape to burning. Additionally, because the density of ignitions is high in oil palm concessions and within 5km of settlements, it is clear that these land use types have the potential to contribute substantially to the fire landscape if they continue to expand, and peat and fire management practices do not improve, particularly if fragmentation and/or climate change leave the landscape even more predisposed to burning.

Our results support previous research that most fires occur in non-forest or degraded areas (including oil palm in Gaveau *et al.,* 2014; Miettinen *et al.,* 2007) by showing both that the majority of fires are ignited in non-forest, and highlighting that fires actually start in non-forest rather than merely just occur in non-forest (with the possibility that ignition started there or elsewhere). Management to reduce ignitions in degraded non-forest areas, in addition to reducing the probability of continued burning when ignitions do occur, will be pivotal in reducing fire across the landscape. This is also key to preventing forest fires and the associated loss of habitat, as we found that the majority of forest fires start in non-forest.

CONCLUSION

Results of this research, which uses remotely sensed data and modeling to analyze where fires originate and spread in tropical peat-swamp forest in Central Kalimantan from 2000-2010, indicate that most fires (70%) originate in non-forest areas, and refute the claim that fires occurring on or escaping from oil palm concessions and settlements constitute the major proportion of fires in this study region during 2000-2010. We find that only 18% of fires are ignited on oil palm concessions, and that most fires that start on oil palm concessions stay on the concession (90%). Similarly, few fires start within 5km of settlements (5%) and most stay within those boundaries (88%). However, we do find a detectable pattern of fire ignitions around oil palm concessions and settlements, and a high density of ignitions within them (0.055 ignitions km^{-2} and 0.125 ignitions km^{-2}, respectively), suggesting that increased anthropogenic activity around these land use classes contributes to fire activity, and that the expansion of settlements or concession areas could substantially increase fire on the landscape, if peat and fire management is not improved. Effective fire management should therefore target not just legal oil palm concessions or areas around settlements, but should also focus strongly on non-forested, degraded areas and illegal oil palm plantations – and in particular those near legal oil palm concession boundaries and outside the immediate vicinity of settlements – where ignitions are most likely to occur.

ACKNOWLEDGEMENTS

We thank the United States Indonesia Society (USINDO), The Explorer's Club, the Center for International Forestry Research (CIFOR), StOLT Foundation, The American Indonesian Exchange Foundation (AMINEF), and the Fulbright Program for financial and other support. We also thank the DeFries lab at Columbia University and Dr. Bénédicte Bachelot for feedback that improved this paper substantially, and Simon Husson for providing settlement data. We thank the staff and volunteers at the Orangutan Tropical Peatland Project, which works in partnership with the Center for International Cooperation in Sustainable Management of Tropical Peatland (CIMTROP). We thank the University of Palangka Raya for ongoing support and the Ministry of Research and Technology (RISTEK) for permission to conduct research in Indonesia.

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