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LETTER

Fire emissions and regional air quality impacts from fires in oil palm, timber, and logging concessions in Indonesia

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Abstract

Fires associated with agricultural and plantation development in Indonesia impact ecosystem services and release emissions into the atmosphere that degrade regional air quality and contribute to greenhouse gas concentrations. In this study, we estimate the relative contributions of the oil palm, timber (for wood pulp and paper), and logging industries in Sumatra and Kalimantan to land cover change, fire activity, and regional population exposure to smoke concentrations. Concessions for these three industries cover 21% and 49% of the land area in Sumatra and Kalimantan respectively, with the highest overall area in lowlands on mineral soils instead of more carbon-rich peatlands. In 2012, most remaining forest area was located in logging concessions for both islands, and for all combined concessions, there was higher remaining lowland and peatland forest area in Kalimantan (45% and 46%, respectively) versus Sumatra (20% and 27%, respectively). Emissions from all combined concessions comprised 41% of total fire emissions (within and outside of concession boundaries) in Sumatra and 27% in Kalimantan for the 2006 burning season, which had high fire activity relative to decadal emissions. Most fire emissions were observed in concessions located on peatlands and non-forested lowlands, the latter of which could include concessions that are currently under production, cleared in preparation for production, or abandoned lands. For the 2006 burning season, timber concessions from Sumatra (47% of area and 88% of emissions) and oil palm concessions from Kalimantan (33% of area and 67% of emissions) contributed the most to concession-related fire emissions from each island. Although fire emissions from concessions were higher in Kalimantan, emissions from Sumatra contributed 63% of concession-related smoke concentrations for the population-weighted region because fire sources were located closer to population centers. In order to protect regional public health, our results highlight the importance of limiting the use of fire by the timber and oil palm industries, particularly on concessions that contain peatlands and non-forest, by such methods as improving monitoring systems, local-level management, and enforcement of existing fire bans.

1. Introduction

Primary forest clearance in Indonesia totaled 6.02 Mha from 2000 to 2012 (Margono *et al* 2014), with some of the highest deforestation rates observed in carbon-rich peatland forests in Sumatra and Kalimantan (Miettinen *et al* 2011, Margono *et al* 2014). Forty-five percent of Indonesia's deforestation from 2000 to 2010 was observed on oil palm, timber, logging, and coal mining concessions (Abood *et al* 2015) and by 2010, industrial plantations covered 2.3 Mha of peatlands in Sumatra and Kalimantan, with approximately 70% developed since 2000 (Miettinen *et al* 2012a). Fires are considered to be a cheap and effective method to clear and maintain land for agricultural and plantation development (Simorangkir 2007), but also damage biodiversity, reduce carbon storage potential, and can severely degrade regional air quality. Air quality impacts are not limited to source regions (primarily in central and Southern Sumatra and Southern Kalimantan), but can be transported in the atmosphere to affect transboundary locations such as Singapore (Hyer and Chew 2010, Atwood *et al* 2013, Reddington *et al* 2014, Kim *et al* 2015). Previous work has demonstrated that population exposure to smoke concentrations is highly dependent on the spatial location of fire emissions and the extent of burning on peatlands (Heil *et al* 2007, Kim *et al* 2015), but has not tested the relative contribution of different industries to fire emissions and regional air quality degradation due to enhanced concentrations of fine particulate matter (to which fires contribute black and organic carbon).

Fire activity in Indonesia is driven by complex interactions between climate, land cover, and land management. While drought conditions, such as during El Niño events, increase the flammability of fuel sources by causing vegetation to shed leaves and lower moisture content (Goldammer 2007), visibility records since the 1960s indicate that before intensive land use development and higher population densities in Sumatra and Kalimantan, severe fires did not occur (Field *et al* 2009). El Niño conditions not only increase the potential for vegetation to burn by drying fuels, but reduced aerosol scavenging due to low precipitation and wind patterns that transport emissions from source regions towards population centers can promote regional haze development (Heil *et al* 2007). Recent observations in Sumatra have also indicated that intense, localized fire events can occur during brief drought periods (~2 months) during non-El Niño conditions (Gaveau *et al* 2014).

Peatland drainage exposes peat at the surface, where it is highly susceptible to fires and releases emissions during the peat oxidation process (Wösten *et al* 2008). Fire activity is concentrated in heavily degraded (logged) peatland forests instead of intact peatland forests, which typically leads to further degradation by fires either unintentionally or for conversion to managed land uses like plantations and agriculture (Miettinen *et al* 2012a, Romijn *et al* 2013). In addition, fire regimes vary according to land management, with annual large-scale land clearance fires observed repeatedly in highly managed Sumatran peatlands contrasted with more weather-dependent fires occurring during drought conditions in unmanaged Kalimantan peatlands (Miettinen *et al* 2010). This confirms work from Sumatra that logging companies tend to control fires within their concessions but found higher fire activity in previously logged-over forests and forests within concession boundaries that are not under production (Stolle *et al* 2003), in addition to the observation of high fire activity in previously burnt areas, which could suggest the early stages of plantation conversion as well as the susceptibility of extremely degraded peatlands to fire (Miettinen *et al* 2012b).

In May 2011, Indonesia announced a moratorium on granting new concession licenses in primary forests and peatlands while working towards land use planning reforms that would help Indonesia achieve its greenhouse gas reduction targets (Austin *et al* 2012). However, recent work analyzing the effect of this moratorium indicates that it would have offered only slight reductions (~5%) in national greenhouse gas emissions from deforestation if the policy had been in place over the prior decade (Busch *et al* 2015). In addition, it remains unclear how much fire activity was associated with deforestation and management within different concession types during this time period. Logging concessions tend to have much lower deforestation rates than oil palm or timber concessions (Abood *et al* 2015, Busch *et al* 2015); Gaveau *et al* (2012, 2013) found that, after controlling for geographic access, deforestation rates in Sumatra and Kalimantan were not significantly different between protected areas and logging concessions where conversion to plantations is not permitted. However, given the tendency of logging concessions to be reclassified into other types of plantations (Gaveau *et al* 2013) and with 35% of Indonesia's remaining forest area located within industrial-scale (not smallholder) concessions (Abood *et al* 2015), it is crucial to understand differences among various industries regarding both deforestation and fire activity, along with the subsequent impacts on air quality and public health.

Though much attention has focused on the role of the oil palm industry with regards to deforestation, peatland destruction, fires, and initiatives such as the Roundtable on Sustainable Palm Oil (http://rspo.org/), we aim to compare deforestation and fires in oil palm concessions with other industries in Indonesia. Building on previous work in Indonesia that has examined the relative changes in forests and carbon stocks by industry type (Abood *et al* 2015, Busch *et al* 2015) and the overall contributions of fire emissions to regional air quality (Hyer and Chew 2010, Atwood *et al* 2013, Reddington *et al* 2014, Kim *et al* 2015), we address the following questions: (1) What were the fire patterns associated with oil palm, logging, and timber concessions from 2003 to 2013, (2) How did the patterns of fire activity on peatlands vary by concession type, and (3) How much did each concession type contribute to smoke concentrations at various receptor sites in the region?

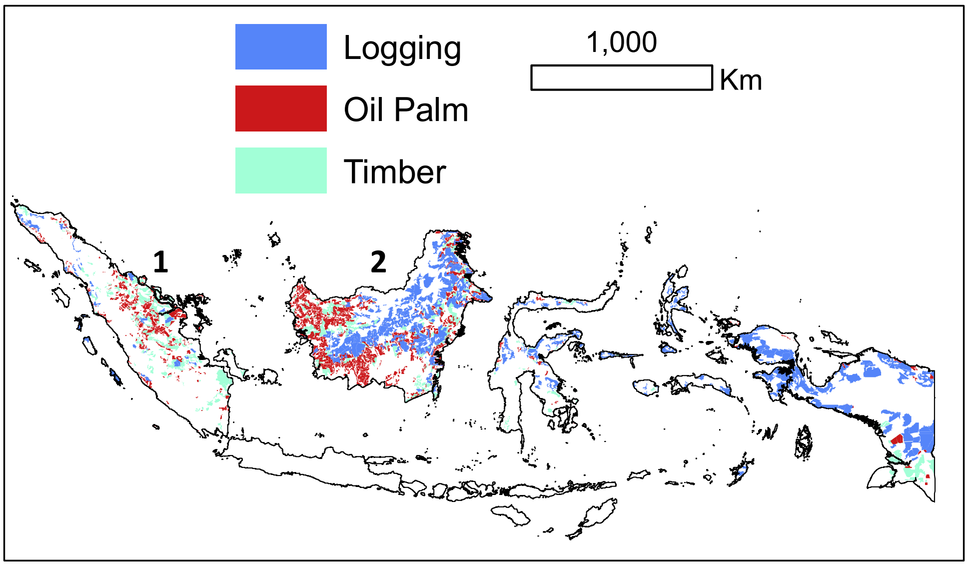

Figure 1. Distribution of logging, oil palm, and timber (for wood pulp and paper) concessions across Indonesia based on data from the Indonesian Ministry of Forestry (World Resources Institute 2015a, 2015b, 2015c). Our analysis is focused on concessions in (1) Sumatra and (2) Kalimantan.

2. Data and methods

2.1. Concessions

Concession boundary data for industrial-scale oil palm (World Resources Institute 2015b), timber (World Resources Institute 2015c), and logging (World Resources Institute 2015a) are available from the Global Forest Watch based on data provided by the Indonesian Ministry of Forestry. This data includes boundaries current or planned by 2010, although the precise year is not available. Oil palm refers to industrial-scale concessions for oil palm plantations. Timber refers to plantations of fast-growing tree species for wood pulp and paper production. Logging refers to concessions to manage natural forests for selective timber extraction. As shown in figure 1, the largest concession areas are found on the islands of Sumatra and Kalimantan, which are the focus of the remainder of this analysis. Although concession areas in Papua are also relatively high (figure 1), primarily attributed to logging concessions, 74–94% of forest cover was remaining in each concession type and fire activity was substantially lower than Sumatra and Kalimantan (figure S1). Papua is therefore not considered in this analysis, although it may become an important fire source in the future. Overlapping boundaries between oil palm, timber, and logging concessions are hereafter referred to as 'mixed'.

2.2. Land cover

We overlaid concession boundaries on land cover and landform classification maps for Indonesia provided by Margono *et al* (2014). This dataset, available for 2000, 2005, 2010, and 2012, separates land cover into three classes: (1) primary intact forest: mature natural forest that retains natural composition and structure, (2) primary degraded forest: subject to forest utilization and partial canopy loss, and (3) non-forest, defined by tree height <5 m and canopy cover <30%, and including plantations, agriculture, degraded lands, and urban areas. Landform types from Margono *et al* (2014) include lowlands, wetlands, upland, and montane. We aggregated the original 30×30 m data to 1 km^2 resolution by dominant land cover type to match fire observation data (see below). In addition, we created a fifth landform class for peatlands developed by Wahyunto *et al* (2003, 2004) to separately delineate peatland areas, since they contain substantial belowground carbon stocks with the potential for high fire emissions (Page *et al* 2011). The distribution of peatlands in Sumatra and Kalimantan is shown in Supplementary figure S2.

2.3. Fire observations

We used fire radiative power (FRP, measured in MW) observations from the MODIS Aqua and Terra satellites to analyze the differences in fire activity associated with each concession and landform type. FRP is a measure of the radiant energy released by a fire and is related to fuel consumption and emissions (Wooster *et al* 2005). We used the MOD14A1 and MYD14A1 products at 1 km^2 resolution (available at https://lpdaac.usgs.gov/), representing 10:30 am and 1:30 pm local overpass times (Giglio *et al* 2003, Giglio 2010). Given uncertainty in the timing of when concessions were granted and management started, we overlaid ten years of FRP data (2003–2013), but acknowledge differences in concession boundaries and development over time as previously described.

Fire emissions associated with concession types were estimated by combining high-resolution FRP observations (1 km^2) with more comprehensive, but lower spatial resolution, information from the Global Fire Emissions Inventory (GFED3) on the relationship between fire activity and emissions. GFED3 combines satellite observations of burned area and active fires to drive a biogeochemical model that estimates fuel loads, combustion completeness, and emissions (van der Werf *et al* 2010). In addition, given the large proportion of small (<25 ha) burn scars in this region (Miettinen and Liew 2009), we included a correction dataset for small fires that may have been missed by the original GFED3 mapping algorithm, which increased fire emissions from Equatorial Asia by 55% from 2001 to 2010, and increased the resolution to 0.25° × 0.25° (Randerson *et al* 2012).

In order to estimate fire emissions at a finer spatial resolution more relevant to concession maps, we downscaled total GFED3 fire emissions, in mass of dry matter (DM) combusted per unit area, for the July to November burning season of 2006 (a high fire year), in proportion to the monthly sum of 1 km^2 FRP detections, relative to the sum of all 1 km^2 FRP detections with each 0.25° × 0.25° GFED grid cell. We then estimated individual fire emissions inventories by overlaying concession boundaries on the downscaled (1 km^2) GFED3 dataset. These emissions were ultimately scaled to 0.50 × 0.67° resolution for the atmospheric model and converted to black and organic carbon, using vegetation-specific emissions factors for burning from peatlands, forests, agricultural waste, savannas, and woodlands (van der Werf *et al* 2010).

2.4. Adjoint model

We used the adjoint of the GEOS-Chem chemical transport model (Bey *et al* 2001, Henze *et al* 2007) to determine the sensitivity of smoke concentrations (primary fine particulate matter), defined here as organic carbon and black carbon, at various receptor sites to the spatial distribution of fire emissions. First, we completed forward model runs with GEOS-Chem v8-02-01 (www.geos-chem.org), which is driven by assimilated meteorological data from the Goddard Earth Observing System (GEOS-5) of the NASA Modeling and Assimilation Office (GMAO). Fire emissions are released into the boundary layer and generally remain in the atmosphere for 1–2 days (Pan *et al* 2013), during which time they can be transported throughout the region depending on windspeed and direction. We then determined the sensitivities of smoke concentrations to fire emissions at three receptors: Singapore, Palembang (in Southern Sumatra), and population-weighted Equatorial Asia, in which the sensitivities of each grid cell were weighted according to the population of that grid cell (figure S3). These receptors were selected as examples of transboundary, national, and regional population centers that have been repeatedly impacted by smoke exposure given the prevailing Southwesterly flow during the burning season (Kim *et al* 2015), but the adjoint model can be used at other locations as well. Sensitivities were calculated for fire emissions during the 2006 burning season with the adjoint model (version 34) at 0.50 × 0.67° resolution and were applied to each of the three concession types. A moderate El Niño took place in 2006, so these sensitivities are characteristic of such meteorological conditions. In addition, boundary layer wind patterns for 2006 were representative of 2004–2010 mean conditions (Kim *et al* 2015). See Kim *et al* (2015) and Marlier *et al* (2015) for a detailed description of the model set-up.

3. Results

3.1. Concessions and forest cover

Concessions cover 21% of the land area in Sumatra and 49% in Kalimantan. For both islands, most concessions were located in lowlands on non-peat soils (figure 2, top row). The highest concession areas were found in oil palm and timber concessions in Sumatra and oil palm and logging concessions in Kalimantan. Concession area in Kalimantan was higher than Sumatra by a factor of 3, driven by an order of magnitude higher area in logging concessions. The proportion of concessions in peatlands relative to all other landform types was 32% in Sumatra and 10% in Kalimantan.

Using the 2012 land cover data available from Margono *et al* (2014), we determined the remaining intact or degraded forest area located within concession boundaries (figure 2, bottom row). In Sumatra, most of the remaining forest area in 2012 was in logging or timber concessions, with a similar amount in lowlands and peatlands. For all concessions combined, 77% and 62% of upland and montane concessions, respectively, were still classified as forest in 2012, while lowlands, peatlands, and wetlands were between 13–27% of remaining forest. Kalimantan's remaining forest area was mostly within logging concessions with the overall highest area in lowlands. There was higher remaining 2012 forest area in Kalimantan versus Sumatra for all concessions combined, with lowlands, peatlands, and wetlands between 33 and 46% and uplands and montane areas at 86% and 100%, respectively.

3.2. Fire activity

We examined FRP observations within concession types on an annual basis (figure 3, top row) and by landform type (figure 3, bottom row). Given uncertainties in the timing of concession licenses and development, we present data for 2003–2013 but acknowledge that for some concessions this time period likely captures fire observations preceding

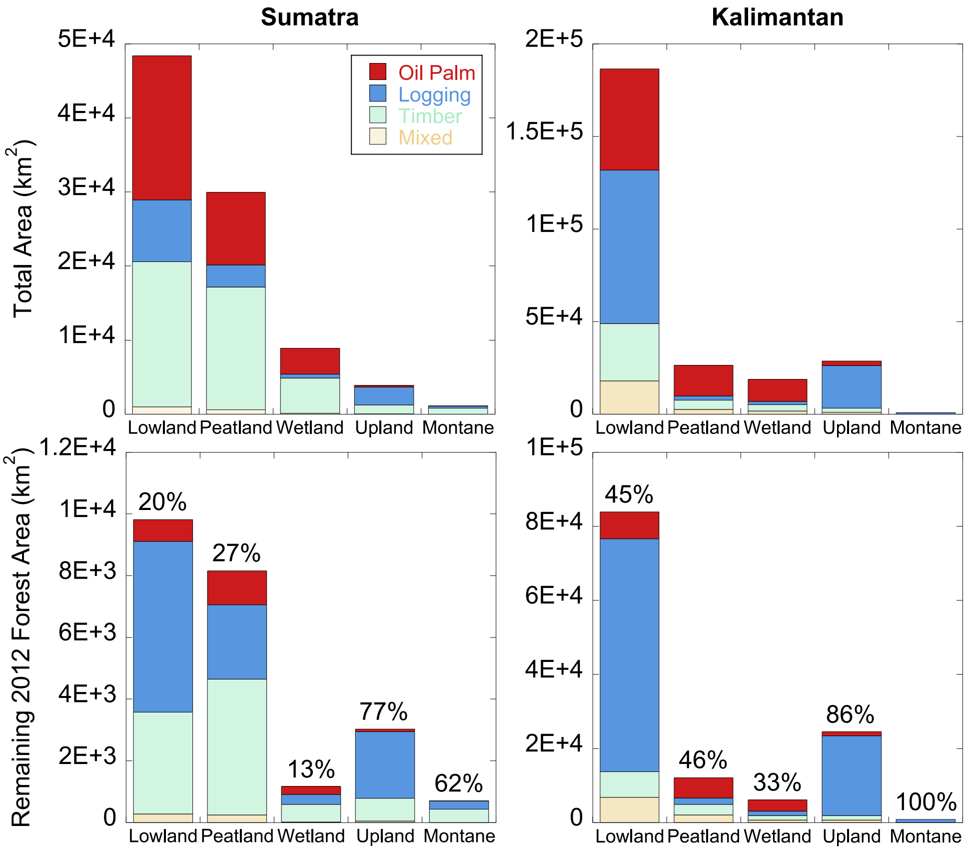

Figure 2. Total concession area (km^2) by island and landform type for oil palm, logging, timber, and mixed concession types (top row). Remaining intact and degraded forest area (km^2) in 2012 (bottom row), with percentages indicating 2012 forest area relative to the total area of all concessions, for each landform type.

official concession licensing. Sumatra's highest annual FRP was found in timber concessions, with a maximum observed in 2005. Despite having lower concession area in Sumatran peatlands (figure 2; 38% of total concession area), the corresponding 2003–2013 FRP comprised 69% of the total. FRP observations in Kalimantan were highest in oil palm concessions (33% of area and 57% of FRP relative to all concessions), with peatlands contributing 24% of total FRP from all landform types. Annual fire activity peaked in 2006 in Kalimantan.

We then analyzed fire emissions by concession type using downscaled GFED3 fire emissions (in Tg DM) for the 2006 burning season. 2006 was a high fire year, but we include 2009 as a part of a sensitivity analysis (table S1) and found that the relative contribution of each concession type was similar. Using the peatland mask from Wahyunto *et al* (2003, 2004) and land cover distribution from Margono *et al* (2014), table 1 gives the percentage of emissions originating from fires in peatlands, forested areas, and non-forested areas on each concession type, relative to the total emissions from all concessions for each island. Note that deforestation and non-forest emissions do not include any fires on peat soils. In Sumatra, timber plantations represented 86% of the fire emissions from all concession types (compared with 47% of concession area), with most from peatland areas. Oil palm plantations in Sumatra represented 13% of the emissions relative to all concession types. The contribution of timber emissions relative to all concessions was higher than was observed in the FRP analysis, mostly due to the focus here on the burning season only and the contribution of peat emissions from timber concessions. In Kalimantan, oil palm and timber plantations represented 65% and 26%, respectively, of emissions from all concessions (compared with 33 and 16% of concession area). Sixty-two percent of concession emissions from Sumatra were from peatlands and 35% from non-forested areas, whereas in Kalimantan, 51% of concession emissions were from non-forested areas and 36% from peatlands. In contrast to forested areas, non-forest and peatlands were also more likely to burn multiple times, especially when located within oil palm and timber concessions (figure S4).

3.3. Regional air quality impacts

We converted total DM to $PM_{2.5}$ emissions using vegetation-specific emissions factors (van der Werf *et al* 2010). The emissions were implemented into the GEOS-Chem adjoint model, in order to estimate the contribution of fires from each concession type to smoke concentrations for various receptor sites within the region for the 2006 burning season (table 2, figure 4). Emissions from concessions in Sumatra

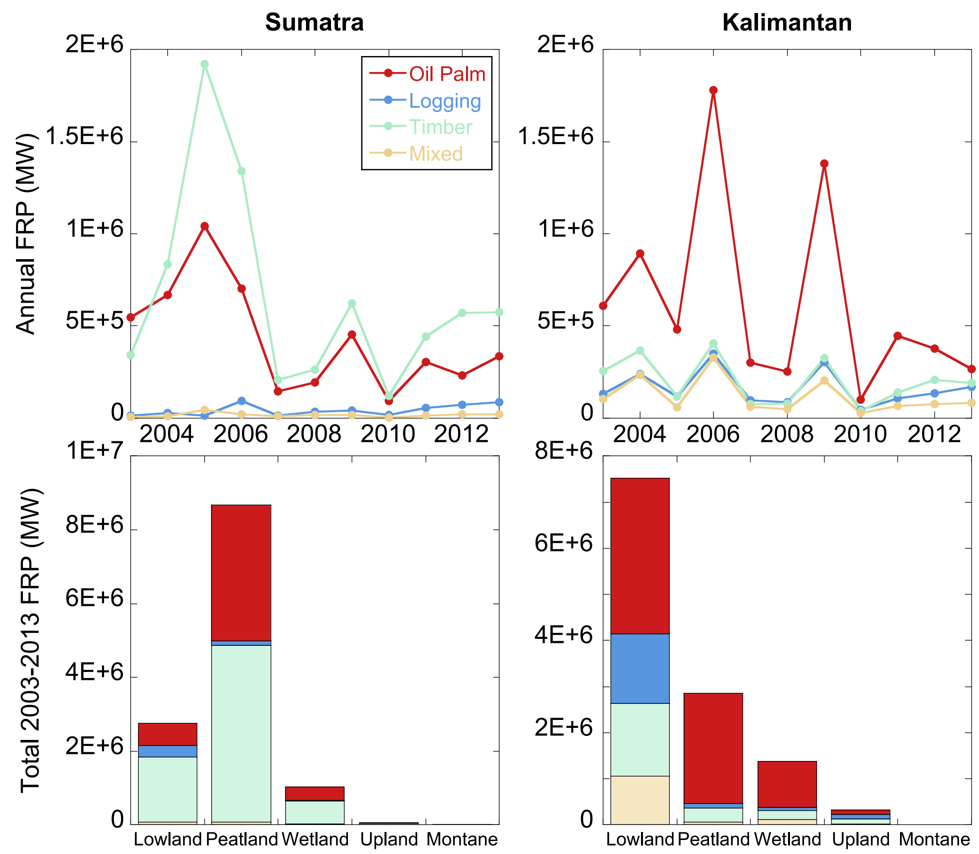

Figure 3. Annual FRP (MW) for 2003–2013 by island and landform type for oil palm, logging, timber, and mixed concession types (top row). Total FRP (MW) from 2003 to 2013 by landform type (bottom row).

Table 1. Contribution of individual concession types to fire emissions estimates for July to November 2006 (in % of emissions from all concessions, by island). Total concession emissions from Sumatra and Kalimantan were 79 Tg and 91 Tg dry matter (DM), respectively. DEF = deforestation, PET = peatland, and NF = non-forest fires. Mixed concessions are due to overlapping boundaries of oil palm, timber, and/or logging concessions.

	Sumatra (79 Tg DM total)			Kalimantan (91 Tg DM total)		
Fire Source	DEF	PET	NF	DEF	PET	NF
Oil palm	1%	5%	7%	7%	32%	26%
Timber	3%	56%	27%	3%	4%	19%
Logging	0%	1%	0%	1%	0%	1%
Mixed	0%	0%	1%	2%	0%	5%

comprised 41% of all emissions from fires within and outside of concession boundaries for this period (using the 1 km^2 downscaled GFED3 product for consistency). Relative to the combined contribution of oil palm, timber, logging, and mixed concessions in Sumatra, timber concessions contributed 93%, 98%, and 90% for Singapore, Palembang, and population-weighted Equatorial Asia. Most emissions from timber concessions in Sumatra were from peatlands (table 1). In Kalimantan, fires from concessions comprised 27% of all fire emissions (within and outside of concessions). Compared to the combined contribution from all concession types, oil palm concessions in Kalimantan contributed 71%, 74%, and 54% to smoke concentrations in Singapore, Palembang, and population-weighted Equatorial Asia.

3.4. Limitations and uncertainties

There are several uncertainties associated with the datasets used in this analysis. First, we attributed all land cover change and fire activity to the area within each industry's concession, though it is possible that some of this fire activity was due to escaped fires from other areas or from fires were used by smallholders or during land tenure disputes, but not by the concession owner (Dennis *et al* 2005). We also do not consider activities by companies that occur outside of legal boundaries. Second, we overlaid eleven years of FRP observations (2003–2013) on the spatial distribution of concessions (figure 3), though there are likely some discrepancies in the timing of granting plantation leases, as well as differences in initial clearing and management fires among individual concessions. The FRP analysis included a longer time period (2003–2013) than the emissions and air quality estimates, which could overestimate the FRP contributions of certain concessions. Third, there are uncertainties with using GFED3 emissions, which are estimated at 20% globally and more in Equatorial Asia due to peat burning (van der Werf *et al* 2010). Fourth, although we observed low forest clearance and fire

Table 2. July to November 2006 fire emissions (in 10^9 g $PM_{2.5}$) and the contribution of individual concession types to smoke concentrations ($PM_{2.5}$, in $\mu g\ m^{-3}$) in Singapore, Palembang, and population-weighted Equatorial Asia. Mixed concessions are due to overlapping boundaries of oil palm, timber, and/or logging concessions, 'All Concessions' refers to the sum of all individual concession types, and 'Total GFED' refers to all fires within and outside of concession boundaries.

	Sumatra				Kalimantan			
Source	Emissions	Singapore	Palembang	Eq. Asia	Emissions	Singapore	Palembang	Eq. Asia
	(10^9 g)	(Smoke contribution in $\mu g\ m^{-3}$)			(10^9 g)	(Smoke contribution in $\mu g\ m^{-3}$)		
Oil palm	48.9	0.1	1.2	0.1	510.5	0.6	0.2	0.4
Timber	434.4	1.6	60.1	1.1	183.4	0.2	0.06	0.3
Logging	5.7	0.03	0.00	0.01	16.1	0.00	0.00	0.01
Mixed	4.5	0.00	0.01	0.01	52.0	0.05	0.01	0.03
All Concessions	493.5	1.8	61.34	1.3	762.0	0.8	0.2	0.7
Total GFED3	1207.3	3.8	156.2	3.3	2845.5	3.2	1.1	3.0

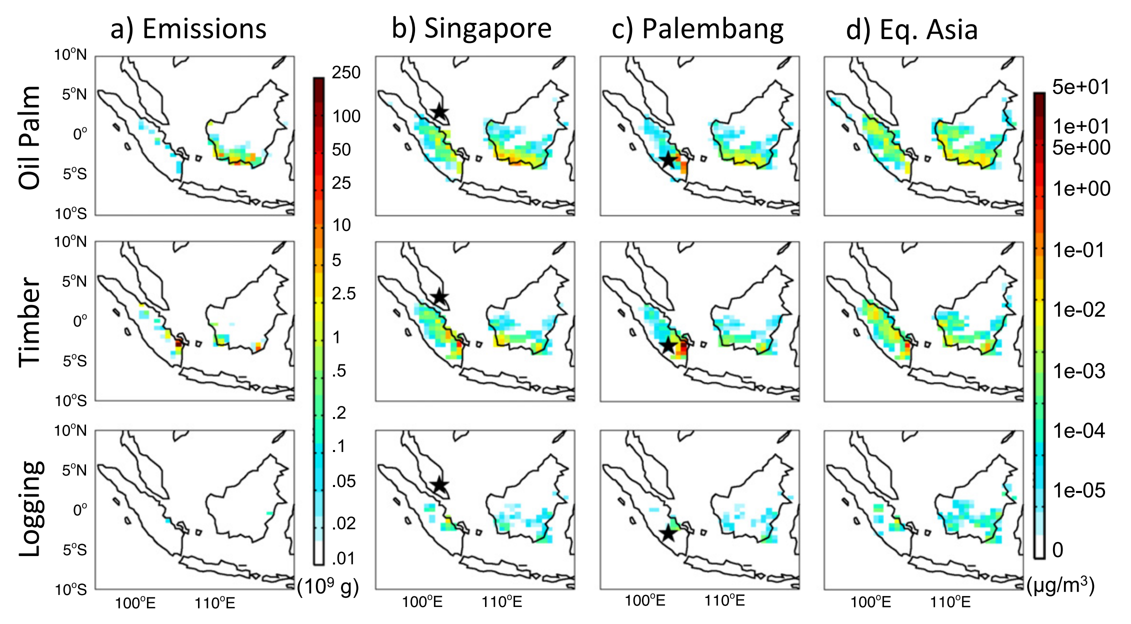

Figure 4. (a) Total July–November 2006 emissions from oil palm, timber, and logging concessions, in 10^9 g $PM_{2.5}$. Contribution of fire emissions from each concession type to smoke concentrations (in $\mu g\ m^{-3}$ $PM_{2.5}$) in Singapore (b), Palembang (c), and population-weighted Equatorial Asia (d). Black stars indicate receptor location.

activity in logging concessions, previous studies have noted that logging concessions can be reclassified into oil palm and timber plantations (Gaveau *et al* 2013), a change which is not captured by our dataset. Fifth, we assumed that atmospheric transport patterns during the 2006 burning season were representative of mean conditions (Kim *et al* 2015), though it is possible that the sensitivity of population centers would be affected differently by concession-based fire emissions in other years. While 2006 was the year with highest combined fire activity for Sumatra and Kalimantan (figure 3) and therefore was selected for the analysis with the adjoint model, the contributions of various industries can vary depending on the time period of analysis. This is the topic of ongoing research. Sixth, our estimates of smoke exposure at different receptor sites do not consider individual exposure factors, such as time spent outside, which could alter public health outcomes.

4. Discussion

Our analysis of industrial concessions by land cover and landform type revealed several key differences between Sumatra and Kalimantan. Regarding landform type, Sumatra had a larger proportion of industrial concessions on peatlands than Kalimantan. Though lowlands comprised the largest area of concessions relative to other landform types on all three islands, 2003–2013 FRP was highest in the peatlands in Sumatra and comprised a larger proportion of FRP in Kalimantan per unit area (figures 1 and 2). For Sumatra and Kalimantan, 86% and 65% of July to November 2006 emissions from all concessions were attributed to timber and oil palm concessions, respectively (table 1). Deforestation emissions comprised a small percentage of emissions from concessions, with emissions from peatlands in Sumatra and non-forested areas in Kalimantan dominating emission totals.

Table 3. Percentage contributions of total concessions and land outside of concessions to total land area (figure 1), July to November 2006 emissions (table 2), and subsequent population-weighted Equatorial Asia smoke exposure (table 2). The contributions of individual concession types (italicized) to 'Total Concessions' are given as percentage of 'Total Concessions' for each category.

	Sumatra			Kalimantan		
	% Area	% Emissions	% Contribution to Eq. Asia Smoke Exposure	% Area	% Emissions	% Contribution to Eq. Asia smoke exposure
Total Concessions	20.8	40.9	38.1	49.2	26.8	24.3
Oil palm	36	10	10	33	67	58
Timber	47	88	88	16	24	36
Logging	16	1	1	42	2	2
Mixed	2	1	1	9	7	5
Outside of Concessions	79.2	59.1	61.9	50.8	73.2	75.7

We used fire emissions and atmospheric transport patterns from July to November 2006 to illustrate the contribution of each concession type to population exposure at three receptors: Singapore, Palembang, and population-weighted Equatorial Asia (table 2 and figure 4). This analysis highlighted the contribution of the timber industry in Sumatra to smoke concentrations within Indonesia and across the region. Timber concessions in Sumatra were mostly found in peatland areas on the Eastern coast of Sumatra, which were associated with high FRP values and were located in close proximity to both Palembang and Singapore. In Kalimantan, oil palm concessions contributed more than other concession types to smoke concentrations at our receptor sites. Population exposure to fire emissions from Kalimantan was less than Sumatra, even though emissions from concessions in Kalimantan were higher than Sumatra, due to the spatial relationship between Sumatran fire emissions and the population centers used in this analysis. The contribution of land within and outside of concessions to areal totals, $PM_{2.5}$ emissions, and regional smoke exposure is summarized in table 3.

Most remaining forest cover in 2012 was found in logging concessions, supporting previous analysis of forest cover and carbon stock changes by concession type (Abood *et al* 2015, Busch *et al* 2015). However, prior work has also found that logging concessions can be reclassified into other plantation types, especially in areas with higher forest clearance because the Indonesian government tends to discount the value of degraded (logged) forests (Gaveau *et al* 2012, 2013). This suggests that remaining forest cover in logging concessions may be vulnerable to reclassification to oil palm or timber plantations, which have higher forest clearance rates, fire activity, and contribution to regional air quality degradation. In addition, the typical rotation period for some species of timber plantations can be as short as seven years (Effendy and Hardono 2001) versus oil palm with a typical rotation of ~25 years (Feintrenie *et al* 2010), which could increase fire activity if it is used between productive phases.

In order to improve public health, our results emphasize several key findings. First, similar to previous work that has looked at fires both within and outside of industrial concession boundaries, fires from peatlands and non-forested land cover types contributed most to emissions (table 1). Second, while the oil palm industry in Kalimantan and the timber industry in Sumatra dominated emissions totals on each island, relative to all concession types, emissions from fires occurring outside of concession boundaries were more important contributors to population exposure at our three receptors (table 2). Third, the influence of concessions on population exposure depends on the location of fires relative to receptor sites. For example, fires in Sumatra affect nearby populations in Palembang and Singapore more than fires in Kalimantan (table 2; figure 4). Finally, the Indonesian government's enforcement of the existing legal status of concessions, especially by limiting reclassification of logging concessions to other plantation types, where we observed high fire activity in concessions on peatlands and previously cleared lands, would limit public health impacts from emissions.

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