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Sources of anthropogenic fire ignitions on the peat-swamp landscape in Kalimantan, Indonesia

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ABSTRACT

Fire disturbance in many tropical forests, including peat swamps, has become more frequent and extensive in recent decades. These fires compromise a variety of ecosystem services, among which mitigating global climate change through carbon storage is particularly important for peat swamps. Indonesia holds the largest amount of tropical peat carbon globally, and mean annual CO_2 emissions from decomposition of deforested and drained peatlands and associated fires in Southeast Asia have been estimated at ~2000 Mt y-1. A key component to understanding and therefore managing fire in the region is identifying the land use/land cover classes associated with fire ignitions. We assess the oft-asserted claim that escaped fires from oil palm concessions and smallholder farms near settlements are the primary sources of fire 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 to 2010 to evaluate the fire origin and spread on the land use/land cover classes of legal, industrial oil palm concessions (the only type of legal concession in the study area), non-forest, and forest, as well as in relation to settlement proximity. We find that most fires (68–71%) originate in non-forest, compared to oil palm concessions (17%–19%), and relatively few (6–9%) are within 5 km of settlements. Moreover, most fires started within oil palm concessions and in close proximity to settlements stay within those boundaries (90% and 88%, respectively), and fires that do escape constitute only a small proportion of all fires on the landscape (2% and 1%, 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 km-2 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}. Furthermore, increased anthropogenic activity in close proximity to oil palm concessions and settlements produces a detectable pattern of fire activity. The number of ignitions decreases exponentially with distance from concessions; the number of ignitions initially increases with distance from settlements, and, around from 7.2 km, then decreases with distance from settlements. These results refute the claim 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 substantially to the fire landscape if their area expands. Effective fire management in this area should therefore target not just oil palm concessions, but also non-forested, degraded areas where ignitions and fires escaping into forest are most likely to occur.

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1. Introduction

Fires in humid tropical forests, both natural and anthropogenic in origin, have been a source of disturbance over millennia (e.g., Goldammer, 1990), but large, intense fires have been relatively infrequent prior to anthropogenic land use change. Fire has been increasing across the tropics both in size and in frequency in recent decades (Goldammer, 1991; Cochrane, 2009; Cochrane, 2003). In that time, both the largest and greatest number of fires have occurred in the tropics relative to other regions (Cochrane, 2003; Cochrane and Ryan, 2009). Tropical and subtropical moist broadleaf forests are considered the most fire-sensitive of the major ecoregions (Shlisky et al., 2007; Shilisky et al., 2009), and thus the ecological consequences for increased fire in the tropics are far-reaching, including changes in forest composition (Cochrane and Schulze, 1999) and structure (Gerwing, 2002) that are potentially long-term in nature (e.g., Ferry Slik et al., 2002). Furthermore, biomass burning in the tropics releases carbon and other gases into the atmosphere, contributing to global climate change, air pollution, acid rain, and property damage (Crutzen and Andreae, 1990; Hao and Ward,1993; Hao et al., 1990; Langmann and Graf, 2002).

Trends of fire activity in Southeast Asia follow pantropical trends (Taylor et al., 1999; Field et al., 2009), and peatland fires in Indonesia have been increasing in frequency, number, and severity since the 1980's (Meijaard and Dennis, 1997). Consequently, tropical peatlands, the majority of which are found in Southeast Asia (57% of the tropical peatland area and 77% of the volume) (Page et al., 2011), are at heightened fire risk. During El Niño phases of the El Niño Southern Oscillation (ENSO), there is increased likelihood of drought in Southeast Asia and, thus, a well-established coupling of fires in Indonesia with El Niño conditions and precipitation, including in Kalimantan (e.g., Wooster et al., 2012; Deeming, 1995; Fuller and Murphy, 2006; Spessa et al., 2015; Kita et al., 2000; Siegert et al., 2001; Wang et al., 2004; Page et al., 2002). There is some evidence that large fires do not occur unless precipitation falls below a particular threshold (Goldammer, 2007; Field et al., 2009). However, fire is increasing in tandem with land use change and increased population density (Field et al., 2009) and, without anthropogenic influence on the landscape, extreme fire events would not exist.

Carbon emissions as a result of fires in peatlands are particularly high, as peat is extremely rich in belowground organic carbon; peat-swamp forest with a depth of 10 m can store 12–19 times the amount of carbon as other tropical forest types (FRIM-UNDP/GEF, 2006). Mean annual CO_2 emissions from decomposition of deforested and drained peatlands and associated fires in Southeast Asia are estimated at ~2000 Mt y^{-1} (Hooijer et al., 2006). However, there is annual variability in emissions, and emissions during El Niño phases of ENSO far exceed those from non-El Niño periods (van der Werf et al., 2008). Over 90% of these peat emissions come from Indonesia, which has the largest amount of tropical peat carbon globally (Page et al., 2011; Page et al., 2006; Rieley et al., 1996). It is estimated that 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). Fires in the 2015 dry season were the most severe since 1997/98, but, at the time of writing, peer-reviewed estimates for land area burned and emissions are not yet published. Indonesia has become the world's fourth largest emitter of CO_2, largely as a result of emissions from the 2015 fires, which have reached 1.62 billion tons of CO_2 (Harris et al., 2015).

Peat fires in Southeast Asia, and Indonesia in particular, 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 (Kunii et al., 2002; Kunii, 1999; Marlier et al., 2012; Wooster et al., 2012) and local blocking of sunlight that can suppress plant photosynthesis (Davies and Unam, 1999). In addition, peatland fires are responsible for forest habitat loss and degradation for flora and fauna, including those in marine systems (Jaafar and Loh, 2014; Posa et al., 2011; Yule, 2010). Fire suppression efforts, lost timber and crop resources, missed workdays, and travel disruptions incur high economic costs (Barber and Schweithelm, 2000; Tacconi, 2003; Ruitenbeek, 1999), and it is estimated that Indonesia lost US$20.1 billion during the 1997/98 fire season alone (Varma, 2003). Both national and international policy has been implemented to attempt to reduce fire in Indonesia prior to the 2015 fire season (e.g., ASEAN Agreement on Transboundary Haze Pollution, Singapore's Transboundary Haze Pollution Act, and Indonesia's national law (Act No 41/1999) banning corporations from using fire to clear land for palm-oil plantations), but with limited success. Given the variety and severity of the consequences of tropical peatland fires, particularly those in Indonesia, it is of global interest to understand this changing disturbance regime and reduce fire occurrence (Harrison et al., 2009).

Before large-scale anthropogenic land use change, the most common cause of ignition in tropical forests was natural, primarily lightning strikes (Baker and Bunyavejchewin, 2009). Now, far more fires in the tropics are started by people than by natural sources (Stott, 2000; Baker and Bunyavejchewin, 2009). Ignitions in Indonesia, as in many parts of the tropics, are primarily of anthropogenic origin (Bompard and Guizol, 1999; Bowen et al., 2000), resulting in either accidental or deliberate fires. The human contribution to changing fire regimes and our capacity to manage fire remains somewhat uncertain (Bowman et al., 2009; Bowman et al., 2011). Thus, a key component to understand changing fire regimes in the tropics 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., 2009b), often resulting in a chain of finger-pointing (e.g., Suyanto, 2000). Although some large-holders do clear land mechanically, most land is cleared in Indonesia through use of fire (Stolle et al., 2003). Because fires set for clearing can 'escape' beyond their intended boundaries, both large and small holders have been held responsible (e.g., Stolle et al., 2003; Page et al., 2009b), as is often the case in rainforest fires more generally (Goldammer, 1991). Burning to clear land has been the traditional practice of smallholders and indigenous groups, and there is some evidence that smallholders' use of fire has been historically relatively small-scale and well-managed (Tomich et al., 1998; Bowen et al., 2000; Seavoy, 1973; Dove, 1985; Gönner, 1998; Wibowo et al., 1997; Nicolas, 1998). However, this is likely not the case today. The scale of land cleared by fire has expanded with increased use of burning by both smallholders and larger-scale rubber and oil palm concessions (Brauer and Hisham-Hashim, 1998; Potter and Lee, 1998; Stolle et al., 2003). Originally, the Indonesian government blamed smallholder shifting cultivators for fire, but later publically claimed that it was more likely larger-scale companies opening land on commercial plantations for palm oil, pulpwood, and timber, some of which was promoted by government policies themselves (Brown, 1998; Page et al., 2009b). There is evidence that high-impact fires often originate on plantations, logging concessions, and large land-clearing projects (Hoffmann et al., 1999) and that wildfires escaping from oil palm concessions contribute to deforestation (Carlson et al., 2012). However, much evidence still points to small- and mid-scale farmers outside of large concessions as the main contributors to fire. For example, although concessions do contribute substantially to emissions, particularly in peatlands and non-forested areas, the majority of emissions can be attributed to fires outside of concessions in both Sumatra and Kalimantan (Marlier et al., 2015b). Additionally, it is often complicated to attribute ignitions to agro-industrial plantations or to local communities because communities can be given land to plant within concession boundaries (Gaveau et al., 2014). Furthermore, fire is used in social conflicts over forest conversion and land tenure, which may include fires started inside concessions by people from outside of the concession (Tomich et al., 1998). However, the argument can also be made that large companies should be responsible for activities occurring within the boundaries of their concessions, especially considering the financial resources available to them to do so.

Because many studies using satellite data to evaluate fire consider individual fire detections at the 1 km^2 resolution (e.g., Langner and Siegert, 2009) and not individual fire events (i.e., a fire with a common ignition source, which may consist of multiple fire detections), it is often difficult to pinpoint the LULC classes on which ignitions occur rather than the LULC classes associated with fire or that are predisposed to burning. This issue complicates efforts to determine who should be blamed for fires and the associated pollution and damage, particularly if fires quickly escape a LULC boundary and burn into another LULC class. 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. We focus on ignition sources in this study area because of the global importance of peatland areas in Indonesia and the consequences of peatland fires.

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?
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?

2. Materials and methods

2.1. Study site

We analyze fire ignitions in an area of lowland tropical peat-swamp forest in Central Kalimantan, Indonesia (Fig. 1). The study area consists of the Sabangau-Katingan Forest and the recently degraded failed agricultural project 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. The 630,000 ha Sabangau-Katingan Forest consists of the now-protected Natural Laboratory of Peat Swamp Forest and the Sebangau National Park. It has been previously subjected to both concession and illegal logging throughout, and as a consequence of the latter is criss-crossed by small illegal logging timber extraction canals, on many of which canal damming initiatives are currently underway. Some parts of the forest have suffered fire damage. Currently, the area is not open for human use apart from some small-scale activities, but enforcement capability is limited. There are several villages located along the Katingan and Sabangau Rivers.

The MRP is a failed and abandoned agricultural conversion project that was initiated in 1995 and aimed to convert 1 Mha of peat-swamp forest into rice plantations. Much of the area's forest was cleared and wide, deep irrigation canals totaling over 4000 km in length have resulted in extreme drainage and subsequent fire susceptibility. The MRP has burned regularly since 1997, particularly during the dry seasons in El Niño phases, and it now contains patchy forest remnants surrounded by degraded fire-prone peat swamp. In 2000, less than half of the original peat-swamp forest remained in the MRP (Boehm and Siegert, 2001), and fire has been identified as a primary factor of forest cover loss in the area (Hoscilo et al., 2011). Currently, tens of thousands of families live along the Kahayan, Kapuas, and Barito Rivers that border the area. Many of these people rely upon forest resource extraction for their livelihoods, some in combination with smallholdings. There are no legal wood fiber, rubber, or logging concessions in the study area, but there are several oil palm concessions located throughout the MRP and on the southeastern edge of the Sabangau basin. There are still several large transmigration settlements in the study area, many of which are located adjacent to the oil palm concessions.

It is estimated that the carbon store of the MRP and the Sabangau Forest was 2.82–5.40 Gt C before the most destructive fire season in 1997–98, and that emissions totaling 0.19–0.23 Gt C from the peat and 0.05 Gt C from aboveground biomass occurred during this period (Page et al., 2002). The Sabangau Forest is home to the largest remaining population of Bornean orangutans (Wich et al., 2008) and southern Bornean gibbons (Cheyne et al., 2008), and the adjacent portion of the Mega Rice Project also hosts a substantial population of Bornean orangutans (Cattau et al., 2014). As is typical for the region, more fires occur in the study area during the dry season and particularly El Niño phases (Fig. 2).

2.2. Data

Fire detections at the 1 km^2 resolution across the study area from 2000 to 2010 are obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) Active Fire Detections, extracted from MCD14ML and distributed by NASA FIRMS. The MODIS Active Fire Product includes, for each fire detected by either the Terra or Aqua MODIS sensor, the location of the center of the 1 km^2 pixel in which the fire was detected, the date and time of detection, the Fire Radiative Power (FRP, a measure of fire heat output), and the detection confidence. MODIS hotspots are considered the most accurate and complete among alternative methods for detecting fires (Langner and Siegert, 2009) and correlations between the number of MODIS hotspots and the area burned on the ground is reasonably high, especially in peatlands ($R^2 = 0.75$ in Tansey et al., 2008). However, MODIS can miss fires that spread quickly or that are extremely short-burning, as the sensor passes only one or twice a day, and it can also miss ground fires in dense canopy if they do not produce sufficient heat (Ballhorn et al., 2009, Langner and Siegert, 2009). We therefore focus here on persistent fires, which are more likely to be detected as they emit heat during at least one satellite pass. Additionally, fires in peat are generally characterized by smoldering combustion, for which the rate of spread is quite slow, thus increasing their chances of detection over a multi-day period (Turetsky et al., 2015; Rein, 2013; Rollins et al., 1993; Wan Ahmad, 2001). However, smoke from fires can prevent their detection, and it is possible that we also miss ground fires under dense canopy, thus under-estimating the number of fires in forest, or peat fires that smolder underground before resurfacing. In Kalimantan and Sumatra, the omission rate for MODIS active fire detections has been estimated from 34 to 60%, depending upon the LULC class (Liew et al., 2003; Miettinen et al., 2007; Tansey et al., 2008).

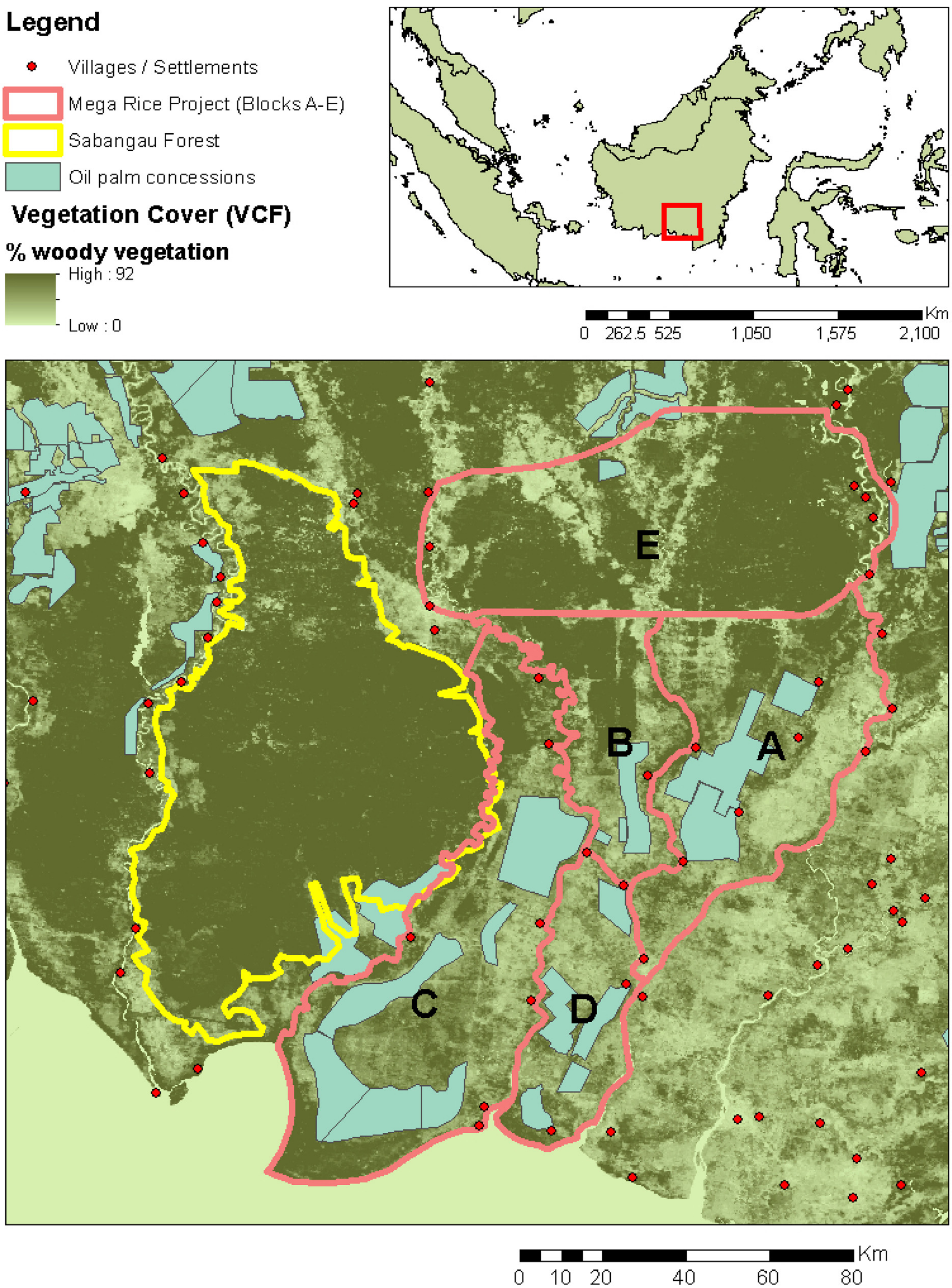

Fig. 1. The study area: lowland peat-swamp forest in Central Kalimantan, Indonesia, consisting of the failed Mega Rice Project (pink borders; letters indicate administrative zones) and the adjacent Sabangau Forest (yellow border), including the percent woody vegetation, legal oil palm concession boundaries, and major villages and settlement locations. Inset: Location within Indonesia. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

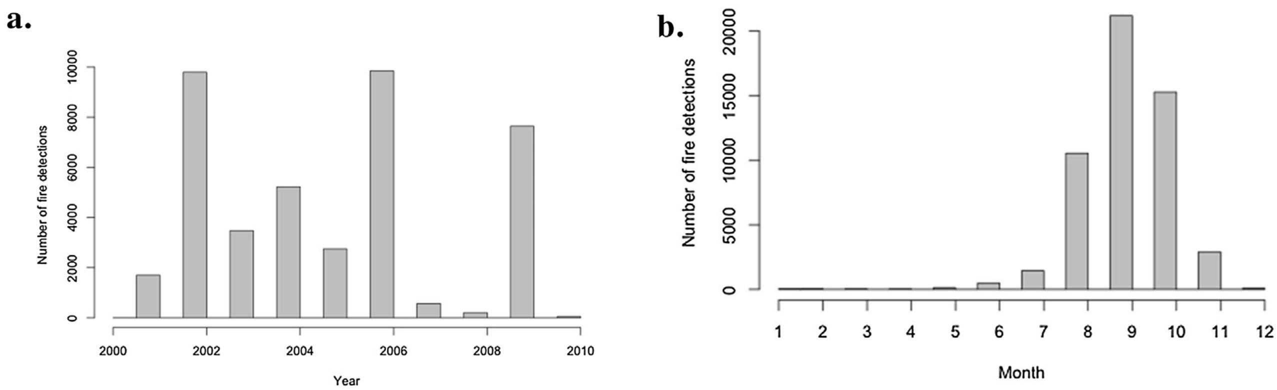

Fig. 2. Temporal pattern of fire in the study area 2000–2010: the number of MODIS fire detections per year and per month within the study area. Fire activity peaks during a. El Niño phases (2002, 2004, 2006, and 2009) and b. during the dry season months (August–October). Data source described below in *Data*.

We create a LULC layer at the annual temporal resolution consisting of oil palm concessions, forest, and non-forest classes. Oil palm concession boundaries according to the Indonesian Ministry of Forestry are obtained from the Global Forest Watch portal (WRI, 2014). Oil palm plantations almost certainly exist outside of these official concession boundaries, particularly small-scale plantations or plantations immediately adjacent to concessions, but these have not been mapped and so we focus on legal concessions in this analysis. According to these data, there are no wood fiber, rubber, or logging concessions in the study area. The forest and non-forest classes 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 (Dimiceli et al., 2011). 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. This classification is 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%. Because this classification is based on woody vegetation, it is possible that the forest class also includes some mature illegal plantations, particularly if trees are present. We use a relatively coarse non-forest class because degraded LULC classes can be highly spectrally variable and LULC verification points are not available for all possible degraded LULC classes. This non-forest class includes a relatively heterogeneous mixture of non-forest LULC classes, including fern-dominated, shrub/bushland, bare peat, and possibly even young plantations and some highly degraded forest. We assign non-forest conservatively to reduce classification error. Furthermore, land use policy for degraded areas in Indonesia is targeted at non-forest broadly (e.g., national policy to develop oil palm plantations on degraded land rather than primary forest or peatland) and more precise definitions of 'degraded land' vary between the relevant government institutions (e.g., Ministry of Environment and Forestry, Ministry of Agriculture, Land Agency). Finally, settlement locations, or points indicating the center of major villages and cities, are used to calculate distance from settlement across the study area.

2.3. Analysis

Data analysis covers the period from 2000 to 2010. We group multiple fire detections into single fire events, identify high-impact fires based upon fire duration and heat, and trace the LULC class on which that ignition occurs and to which that fire spreads. We also evaluate if increased anthropogenic activity in close proximity to oil palm concessions and settlements results in a detectable pattern of fire activity. Data processing is conducted in ArcGIS (ESRI, 2011) and the R programming environment (Team, 2012), and statistical analyses are conducted in R.

2.3.1. Grouping fire detections into single fire events and identifying high-impact fire events

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 (Miettinen et al., 2007; Langner and Siegert, 2009; Langner et al., 2007). 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 (Fig. 3). In the more conservative single-pixel technique, fire detections that occur within a given pixel are assigned to the same fire and fire detections in neighboring pixels are not included. Thus, fires are restricted to a 1 km^2 area, and fires are not allowed to spread beyond their pixel of origin. In the neighborhood-pixel technique, fire detections that occur within a given pixel or the eight adjacent pixels (3×3 window) are assigned to the same fire using hierarchical clustering with the 'dplyr' package in R (Wickham and Francois, 2014). Fires are not confined to one 3×3 window; they are allowed to spread provided there is a fire detection in a pixel adjacent to any pixel already within a given fire.

Because the MODIS Active Fire Product has a relatively high and variable rate of omission, we allow for fire detections that do not occur on consecutive days to be considered the same fire, to account for missed detections or subterranean fires that resurface. We use a variety of temporal thresholds (1, 2, 4, 6, 8, 10, 12, and 14 days) to define the temporal window in which fire detections are considered to originate from the same ignition event. We run all further analyses using the various temporal thresholds to designate fires. Thus, we use a relatively conservative four-day fire detection temporal threshold for all figures and tables in the remainder of the manuscript; this threshold is sufficiently high to account for the 60% upper omission rate for MODIS active fire detections and also the possibility of subsurface fires. Lower thresholds are even more conservative in terms of fire spread. We include results using the full range of temporal thresholds in Appendix A of Supplementary material.

Fires with a duration (determined by the difference in days between the earliest and latest fire detection date in each fire) and/or maximum heat (determined by the fire detection with the highest fire radiative power (FRP) in each fire) within the top decile of fires are considered "high-impact". This distinction is made because these factors affect the fires' potential environmental damage – for example, burning the seed bank in the soil (Van

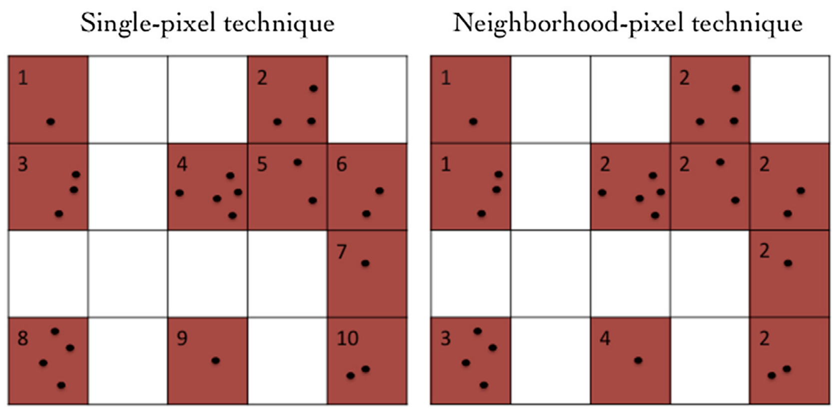

Fig. 3. An example of the methodology for identifying individual fire events from fire detections using (a) the single-pixel technique and (b) the neighborhood-pixel technique. Using the single-pixel technique, fire detections within a given temporal threshold and within the same pixel are assigned to the same fire (designated by the same number). Using the neighborhood-pixel technique, fire detections within a given temporal threshold and within the same and adjacent pixels are assigned to the same fire. In this example, all fire detections are all within the temporal threshold.

Nieuwstadt et al., 2001). Additionally, the fire detections with high-FRP and the long-duration fires tend to have consistently average to high detection confidence (Fig. A.1 in Appendix A of Supplementary material). We isolate the 'high-impact' fires for fires identified using both the single- and neighborhood-pixel techniques.

We evaluate the agreement between fire events identified with our model and finer spatial resolution data. We acquire Normalized Burn Ratio (NBR) data at the 30 m resolution based on surface reflectance generated by the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) for every Landsat 5 TM and Landsat 7 ETM+ scene (WRS 2 Path 118 row 62, covering 83.5% of the study region) with less than 10% cloud cover available from 2000 to 2010 from USGS Earth Resources Observation and Science (EROS) Center Science Processing Architecture (ESPA) On Demand Interface. For any two images fewer than 90 days apart, we calculate the differenced NBR (dNBR), for a total of 4 scene-pairs consisting of 6 scenes. We do not include image pairs with longer periods in between acquisition dates in order to avoid the confounding effects of seasonal changes. We create a binary burned – unburned raster by thresholding dNBR layers at 1500, based on-the-ground knowledge of the study area and visual inspection of burn scars seen in composite images of surface reflectance in the green, near infrared, and short-wave infrared parts of the spectrum (i.e., Landsat 5 TM and Landsat 7 ETM+ bands 2, 4, and 7), and also include results from using thresholds of 1000 and 2000 (Fig. A.3 in Appendix AA of Supplementary material). Because thresholding dNBR excludes areas that burn between the acquisition dates of the two scenes if that area is also burned in the first scene, we also include areas that were burned in the first scene (NBR is 2000 or lower). To compute a pixel-based error matrix (Table A.2 in Appendix A of Supplementary material), we sample our MODIS-derived fire layer and the Landsat-derived fire layer at approximately 2000 random points stratified by burn status as predicted by our algorithm. We also evaluate the polygon-based output of our algorithm by calculating the percent of the burned area predicted by our MODIS-derived fire layer that is predicted as burned by the Landsat-derived fire layer (Table A.3 in Appendix A of Supplementary material).

2.3.2. In which LULC classes do fires originate and to which LULC classes do they spread?

We consider the earliest fire detection in each fire event to be the ignition for that fire event. In some cases, fire events can have multiple ignitions if there are multiple fire detections with the same time stamp associated with that fire (Fig. 4). On the other hand, if the fire event consists of only one detection, ignition and detection are the same. We calculate the percentage of fire ignitions located on the different LULC categories, plus the percentage of fire ignitions in close proximity to settlements (within 1–5 km, which could include oil palm concessions, forest, or non-forest). Analyses of fire spread between LULC classes are restricted to fires identified using the neighborhood-pixel technique, as fires using the single-pixel technique were restricted to one pixel and, thus, cannot indicate fire spread. For each fire detection, we identify the LULC class in which the fire originates (i.e., the location of the earliest fire detection in the fire detection cluster) and calculate how many fire detections are associated with fires whose ignitions are located on the different LULC categories. We determine the density of ignitions per LULC class by dividing the number of ignitions in each LULC class by the area of that LULC class in the entire study region for each year and taking the mean.

2.3.3. 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 (i.e., have at least one fire detection outside of the concession boundaries). Similarly, we identify fires that escape from settlements by isolating fires that start near settlements (we use a 5 km threshold, following Stolle et al., 2003) and burn outside that boundary at some point during the burn. We determine if the mean duration in days and mean maximum FRP of these escaped fires are significantly different from all other fires in the study area using Welch's *t*-tests. We also test whether the difference is significant for all other fires that start on the same LULC class but are not escaped.

2.3.4. 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 using the MASS package in R (Venables and Ripley, 2002). Because we find no relationship between distance from oil palm concession and distance from settlement (e.g., most settlements are not necessarily found only

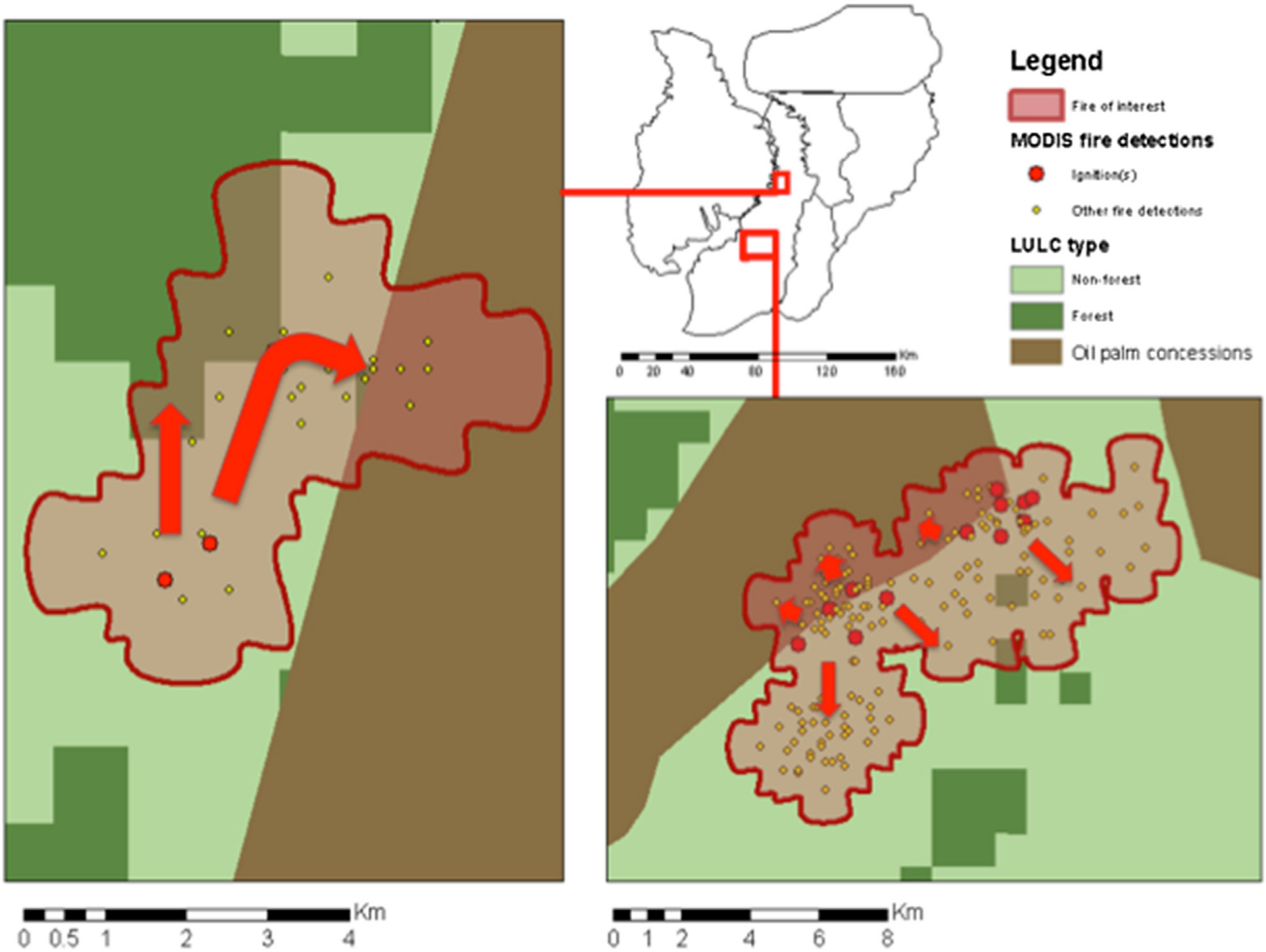

Fig. 4. Two examples of individual fires in the study area identified by clustering MODIS fire detections together based on spatial and temporal rules. One fire (left) starts in non-forest and spreads into both forest and oil palm concession. Another (right) starts from several ignition points near the boundary of oil palm concession and non-forest and spreads further into each of these LULC classes.

within close distances to oil palm concessions), these factors are evaluated separately. We fit exponential regression models for distance from oil palm concessions (binned into 50 m increments) 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). We fit a Ricker function of the form $y \sim ax\ exp\ (-bx)$, where y is the number of ignitions and x is the distance from settlements binned into 50 m increments, and estimate the parameters a and b using the 'nls' package in R. We select a Ricker model, which has been commonly used to model density-dependent population growth, 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. This function allows us to estimate $1/b$, or the distance from settlements at which ignitions peak. We also evaluate the relationship between both fire duration and maximum FRP with distance from both oil palm concessions and settlements after examining exploratory plots. We apply linear, second order polynomial, third order polynomial, forth order polynomial, and exponential regressions. We use fires detected using both the single-pixel and neighborhood techniques, using all fires and all high-impact fires.

3. Results

3.1. Grouping fire detections into single fire events and identifying high-impact fire events

For fires identified using the single-pixel and neighborhood detection techniques, mean fire duration is 1.6 ($\pm$1.6) days and 2.1 ($\pm$3.3) days, respectively, and mean maximum FRP is 45.7 ($\pm$65.0) MW_{th} and 43.8 ($\pm$79.6) MW_{th}, respectively. For both detection techniques, ~80% of fires burn for just one day (Fig. 5) The lower bound of high-impact fires, or the threshold above which a fire is considered high-impact, is 3 days or 95.1 MW_{th} using the single-pixel technique, and 4 days or 87.0 MW_{th} using the neighborhood-pixel technique, resulting in 19% and 18% of the fires being classified as 'high-impact,' respectively. See Fig. A.2 and Table A.1 in Appendix A of Supplementary materialA for characteristics of fires identified across the range of temporal thresholds. Overall pixel-based accuracy of fires identified by our algorithm is 73 ($\pm$3)% (see Table A.2 in Appendix A of Supplementary material for overall accuracy of fires identified by our algorithm broken down by each time period, as well as producer's and user's accuracy for burned

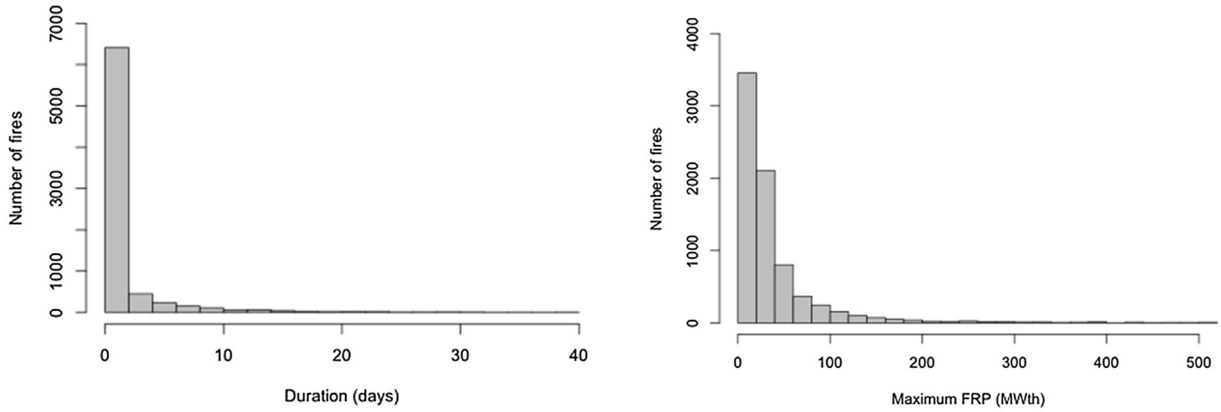

Fig. 5. Distribution of fire duration and FRP for all fires in the study area identified using the neighborhood-pixel technique.

and unburned land cover classes broken down by each time period). Polygon-based comparisons show that 34 (±4)% of the total area of fires identified by our algorithm is also identified as burned by Landsat-derived dNBR thresholded at 1500 (see Table A.3 in Appendix A of Supplementary material for percent broken down by each time period).

3.2. In which LULC classes do fires originate and to which LULC classes do they spread?

Fires ignited in non-forest areas have the biggest impact on the landscape. By far the majority of ignitions occur in non-forest (Table 1; Table A.4 in Appendix A of Supplementary material). The same pattern is found for 'high-impact' fires, and results are consistent when using both the single- and neighborhood-pixel detection techniques and across the temporal thresholds chosen to identify fires. When we evaluate fire spread between and among LULC classes, we find that the majority of fire detections are associated with fires that start on non-forest (Fig. 7; Fig. A.4 in Appendix A of Supplementary material). Fires that start on non-forest are also the primary ignition source for fires that burn non-forest itself and for fires that burn forest (Table 2 and Fig. 7; Table A.5 and Fig. A.4 in Appendix A of Supplementary material).

Fires that begin on oil palm concessions constitute approximately 20% of all fires and 20% of high-impact fires (Table 1; Table A.4 in Appendix A of Supplementary material). Fire detections from fires started on oil palm constitute 18% of all detections and 16–18% of detections associated with high-impact fires (Fig. 7; Fig. A.4 in Appendix A of Supplementary material). Most fires that burn oil palm concessions are started on the concessions. Fires that begin on oil palm concessions, however, are not the main source of ignition for fires on any other LULC class. The fewest fires originate in forest (Table 1; Table A.4 in Appendix A of Supplementary material). Fire detections from fires starting on forest constitute 7–13% of all detections and 7–12% of detections associated with high-impact fires (Fig. 7; Fig. A.4 in Appendix A of Supplementary material). The number of fires that are started close to settlements, which could occur on oil palm concessions, non-forest, or forest, are low in comparison (6–9%). A very low percentage of fires and high-impact fires are ignited close to settlements (Table 1; Table A.4 in Appendix A of Supplementary material).

Non-forest has the highest density of ignitions followed by oil palm concessions, and these LULC classes have an identical density of ignitions for high-impact fires (Table 1 and Fig. 6; Table A.4 in Appendix A of Supplementary material). For both all fires and high-impact fires, this is about ten times the density of ignitions in forest. The density of ignitions near settlements is 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. This density is higher than can be explained by LULC near the settlements alone. So, the density of fires near human settlements is high, but the overall contribution of fires near settlements is low.

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

Most fires that are started within oil palm concessions stay on the concession, and most fires that are started near settlements stay near settlements (Table 3; Table A.6 and Table A.7 in Appendix A of Supplementary material). However, high-impact fires that begin on oil palm concession and near settlements are more likely to escape than non-high impact fires. Although some fires, and particularly high-impact fires, do escape from oil palm

Table 1
The percent of all fire ignitions that are located in each land use/land cover class for fires identified using the single-pixel technique (fires less than or equal to 1 km) and the neighborhood pixel technique (fires allowed to spread beyond 1 km) and the density of those fire ignitions. Numbers for high impact fires are in parentheses.

		Land use / land cover class								
	Fire ID method	Oil palm concession	Forest outside of concession	Non-forest outside of concession	Multiple	Within 5 km	Within 4 km	Within 3 km	Within 2 km	Within 1 km
Percent of ignitions	Single-pixel	18.5 (16.8)	13.1 (13.4[a])	68.3 (69.5)	0.2 (0.3)	5.8 (3.1)	3.6 (1.9)	2.0 (0.8)	0.9 (0.4)	0.2 (0.1)
	Neighborhood-pixel	17.0 (17.7)	8.8 (9.3)	71.2 (68.3)	3.1 (4.6)	9.1 (6.0)	5.6 (3.4)	3.3 (1.8)	1.5 (0.9)	0.4 (0.3)
Density (ignitions km^{-2})	Neighborhood-pixel	0.055 (0.010)	0.006 (0.001)	0.060 (0.010)	NA	0.125 (0.015)	0.096 (0.011)	0.077 (0.008)	0.058 (0.006)	0.051 (0.008)

[a] Numbers in parentheses are for high-impact fires.

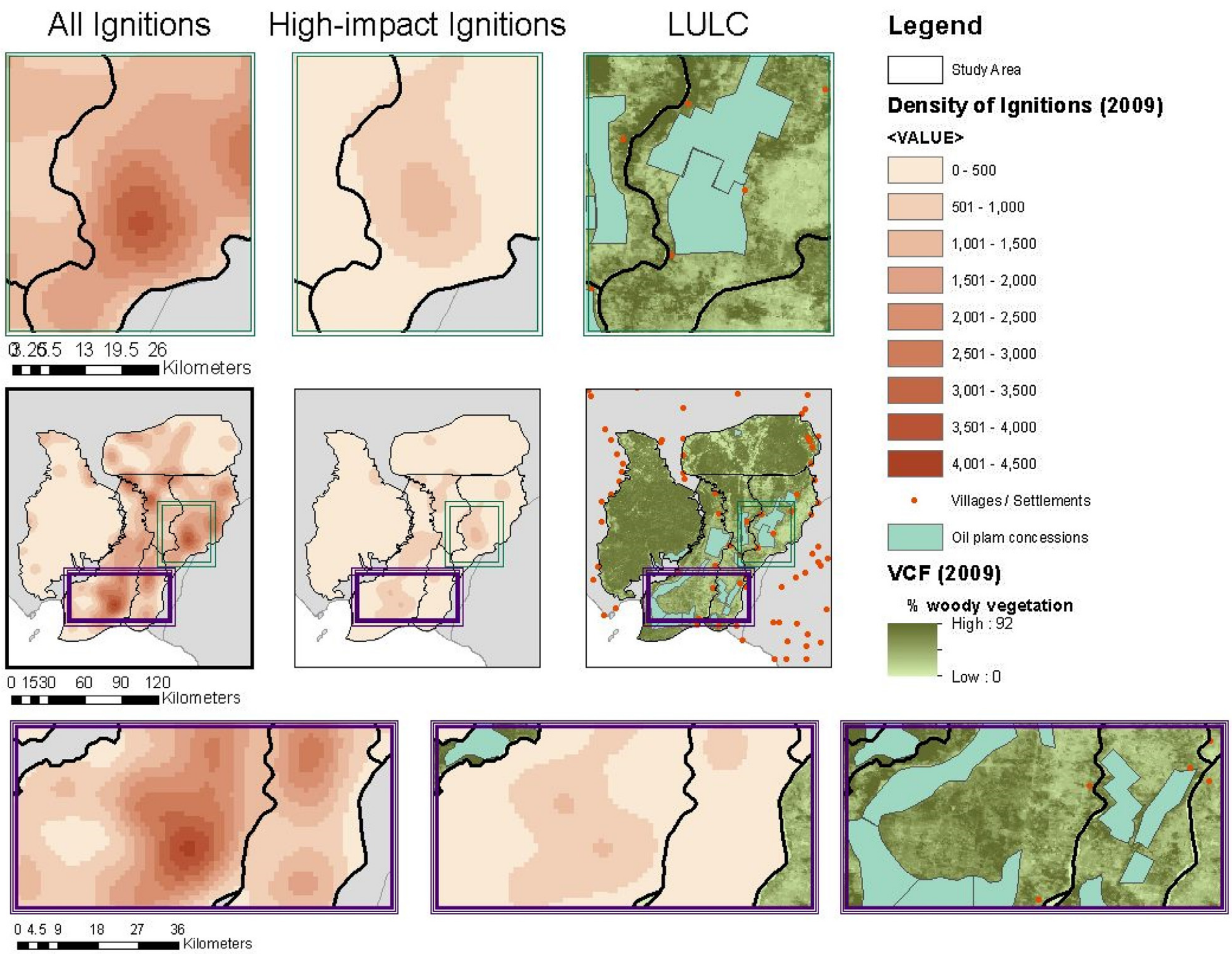

Fig. 6. Spatial distribution of the density of ignitions for all fires and for high-impact fires shown with LULC class. Top row: details of an area of high ignition density that occurs on oil palm concession. Middle row: the entire study area. Bottom row: details of an area of high ignition density that occurs on non-forest near oil palm concession. For all rows, from left to right: the density of ignitions for all fires, the density of ignitions for high-impact fires, and LULC class.

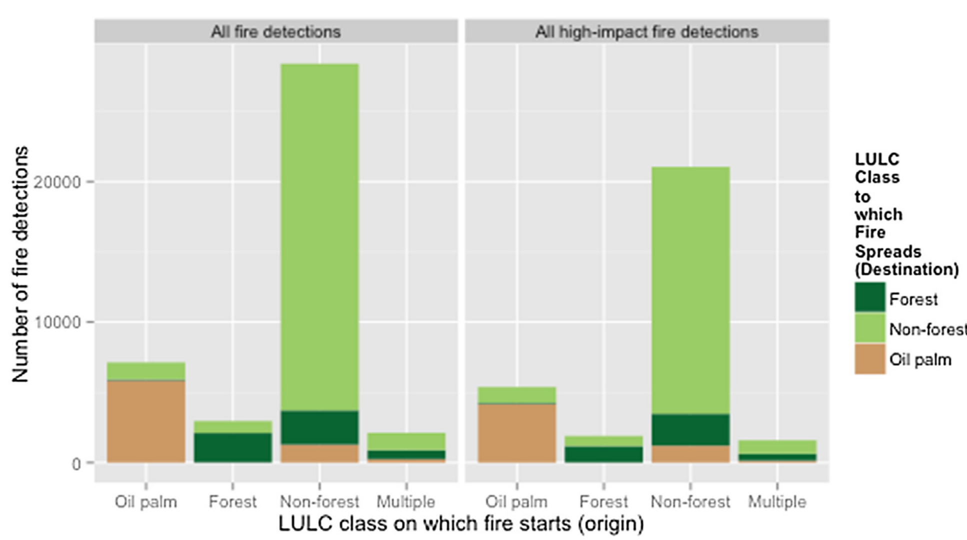

Fig. 7. Fire origin and spread for all fires and high-impact fires: The number of fire detections associated with fires that start on each LULC class (origin), broken down by LULC class to which the fire spreads (destination).

Table 2
The percent of all fire detections in forest that are associated with all fires and with high-impact fires that originate in each land use/land cover class.

Fire type	LULC class on which fire starts (origin)				
	Oil palm Forest	Non-forest	Multiple	Within 5 km of settlements	
All fires	1.5	39.9	46.4	12.2	2.4
High-impact	2.0	29.4	56.7	11.9	1.3

Table 3
Percent of total fires and total fire detections in the study area that start on oil palm concessions or that start within 5 km of settlements rather than other LULC classes, broken down into those which escape from the source LULC class and those which do not escape. In parentheses are the percent of fires and fire detections that start on oil palm concessions or that start within 5 km of settlements, which escape from the source LULC class and do not escape.

Land use class		Fire type	Percent of all fires that start on land use class	Percent of all fires (percent of fires that start on land use class) which escape from land use class	Percent of all fires (percent of fires that start on land use class) which stay on land use class
Oil palm concession	Percent of ignitions	All fires	17.0	1.8 (10.5[a])	15.2 (89.5)
	Percent of detections	High-impact	17.7	6.8 (37.3)	11.1 (62.7)
		All fires	17.5	3.1 (17.9)	14.4 (82.1)
		High-impact	17.9	4.1 (22.7)	13.8 (77.3)
Within 5 km of settlements	Percent of ignitions	All fires	10.2	1.2 (12.2)	8.9 (87.8)
		High-impact	6.8	3.0 (44.1)	3.8 (55.9)
	Percent of ignitions	All fires	5.0	2.2 (44.1)	2.8 (55.9)
		High-impact	3.4	2.4 (70.0)	1.0 (30.0)

[a] Numbers in parentheses are percent of fires that start on oil palm concessions rather than percent of all fires in the study area.

concessions and from settlements, they constitute only a small percent of total fires in the study area. Furthermore, these escaped fires do not serve as a notable ignition source for forest fires; a low percentage of forest fires are associated with fires that were ignited in oil palm concessions or close to settlements (Table 2; Table A.5 in Appendix A of Supplementary material). However, fires that escape from oil palm concessions or from settlements are higher impact than other fires, and have both a longer mean duration and a higher mean maximum FRP than both other fires that start in oil palm concessions or near settlements but do not escape and all other fires in the landscape (Table 4; Table A.8 in Appendix A of Supplementary material).

3.4. Do fire ignitions occur disproportionately in proximity to oil palm concessions and settlements?

Using both the single-pixel and neighborhood techniques, the number of ignitions of all fires and high-impact fires decreases exponentially with increasing distance from oil palm concessions, but fire duration and heat do not have a clear relationship with distance from oil palm concessions (Fig. 8; Fig. A.5 in Appendix A of Supplementary material). Although regressions between both fire duration and maximum FRP with distance from oil palm concessions are significant, they explain less than 1% of the variation in the duration of fires and the maximum FRP of fires identified using both the single-pixel and neighborhood techniques.

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, and then decreases (Fig. 8; Fig. A.6 in Appendix A of Supplementary material). Fire duration and maximum heat do not follow this trend. The distance from settlements at which the number of ignitions is at its maximum is 7.2 km (±0.2). Again, although regressions between fire severity and distance from settlements are significant, they explain very little of the variation in the duration of fires and the maximum FRP of fires.

4. Discussion

Our results provide only limited support to the claim that fires occurring on or escaping from oil palm concessions and settlements are major contributors to fire in this study region during our

Table 4
Mean duration in days and mean maximum FRP of fires that escape from oil palm concessions and from within 5 km of settlements, of fires that start on oil palm concessions and within 5 km of settlements but do not escape, and of all fires in the study area that do not start on oil palm concessions and from within 5 km of settlements.

Land use class	Mean duration (days)			Mean maximum FRP (MW_{th})		
	Escaped from land use class	Other fires that start on land use class	All other fires not started on land use class	Escaped from land use class	Other fires that start on land use class	All other fires not started on land use class
Oil palm concessions	6.7 (±6.6)	1.6 (±2.2)***	2.0 (±3.2)***	102.7 (±134.7)	34.2 (±39.2)***	42.7 (±77.9)***
Settlement	3.2 (±3.9)	1.3 (±1.6)***	2.1 (±3.3)**	84.5 (±144.4)	29.6 (±58.9)***	43.3 (±78.3)**

Significance codes for difference between denoted category and escaped fires: * < 0.05, ** < 0.01, *** < 0.001.

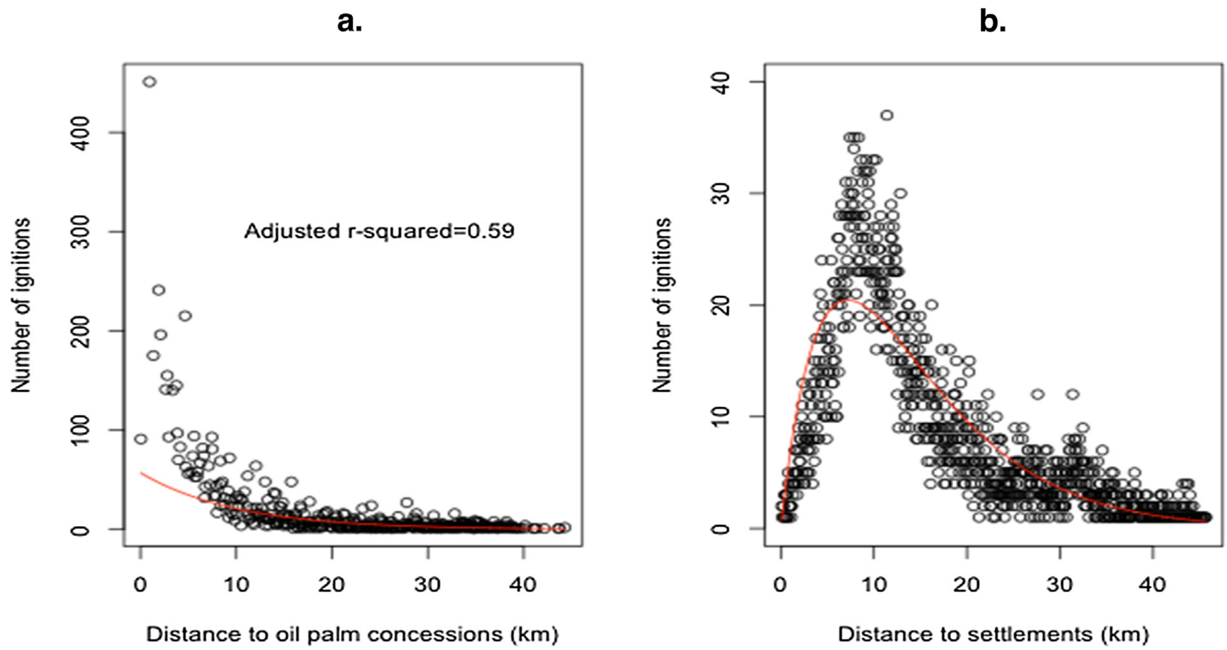

Fig. 8. The number of fire ignitions for all fires identified using the neighborhood-pixel technique as a function of a. distance from oil palm concessions with regression lines fitted for exponential models (Adjusted $R^2 = 0.59$, $p < 0.001$) and b. distance from settlements with regression lines fitted with a Ricker model.

study period. The vast majority of ignitions occurs in non-forested areas, a relatively heterogeneous mixture that includes fern-dominated, shrub/bushland, bare peat, plantations including very young oil palm (outside legal concession boundaries), and degraded forest. A relatively low but still substantial percentage of ignitions occur on oil palm concessions, and very few ignitions occur in close proximity to settlements. The majority of fires started within concessions or near settlements are confined to those boundaries, and a very low percentage of fires on the landscape are escaped fires from oil palm concessions or settlements into other LULC classes.

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 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 the oil palm industry to emissions and hazardous smog in the region (e.g., Stuart, 2012; Marlier et al., 2015b). 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 (e.g., Uriarte et al., 2012). 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. We find that increased anthropogenic activity around oil palm concessions and settlements increases the number of high-impact fires, indicating that fire reduction efforts are needed in these areas through both capacity building and awareness raising to increase the success of management interventions, establishment of effective fire-fighting teams, plus landscape restoration to reduce the predisposition of the landscape to burning. Additionally, because the density of ignitions in oil palm is nine times that in forest, and the density of ignitions within 5 km of settlements is over twenty times that in forest, it is clear that anthropogenic activity within oil palm concessions and settlements has the potential to contribute substantially to the fire landscape if these land use types continue to expand, and peat and fire management practices do not improve, particularly if fragmentation and/or climate change leave the landscape more predisposed to burning. Furthermore, these fires are not only well-managed fires that burn low-heat for a short period of time; the density of ignitions of high-impact fires in concessions and near settlements are 10 and 15 times that in forest, respectively.

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) and that emissions from fire are associated with highly degraded areas (Marlier et al., 2015a), 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 strategy 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. Achieving this goal among numerous smallholders is likely to prove even more difficult than reducing fire ignition and burning in oil palm concessions, however, as the latter have much greater capacity to implement consistent management policies over large areas and provide necessary management resources, and are under higher pressure to do so. There are some existing village-level fire teams (Regu Pemadam Kebakaran = RPK) and community groups for fire management (Kelompok Masyarakat Pengendali Kebakaran = KMPK1) operating in degraded, non-forest areas, but these groups are small-scale and under-funded. It is also easier to identify actors of illegal burning within concessions and bring prosecutions against a single concession holder, compared to numerous smallholders operating illegally in areas with ill-defined land ownership. This approach is likely to be even more challenging in very remote areas that are not being frequented or cultivated by smallholders, as much of this land is discarded wasteland. In these areas, regeneration efforts, including reforestation and hydrological restoration, will be key for fire reduction on the landscape. In making this recommendation, we recognize that some previous projects focusing on restoration in this area appear to have failed due to a combination of insufficient or inconsistent funding, land tenure concerns, misinformation between project organizers and local people, etc. (e.g., Atmadja et al., 2014). However, there are currently active restoration efforts on the ground. Based on our field experience, these efforts, much like the local fire teams, are effective but small-scale and underfunded. Indonesia has recently established a Peatland Restoration Agency with the goal of preventing peatland fires and restoring about 2 million ha of fire-damaged peatland across the nation. Although specific spatially explicit targets areas have not yet been identified, this agency could make peatland restoration more feasible by providing funding and capacity beyond that which is currently available in the region.

The low percentage of and density of ignitions in forest are consistent with the thesis that mature forest has low flammability due to lower levels of peat drainage, increased moisture conditions within a closed canopy and decreased anthropogenic activity (e.g., Langner et al., 2007). One limitation to our methods is that it is possible that small, low-heat fires, particularly those burning under a forest canopy, were missed from detection by MODIS. Thus, we may have underestimated the number of fire ignitions that occur in forest, but notwithstanding the fact that they are in forests, these small, low-heat fires are likely of lower importance in terms of ecological impact. On the other hand, because the forest class may include mature illegal plantations in addition to mature forest, some of the fire ignitions that we attribute to forest will actually have occurred on mature illegal plantations. In the case of tree plantations, low fire occurrence is likely related to more careful management to minimize the risk of damage to valuable mature crop resources.

While we cannot definitively identify the exact source or location of fire ignitions without extensive fieldwork on the ground, including fire forensics (e.g., fire-scene investigations or fire path reconstructions), this was beyond the scope of this study. Because we are assessing trends in fire activity over a large area of inaccessible terrain in which there are potential legal repercussions for igniting fire, fire activity detected empirically through satellite data provides a more comprehensive and unbiased picture than through interviews or empirical observations on the ground. Furthermore, the results of our analysis were not sensitive to the temporal threshold chosen to cluster fire detections into fires, showing that missed detections due to subsurface fires or smoke do not affect the trends in our results. When we compare the output of our algorithm with burned area products derived from satellite data with a finer spatial scale (Landsat dNBR), the overall accuracy of 73($\pm$3)% is reasonably high. However, because only 34 ($\pm$4)% of the total area of fires identified by our algorithm is also identified as burned by Landsat-derived dNBR, we are overestimating fires compared with the Landsat-derived dNBR data, meaning that we may overestimate fire spread. However, how long it takes post-fire regrowth to mask a fire scar from detection by Landsat in this study area is unknown and likely variable, and the Landsat scenes we use for validation are 32–80 days apart; thus, our algorithm, which uses data with a finer temporal resolution, may detect fires that the Landsat-derived dNBR data does not.

While it may be possible to pinpoint ignitions locations reasonably reliably with the methods that we developed, we do not recommend that these methods be used to assign responsibility to specific land owners or other actors for fire occurrence. Additionally, the underlying causes of fire can be both complex and site-specific (Dennis et al., 2005; Applegate et al., 2001; Bowen et al., 2000), and so management and policy actions need to take into account the diverse needs of all stakeholders. Important and complementary information that we cannot deduce through satellite data could be ascertained through interviews (e.g., motivations for lighting fires, willingness or ability to adapt alternative land clearing strategies, etc.). Institutional issues are also relevant to this conversation, as national and regional policies affect land use zoning (Stolle et al., 2003), and how these policies are implemented affects the behavior of stakeholders (e.g., communities and government agencies) on the ground. For example, when the customary laws under the *marga* system, which gave rights to forest resources to local communities, were replaced with current forest laws, local communities were left feeling marginalized, with little incentive to engage in fire-fighting efforts outside the boundaries of their plots (Bompard and Guizol, 1999). Recent law changes are now giving more forest rights back to communities, but there is concern that this too will lead to more forest destruction (Handadhari, 2015).

There has been an Indonesian national law banning corporations from using fire to clear land for palm-oil plantations since 1999 (Act No 41/1999), but it is unclear if the Indonesian government has the capacity to monitor or enforce burning bans or other fire reduction efforts, particularly since decentralization. In 2006, the provincial government in Central Kalimantan banned households and community plantations from using fire to clear land (Someshwar et al., 2010). After much resistance from local communities, the ban was softened in 2008 to incorporate seasonal forecasts informed by the Seasonal Fire Early Warning Tool developed by an international partnership (Wong et al., 2010); farmers are allowed to burn if climatic conditions indicate low fire risk. However, adherence to the ban in high-risk years would likely be low if local people were to feel that they had no choice but to burn to clear land or were unaware of official designated fire risk. Furthermore, the capacity to enforce the ban is limited, particularly in remote areas. Community outreach activities that not only inform local people about the importance of alternative land management strategies but enable them to adopt those strategies will be pivotal in restoration and fire prevention efforts on this degraded landscape (Page et al., 2009a). The ASEAN Agreement on Transboundary Haze Pollution sets the groundwork for international cooperation in fire monitoring and prevention, calls for national efforts, and also resulted in the development of a joint monitoring system. However, haze problems in the region have persisted since the Agreement came into effect in 2003. Additionally, Singapore enacted a Transboundary Haze Pollution Act in 2014, which places criminal and civil liability for haze pollution that reaches Singapore on the responsible agri-business entities. Responses to the recent fire crisis in the region will reveal how effective transboundary, national, and sub-national policy initiatives are in reducing fire in Indonesia. As of yet, efforts do not appear promising, as the haze problem continues to worsen and efforts on the ground have been largely inadequate despite the serious economic and health consequences of these fires.

Fire regimes are dictated by ignition source, the conduciveness of meteorological conditions for burning, and fuel availability (Stolle et al., 2003). Thus, while ignition is a key component to the fire regime because it is necessary for either an open or a smoldering self-sustaining fire, ignition *per se* does not necessarily lead to fire; there must also be sufficient fuel loads, appropriate air temperature and moisture, etc. We focus on ignitions themselves, following the recommendations of Vayda (2006) who makes a call for a distinction between research approaches addressing factors responsible for ignition versus fire occurrence. However, understanding the factors that predispose the landscape to burning is also critical to understanding the fire regime, including altered hydrology from drainage canals for agricultural development, logging history and other vegetation changes, climate change, and fire history itself, all of which can alter the probability of fire occurrence and spread. Certainly more research is needed on the relative influence of various biophysical and anthropogenic factors on increasing fire probability. Because ignition will not turn into a fire if there are sufficient biophysical or spatial controls, management or policy interventions focused on ignitions should be focused on reducing the prevalence of conditions under which fires can and do result (i.e., where ignitions could potentially lead to fire because they are not constrained biophysically), in addition to behavior change leading to reduced ignitions. Additionally, promoting less-flammable LULC classes that may help buffer ignitions could also reduce fire on the landscape (e.g., allowing degraded or logged-over forest to recover or even actively restoring it rather than allocating it for conversion).

5. Conclusions

Fires in Indonesia have consequences from the local to global scale, including burning forest that is home to endemic and endangered flora and fauna, emitting haze that compromises human health and impacts economies across the region, and converting peatlands from a major carbon sink to a major source of CO_2. Identifying the sources of fire ignitions and LULC classes associated with fire ignitions is a key factor for reducing fire on this landscape, as this will allow us to more pointedly target management and policy interventions. Results of this research, which uses remotely sensed data and modeling to analyze ignition sources and fire spread in tropical peat-swamp forest in Central Kalimantan from 2000 to 2010, indicate that most fires (68–71%) 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 17%–19% of fires are ignited on oil palm concessions, and that most fires that start on oil palm concessions stay on the concession (90%), with the relatively few escaped fires from concessions constituting a very low percentage of fires on the landscape (2%). Similarly, few fires start within 5 km of settlements (6–9%), most stay within those boundaries (88%), and fires escaping from settlements constitute only 1% of fires on the landscape. 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 land management activities on oil palm concessions or areas around settlements, but should also focus strongly on disaggregated activities on non-forested, degraded areas –and in particular those near oil palm concession boundaries and outside the immediate vicinity of settlements – where ignitions are most likely to occur. Addressing these issues within degraded, unmanaged, or illegally planted non-forest areas is likely to prove even more challenging than addressing them within oil palm concessions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2016.05.005.

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