Regional air quality impacts of future fire emissions in Sumatra and Kalimantan

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Regional air quality impacts of future fire emissions in Sumatra and Kalimantan

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Abstract

Fire emissions associated with land cover change and land management contribute to the concentrations of atmospheric pollutants, which can affect regional air quality and climate. Mitigating these impacts requires a comprehensive understanding of the relationship between fires and different land cover change trajectories and land management strategies. We develop future fire emissions inventories from 2010–2030 for Sumatra and Kalimantan (Indonesian Borneo) to assess the impact of varying levels of forest and peatland conservation on air quality in Equatorial Asia. To compile these inventories, we combine detailed land cover information from published maps of forest extent, satellite fire radiative power observations, fire emissions from the Global Fire Emissions Database, and spatially explicit future land cover projections using a land cover change model. We apply the sensitivities of mean smoke concentrations to Indonesian fire emissions, calculated by the GEOS-Chem adjoint model, to our scenario-based future fire emissions inventories to quantify the different impacts of fires on surface air quality across Equatorial Asia. We find that public health impacts are highly sensitive to the location of fires, with emissions from Sumatra contributing more to smoke concentrations at population centers across the region than Kalimantan, which had higher emissions by more than a factor of two. Compared to business-as-usual projections, protecting peatlands from fires reduces smoke concentrations in the cities of Singapore and Palembang by 70% and 40%, and by 60% for the Equatorial Asian region, weighted by the population in each grid cell. Our results indicate the importance of focusing conservation priorities on protecting both forested (intact or logged) peatlands and non-forested peatlands from fire, even after considering potential leakage of deforestation pressure to other areas, in order to limit the impact of fire emissions on atmospheric smoke concentrations and subsequent health effects.

1. Introduction

Tropical fire emissions contribute to the rising concentrations of several atmospheric constituents, such as carbon dioxide, ozone precursors, and aerosols. Equatorial Asia, particularly Indonesia, can comprise a substantial fraction of these emissions; the Global Fire Emissions Database, version 3 (GFED3) estimates that from 1997 to 2009, Equatorial Asian emissions averaged 9% of global fire carbon emissions, but with strong interannual variability, ranging from 40% in 1997 to 1% in 2007 (van der Werf *et al* 2010). Atmospheric transport of these emissions can expose populations in the region to elevated concentrations of harmful pollutants. Previously documented events include large long-lived fires (lasting several months)

across Kalimantan and Sumatra during the 1997–1998 El Niño drought that produced regional haze conditions (Heil and Goldammer 2001, Marlier *et al* 2013) to smaller short-lived fires (lasting one week) in central Sumatra that caused severe air quality degradation in Singapore in June 2013 (Gaveau *et al* 2014a). Population exposure is highly dependent on the location and timing of fires, as well as prevailing wind patterns, and this information can be utilized to determine the most critical areas to protect from fires in order to minimize the public health impact from transported emissions (Reddington *et al* 2014, Kim *et al* 2015).

Indonesia's increasing role in global fire activity over the past few decades has been driven by the use of fire to clear forests and degraded lands (that have been previously cleared or logged) for conversion to agriculture and plantations, to establish land rights, and to extract resources (Dennis *et al* 2005). Visibility records since the 1960s indicate that severe fires were less frequent during droughts prior to this intensive land use (Field *et al* 2009). In addition, escaped, or unintentional, fires are common in the drier fuels of degraded areas and during droughts (Dennis *et al* 2005). Margono *et al* (2014) mapped more than 6 Mha of old-growth forest loss in Indonesia from 2001 to 2012, with an annual loss rate exceeding Brazil's in 2012. Within Indonesia, forest loss has occurred primarily in Sumatra and Kalimantan (Miettinen *et al* 2011, Margono *et al* 2014), where several recent studies have found a shift away from clearance of dryland forests towards degraded (logged and/or drained) peatland forests (Miettinen *et al* 2011, Margono *et al* 2014), along with fires concentrated in peatland forests or in non-forested areas (Gaveau *et al* 2014a, Marlier *et al* 2015).

Peatlands are naturally protected from fire by a high water table, but become susceptible when the water table is lowered by drainage, and further compounded by drought conditions, which exposes the peat to fire and oxidation (Wösten *et al* 2008). Oxidation is not considered in this study as it does not affect immediate air quality. Fires on degraded peatlands have the potential to produce large amounts of emissions because of substantial belowground carbon pools that can release combustion emissions several orders of magnitude higher than from aboveground pools (Page *et al* 2011, 2002, Jaenicke *et al* 2008). Although peatlands have typically been most susceptible to burning during El Niño events that bring prolonged drought conditions to Indonesia (Marlier *et al* 2015), record-breaking fires during June 2013, a non-El Niño year, indicated that degraded peatlands can be threatened by fires even during brief rainfall deficits of two months or less (May and June 2013 were near the 10th and 25th rainfall percentile, respectively) (Gaveau *et al* 2014a).
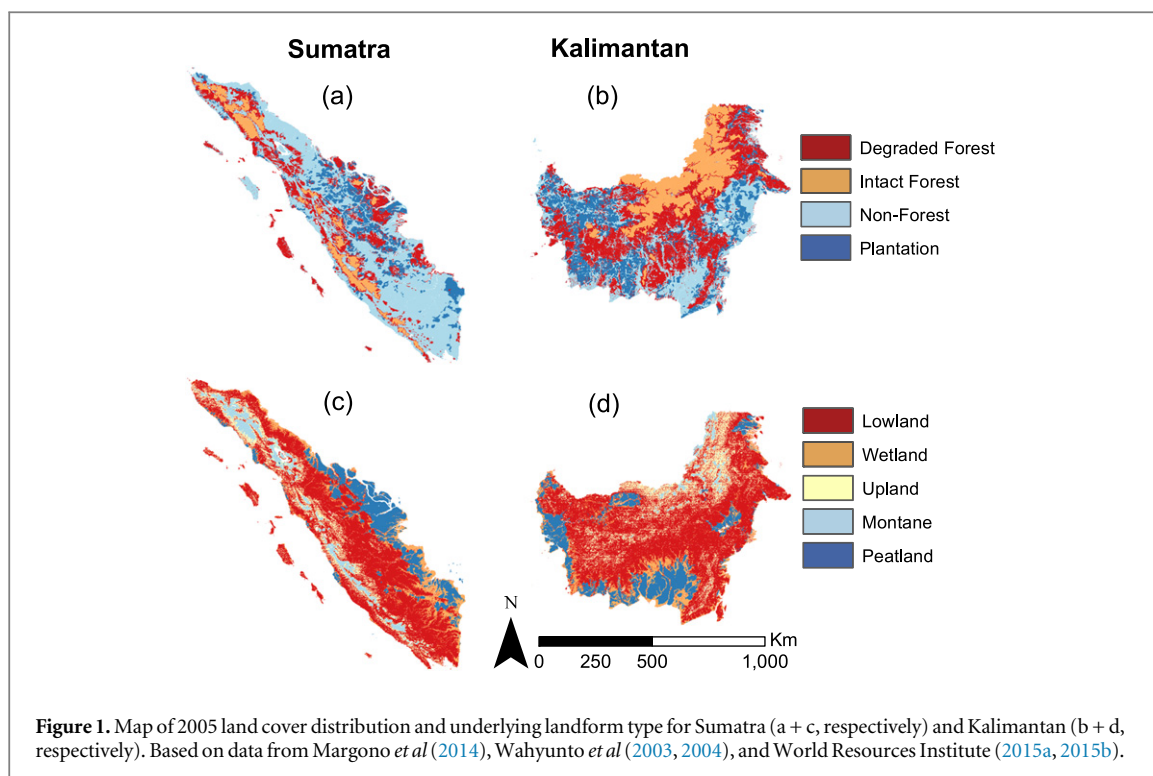
These past observations of fires and land cover change illustrate how future trends in forest degradation and clearance might alter fire activity and subsequent population exposure to emissions. For example, Miettinen *et al* (2012) projected business-as-usual future expansion of industrial plantations, mostly oil palm and pulpwood, on peatlands across Equatorial Asia and estimated that an additional 6 to 9 Mha of peatland would be converted by 2020, compared with the current plantation area of 3.1 Mha. Carlson *et al* (2013) found a 278% increase in oil palm plantation development in Kalimantan from 1990 to 2010; full development of remaining undeveloped leases, which was 79% of total lease area in 2010, would extend the area of oil palm plantations to 34% of lowlands. The level of development on peatlands will determine in large part the magnitude of future emissions: Marlier *et al* (2015) found a factor of ~2.5 higher emissions for Sumatra over the next two decades if rapid plantation development continued as opposed to stringent protection of intact and degraded peatlands, and Harris *et al* (2013) found that halting expansion of oil palm plantations on peatlands across Indonesia would reduce the emissions burden out to 2050 by more than 50%. Protection of dryland forests and peatlands under Indonesia's recent moratorium on new agricultural and logging licenses has the potential to reduce future emissions, especially from peatland areas (Sloan *et al* 2012). In addition, detailed future land cover projections focused on smaller spatial extents have also highlighted specific areas in urgent need of policy interventions to reduce future fire emissions, such as various scenarios of oil palm plantation development in West Kalimantan (Carlson *et al* 2012) and forest loss on peatlands in Central Kalimantan (Fuller *et al* 2011).

In this study, we expand on prior research that has looked at the influence of past fire emissions on public health (Marlier *et al* 2013, Reddington *et al* 2014, Kim *et al* 2015) by examining the air quality effects of future projections of fire activity, using newly published land cover maps (Margono *et al* 2014) of both Sumatra and Kalimantan ((Marlier *et al* 2015) was focused only on Sumatra). We develop spatially explicit future fire emissions inventories from 2010–2030 for Sumatra and Kalimantan based on future land cover scenarios. To map population exposure, we apply the sensitivities of mean smoke concentrations to Indonesian fire emissions calculated by the GEOS-Chem adjoint model in our previous research (Kim *et al* 2015). We use high-resolution observations of land cover and fire activity to explore how conservation and development scenarios impact future fire emissions and air quality for populations in the region.

2. Methods

We estimated spatially explicit future fire emissions for Sumatra and Kalimantan following the methodology described in detail by Marlier *et al* (2015), with

Figure 1. Map of 2005 land cover distribution and underlying landform type for Sumatra (a + c, respectively) and Kalimantan (b + d, respectively). Based on data from Margono *et al* (2014), Wahyunto *et al* (2003, 2004), and World Resources Institute (2015a, 2015b).

several modifications outlined below. Briefly, we used the following datasets: (1) 30 m × 30 m land cover classifications for 2005 and 2010 (Margono *et al* 2014), (2) 0.25° × 0.25° GFED3 emissions for 2005 to 2009 (van der Werf *et al* 2010), (3) 1 km^2 Moderate Resolution Imaging Spectroradiometer (MODIS) fire radiative power observations (FRP) for 2005 to 2009 (http://modis-fire.umd.edu/index.html), (4) ancillary spatial datasets that can influence land cover changes, and (5) three scenarios of projected 1 km^2 land cover at five-year intervals from 2010 to 2030 developed in this study.

2.1. Past land cover observations

Margono *et al* (2014) published 30 m × 30 m resolution land cover classifications. The land cover classes include: (1) primary intact forests consisting mostly of carbon-rich old growth stands of the *Dipterocarp* species that retain natural composition and structure, (2) primary degraded forests that are subject to forest utilization such as logging, and (3) non-forested areas, and all classes are differentiated by four landform types (wetland, dryland, upland, and montane). We aggregated the classification maps from 30 m × 30 m to 1 km × 1 km resolution based on the dominant land cover type and made two modifications to the Margono *et al* (2014) datasets. First, a sub-class of highly managed plantation area was estimated from the non-forest category by overlaying concession boundaries from the Indonesian Ministry of Forestry for industrial oil palm and timber plantations (World Resources Institute 2015a, 2015b). This represents large-scale concessions either currently under

production, cleared, or abandoned, but does not include forested concession areas. Second, we overlaid a separate layer delineating peatland distribution across Sumatra and Kalimantan (Wahyunto *et al* 2003, 2004). As shown in figure 1, the central region of Kalimantan contains the majority of remaining intact and degraded (logged) forests in 2005, typically at higher elevations. Peatlands are mostly found near the southern coastal areas. In Sumatra, intact forest is also located at higher elevations and peatlands are located on the eastern coast.

2.2. Past fire observations

We used two datasets to estimate fire emissions associated with different land cover and landform types: (1) GFED3 emissions that map the susceptibility of land cover types to fire along with observations of fire activity from multiple sources, and (2) MODIS FRP observations of active fires at a finer spatial resolution. The GFED3 fire emissions inventory combines information from several satellites on surface reflectance changes and active fire detections to estimate burned area, which then drives a biogeochemical model to estimate fuel loads, combustion completeness, and emissions (van der Werf *et al* 2010). The GFED3 dataset used here includes a correction for small fires that may have been missed by the original burned area mapping algorithm used to develop GFED3; in Equatorial Asia this correction increased 2001 to 2010 fire emissions by 55% (Randerson *et al* 2012) so no further scaling was applied.

We used an interim version of GFED3 that is available at 0.25° × 0.25° resolution (standard GFED3 is

available at 0.5°), so we used MODIS FRP information at 1 km^2 resolution to characterize the role of fire in land cover change at higher spatial resolution while retaining the detailed GFED3 emissions data. FRP is a measure of the radiant energy released by a fire (in MW) and is related to the rate of fuel consumption (Wooster *et al* 2005). It is measured by the MODIS Terra and Aqua satellites (MOD14A1 and MYD14A1 products, available at https://lpdaac.usgs.gov/) with 10:30 am and 1:30 pm local overpass times, respectively (Giglio *et al* 2003, Giglio 2010). First, we summed maximum daily FRP detected by Terra and Aqua over every month from January 2005 to December 2009 for all potential land cover transitions or stable land cover types (e.g., primary intact forest to non-forest, primary intact to degraded (logged) forest, or primary forest remaining as such) on each landform type (lowland, peatland, etc). Monthly data was used here since predicting future emissions at a daily resolution is highly uncertain, whereas current seasonal variability is more likely to continue. Note that transitions from non-forest or plantation to forest are not permitted in this dataset because the timeframe is too short for forest regrowth.

We then downscaled monthly 0.25° × 0.25° GFED3 emissions data in proportion to the monthly sum of 1 km^2 daily FRP detections, per land cover transition type, relative to the total FRP observed within each 0.25° × 0.25° cell. Note that if a fire detection was missed by the MODIS FRP product (due to cloud cover, etc) in a GFED3 grid cell with non-zero emissions, other FRP detections would be attributed higher GFED3 emissions to compensate. The effect of no FRP detections in a cell with non-zero emissions was small and our downscaled emissions captured ~90% of the coarse resolution GFED3 emissions. With this approach, we could approximate fires associated with the finer scale land cover observations available from Margono *et al* (2014) with GFED3 emissions data (available at a monthly timestep). See Marlier *et al* (2015) for further details.

2.3. Future land cover change

2.3.1. Dinamica EGO set-up

We simulated future land cover dynamics at a five-year timestep with Dinamica EGO (Environment for Geoprocessing Objects), Version 2.4 (Soares-Filho *et al* 2009). Dinamica EGO is a spatially explicit land cover change model and has previously been used to simulate future deforestation in Central Kalimantan (Fuller *et al* 2011) and West Kalimantan (Carlson *et al* 2012).

The first step in simulating future land cover change was to calculate historical transition matrices for each landform type, using the land cover classes from the 2005 and 2010 classification maps. This time interval in the land cover data necessitated a five-year timestep, which captured years of variable fire activity.

Dinamica EGO then uses a Bayesian Weights of Evidence method, which calculates the effect of spatial variables on a given transition independently of other transitions, to calculate the spatial probabilities of transitions, representing the most favorable areas for change (Soares-Filho *et al* 2009). Spatial datasets used in Weights of Evidence calculations (table 1; supplementary information available at stacks.iop.org/ERL/10/054010/mmedia) included nine static variables (soil, elevation, slope, industrial plantation leases, protected area status, distance to major roads (Kalimantan only), distance to logging roads, distance to rivers, and distance to mills) and four dynamic variables, which were updated at each model timestep (distance to intact forest, distance to degraded (logged) forest, distance to non-forest, and distance to plantation). While we expect future increases in road density, we did not include this as a dynamic variable because road development is uncertain (similar to Fuller *et al* 2011) and will likely be co-located with low elevations and low slopes. However, we recognize that this could lead to potential underestimates in the proximate causes of deforestation (Geist and Lambin 2002). We used the variance inflation factor to quantify the multicollinearity of each input dataset and eliminated distance to plantations from Kalimantan projections (supplementary table S1).

We used the *Patcher* and *Expander* functions within Dinamica EGO to reproduce the spatial patterns of change. The first generates new patches of a specific transition through a seeding process that selects the core cells of a new patch and a specified number of cells around each core, while the latter function expands or contracts previous patches. We set the mean and variance of patch sizes separately for each transition using observations for new and expanded patches from the 2005 to 2010 land cover maps for each landform type. Since we cannot determine how patch dynamics will behave in the future, we allocated 50% of transitions to the patcher function and 50% to the expander function, and set isometry to 1 for all transitions. This mostly follows prior modeling in Kalimantan by Carlson *et al* (2012), where the authors used the same parameters except for a 70% expansion in fire-driven transitions.

2.3.2. Future land cover scenarios

We explored three future scenarios using Dinamica EGO: (1) *Business-As-Usual (BAU)*, (2) *High Deforestation*, and (3) *Peatland Protection*. The model set-up described above comprised our *BAU* scenario, along with extending protected areas to include the existing moratorium on granting new plantation concessions (table 1). For *High Deforestation*, we doubled the rate of transitions from intact or degraded (logged) forest to non-forest and plantations and from intact forest to degraded (logged) forest, while maintaining all other transition rates from BAU. For *Peatland Protection*, we prevented land cover conversion from occurring on all

Table 1. Ancillary spatial datasets used in the Dinamica land cover model. See supplementary information (available at stacks.iop.org/ERL/10/054010/mmedia) for further details.

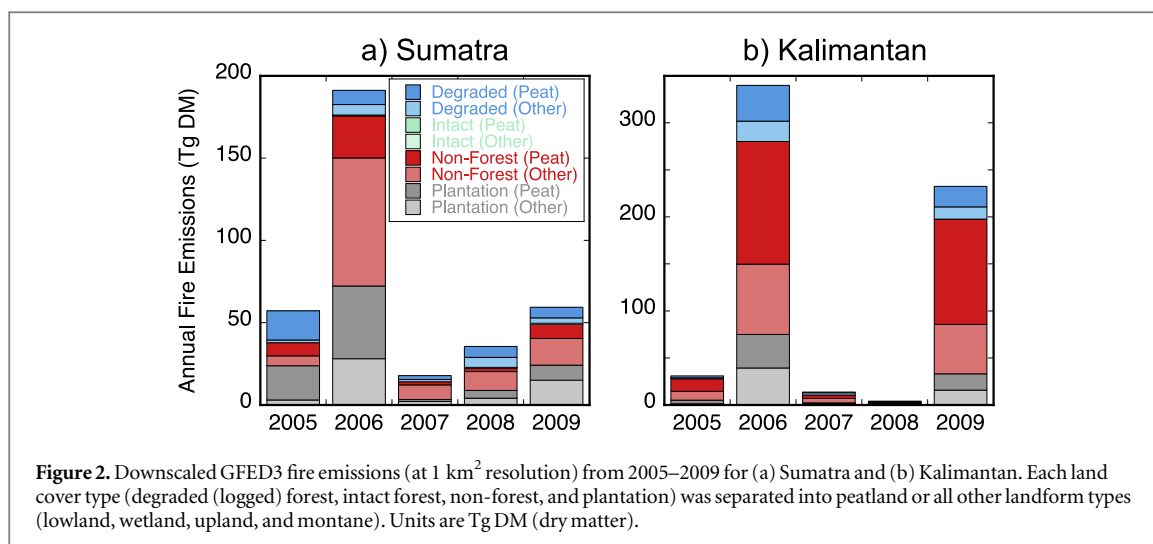| Spatial dataset	Type	Description	Source
Soil	Static	Dominant soil type; 30 arc-second resolution	FAO *et al* (2012)
Elevation	Static	GTOPO30 global digital elevation model (DEM); 30 arc-second resolution	https://lta.cr.usgs.gov/GTOPO30
Slope	Static	Derived from GTOPO30 DEM; 30 arc-second resolution	https://lta.cr.usgs.gov/GTOPO30
Plantation leases	Static	Spatial distribution of oil palm and timber plantation leases	www.globalforestwatch.org/sources/forest_use; Indonesian Ministry of Forestry
Protected areas	Static	Spatial distribution of protected areas	Gaveau *et al* (2009, 2013)
Moratorium	Static	Primary forest and peatlands protected by 2011 moratorium	www.ukp.go.id/informasi-publik/cat_view/20-geospasial
Distance to major roads	Static	Kalimantan only	Gaveau *et al* (2013)
Distance to logging roads	Static	Logging roads used for timber extraction	Gaveau *et al* (2014b, 2012, 2009)
Distance to rivers	Static	WWF hydroshed river network; 30 arc-second resolution	http://hydrosheds.cr.usgs.gov/index.php
Distance to mills	Static	Distance to mills for oil palm processing	Gaveau *et al* (2013)
Distance to intact forest	Dynamic	Based on classes from land cover dataset	Margono *et al* (2014)
Distance to degraded forest	Dynamic	Based on classes from land cover dataset	Margono *et al* (2014)
Distance to non-forest	Dynamic	Based on classes from land cover dataset	Margono *et al* (2014)
Distance to plantation	Dynamic	Based on classes from land cover dataset and plantation concessions	Margono *et al* (2014); www.globalforestwatch.org/sources/forest_use; Indonesian Ministry of Forestry

peatland forests and in areas protected by the moratorium, while retaining all other transition rates from BAU. We also blocked all fires from occurring on peatlands. Though the latter may seem extreme, the high water table and closed canopy cover in intact peatlands naturally protects them from burning, and fires can only occur if these areas are not protected from drainage. However, recognizing that such stringent protections would likely increase deforestation pressure in non-protected areas, we present a peat protection scenario that considers leakage effects by adding the deforestation and degradation rates from peatlands to lowlands, the latter of which are the most accessible areas to convert (supplementary figure S1).

To assess the accuracy of the model projections, we calculated the similarity between observed and simulated maps in a neighborhood context, which assesses model fitness at multiple window sizes instead of solely on a cell-by-cell basis. We present the minimum similarity because the maximum similarity can be inflated when changes are spread across a random map (Soares-Filho *et al* 2009). Although we expect more mismatches at higher spatial resolutions, we were more interested in the performance of our simulations at the 0.25° resolution used for our emissions estimates. The similarity of our simulated 2010 BAU land cover and observed 2010 land cover for Sumatra

and Kalimantan is shown for multiple window sizes, from 1 to 27 km (approximately 0.25° resolution) in supplementary figure S2, reaching ~95% minimum similarity at 0.25° resolution.

2.4. Future fire emissions

Future fire emissions inventories estimated to 2030 in five-year timesteps were created for each scenario by multiplying the estimated future areas by the downscaled historical GFED3 emissions (per unit area) for each land cover transition type. There is substantial interannual variability in fire activity (figure 2) and the 2005–2009 interval captures a large range of emissions (van der Werf *et al* 2010). Given the uncertainty in future changes in the El Niño cycle (Collins 2005, Christensen *et al* 2013), we do not attempt to project future meteorology and assume that this five-year period represents a plausible representation of meteorological variability for the next few decades. To capture monthly variability, we applied the monthly observations from 2005 to 2009 (e.g., all Januarys 2005–2009 relative to the 2005–2009 total) to approximate this variability in our 5-yearly future estimates (figure S3). We apportioned the future emissions according to the GFED3 fire types presented in van der Werf *et al* (2010) to determine relevant emissions factors: all fires on peatlands were assigned to the

Figure 2. Downscaled GFED3 fire emissions (at 1 km² resolution) from 2005–2009 for (a) Sumatra and (b) Kalimantan. Each land cover type (degraded (logged) forest, intact forest, non-forest, and plantation) was separated into peatland or all other landform types (lowland, wetland, upland, and montane). Units are Tg DM (dry matter).

GFED peat fire type, all primary or degraded (logged) forest fires on dryland, upland, or montane were assigned to the GFED deforestation fire type, plantation fires were assigned to the woodland fire type, and non-forest fires on dryland, upland, or montane landform types were assigned to the GFED agricultural waste, savanna, and woodland burning in proportion to GFED observations. Woodland burning was included in the plantation and non-forest fire category following the van der Werf *et al* (2010) definition of woodlands as savanna ecosystems not dominated by herbaceous vegetation.

2.5. Future air quality
The adjoint of the GEOS-Chem chemical transport model (Bey *et al* 2001, Henze *et al* 2007) is a useful tool to assess the sensitivity of smoke concentrations (here defined as organic carbon and black carbon) at a given receptor site to the spatial locations of fire emissions. The model set-up here uses the sensitivities presented by Kim *et al* (2015). Briefly, the contribution of fire emissions from our future scenarios to smoke concentrations were determined for selected receptor sites: Singapore, Palembang in southern Sumatra, and population-weighted Equatorial Asia. In contrast to the single receptor sites where the sensitivity was calculated for one grid cell, in the population-weighted calculation, the sensitivity of each grid cell was set equal to its fraction of the regional population and the contribution of fire emissions to smoke concentrations from each cell was then weighted accordingly (supplementary figure S4). Note that these sites were selected as examples, but similar analyses could be done for other receptors. Forward model runs with GEOS-Chem v8-02-01 (www.geos-chem.org) were driven by assimilated meteorological data with estimated future fires emitted into the boundary layer, following observations of 95% of smoke plumes in Indonesia (Tosca *et al* 2011). Sensitivities were then calculated for the 2006 fire season (July–November)

using the GEOS-Chem adjoint (version 34) at 0.50 × 0.67° horizontal resolution over East Asia nested within a global model at 4 × 5° horizontal resolution. Boundary layer wind patterns for 2006 were typical of the 2004–2010 mean (Kim *et al* 2015), and therefore were used to approximate future conditions.

3. Results

3.1. Past fire observations
The non-forest class and peatlands were the largest overall contributors to annual fire emissions, with variation from year to year (figure 2). These relationships were enhanced during dry conditions, such as observed in 2006. Figure 2 also reveals differences between the interannual variability of fire emissions observed in Sumatra and Kalimantan. Cumulative fire emissions from 2005–2009 reached 621 Tg of dry matter (DM) for Kalimantan and 361 Tg DM for Sumatra. In addition, the majority of emissions for both Kalimantan and Sumatra were in 2006 (55% and 53% of total emissions for all years, respectively), but Kalimantan also had substantial contributions in 2009 (37% of total emissions).

3.2. Future land cover projections
The *BAU* scenario was primarily differentiated from the *High Deforestation* and *Peatland Protection* scenarios by changes in the areas of non-forest, plantations, and degraded (logged) forest, since changes in intact forest covered less overall area (figure 3). Peatlands comprise ~14% of the total land area in Sumatra and Kalimantan but drive the majority of emissions (figure 2); these trends are presented separately in figure S5. In the *High Deforestation* scenario, combined non-forest and plantation area increased (29% from 2010–2030 in Kalimantan and 17% in Sumatra) primarily at the expense of conversion of degraded (logged) forests (−29% and −42% in Kalimantan and
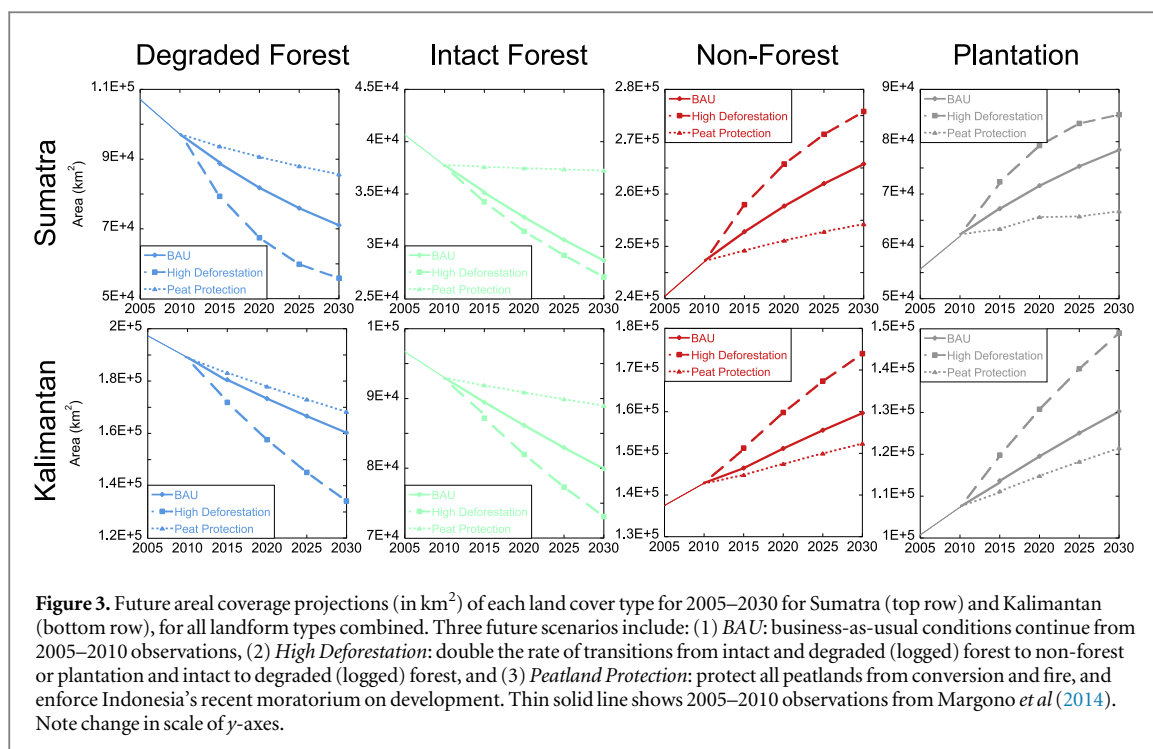
Figure 3. Future areal coverage projections (in km^2) of each land cover type for 2005–2030 for Sumatra (top row) and Kalimantan (bottom row), for all landform types combined. Three future scenarios include: (1) *BAU*: business-as-usual conditions continue from 2005–2010 observations, (2) *High Deforestation*: double the rate of transitions from intact and degraded (logged) forest to non-forest or plantation and intact to degraded (logged) forest, and (3) *Peatland Protection*: protect all peatlands from conversion and fire, and enforce Indonesia's recent moratorium on development. Thin solid line shows 2005–2010 observations from Margono *et al* (2014). Note change in scale of *y*-axes.

Table 2. Future fire emissions (Tg DM) for three land cover change scenarios, given separately for Sumatra and Kalimantan. Total represents the 20-year sum of emissions from 2010–2030, along with the percentage contributed by peatland emissions.

	BAU		High deforestation		Peatland protection	
	Sumatra	Kalimantan	Sumatra	Kalimantan	Sumatra	Kalimantan
2010–15	379	649	402	681	193	243
2015–20	394	674	424	726	195	248
2020–25	406	698	435	764	197	252
2025–30	416	719	441	796	198	255
Total	1596 (50%)	2740 (63%)	1703 (51%)	2967 (63%)	782 (0%)	999 (0%)

Sumatra, respectively). For comparison, increases in combined non-forest and plantation area were 16% in Kalimantan and 11% in Sumatra over the same time period in the *BAU* scenario. Increases in combined non-forest and plantation area in the *Peatland Protection* scenario were slightly more pronounced in Kalimantan versus Sumatra (9% and 4% from 2010–2030, respectively) and changes in intact and degraded (logged) forest area were smaller than the other two scenarios. Primary intact forest comprised the smallest 2010 area of all land cover classes (9.3×10^4 km^2 in Kalimantan and 3.8×10^4 km^2 in Sumatra).

3.3. Future fire emissions estimates

Due to the importance of peat emissions in our 2005–2009 observations, these emissions also drove the major differences between the three future scenarios (table 2). Differences in the cumulative 2010–2030 emissions in the *BAU* and *High Deforestation* scenarios (4336 and 4670 Tg DM, respectively) were relatively small even though we doubled the rate of deforestation and degradation, partly because remaining 2010 intact

and degraded forest area is limited to 30% and 53% of the total area of Sumatra and Kalimantan, respectively. There was a stark difference between these two scenarios and the *Peatland Protection* scenario, which had 1781 Tg DM of cumulative emissions over the same time period. The projected areas of high emissions were found in the peatlands on the eastern coast of Sumatra and southern coast of Kalimantan (figure 4). When we considered leakage effects (figure S1), the cumulative emissions estimates increased by only 2% because of the lower emissions potential in lowland versus peatland areas and the small remaining forest area as previously described.

3.4. Future air quality estimates

We used the GEOS-Chem adjoint model to estimate the contribution of fire emissions to smoke concentrations at different receptor sites, specifically Singapore, Palembang, and all of Equatorial Asia weighted by population. The average 2010–2030 emissions for all three scenarios over the July to November burning season are shown in figure 4(a). Fires that occur outside these months are not considered here. The
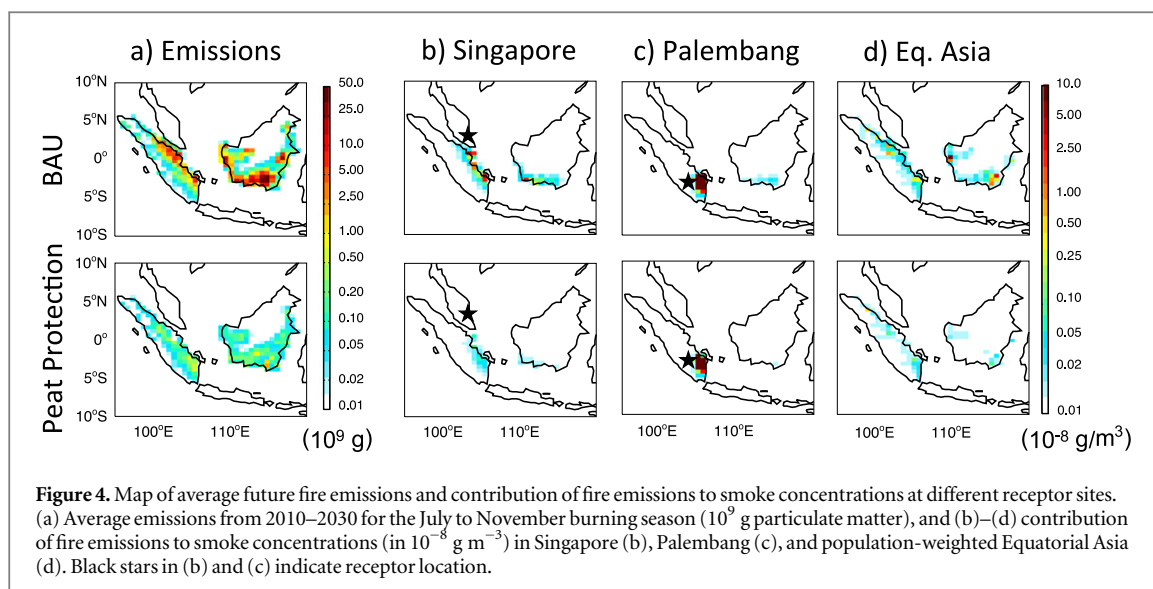
Figure 4. Map of average future fire emissions and contribution of fire emissions to smoke concentrations at different receptor sites. (a) Average emissions from 2010–2030 for the July to November burning season (10^9 g particulate matter), and (b)–(d) contribution of fire emissions to smoke concentrations (in 10^{-8} g m^{-3}) in Singapore (b), Palembang (c), and population-weighted Equatorial Asia (d). Black stars in (b) and (c) indicate receptor location.

Table 3. Average burning season emissions (July–November 2010–2030) and contribution of fire emissions to smoke concentrations at three receptors: Singapore, Palembang, and population-weighted Equatorial Asia. Percentages give contribution of Sumatra and Kalimantan, separately, to total emissions and smoke concentrations for both Sumatra and Kalimantan.

	BAU		High deforestation		Peatland protection	
	Sumatra	Kalimantan	Sumatra	Kalimantan	Sumatra	Kalimantan
Emissions (kg PM)	5.03E + 08 (29%)	1.21E + 09 (71%)	5.40E + 09 (29%)	1.32E + 09 (71%)	2.56E + 08 (40%)	3.85E + 08 (60%)
Singapore (μg m^{-3})	1.16 (62%)	0.71 (38%)	1.24 (62%)	0.75 (38%)	0.45 (72%)	0.17 (28%)
Palembang (μg m^{-3})	13.23 (99%)	0.20 (1%)	13.26 (98%)	0.21 (2%)	8.35 (99%)	0.05 (1%)
Population-weighted Equatorial Asia (μg m^{-3})	1.29 (50%)	1.30 (50%)	1.36 (49%)	1.39 (51%)	0.71 (66%)	0.37 (34%)

highest emissions were projected in the peatland areas of Eastern Sumatra and Southern Kalimantan, with the highest emissions in Kalimantan. Given the similarities between *BAU* and *High Deforestation* emissions, we only present the *BAU* scenario in figure 4.

We then used GEOS-Chem adjoint sensitivities (figure 5 in Kim *et al* 2015) to identify the fire locations that most strongly impact air quality at the various receptor sites. Due to the prevailing meteorology, Singapore was more sensitive to emissions from Sumatra, despite the lower emissions than in Kalimantan (figure 4(b)). Sumatran fire emissions contributed approximately 60% of smoke concentrations in Singapore although Sumatra contributed 29% of emissions overall (table 3). Palembang (figure 4(c)) was more highly sensitive to emissions from Sumatra; 99% of the smoke concentrations were contributed by Sumatra (table 3). For population-weighted Equatorial Asia (figure 4(d)), the highest contributions were along the eastern and southern coasts of Sumatra and Kalimantan, respectively, and each island contributed around 50% to smoke concentrations (table 3). For all receptors, the *Peatland Protection* scenario reduced the contribution of fire emissions to smoke

concentrations by 37–61% for Sumatra and 72–76% for Kalimantan. Note that these results do not include interannual variability, but represent average burning season emissions over 2010 to 2030 and adjoint model results for 2006 only. While 2006 wind patterns were typical of the 2004–2010 mean (Kim *et al* 2015), the low precipitation observed during the 2006 El Niño could enhance smoke transport and lifetime when compared to other years (Xian *et al* 2013).

3.5. Limitations and uncertainties

There are several sources of uncertainty in this analysis. First, we used land cover maps from Margono *et al* (2014) that distinguish between forest and non-forest only, although there may be significant variability in fire management practices across the latter. To help address this, we estimated plantations by overlaying industrial concessions on the non-forest class, using similar concession datasets as in several recent studies (Abood *et al* 2015, Busch *et al* 2015). This approach does not include plantations located outside of these legal concessions or any additional sources of uncertainty in these datasets. For example, it can be difficult to infer the direct causes of land-cover change due to uncertain property rights and tensions among

different stakeholders (Dennis *et al* 2005), which could include smallholders within concession boundaries as well as clearance by industrial plantations outside of existing boundaries (Carlson *et al* 2012, Gaveau *et al* 2014a). In addition, this dataset does not describe the current production status of concessions; we therefore classify all non-forested concessions as plantations. However, this could represent multiple land cover types, such as currently planted industrial-scale plantations, smallholder land use set aside within concessions, or cleared lands that could range from unmanaged or abandoned areas (grassland or shrubland) to clearing prior to planting. Uncertainty regarding these areas not currently in production likely contributes to the higher plantation area estimates in Kalimantan than presented by other studies (Miettinen *et al* 2012, Gunarso *et al* 2013, supplementary information (available at stacks.iop.org/ERL/10/054010/mmedia)). In addition, the inclusion of concession boundaries in both defining our plantation class and determining transition probabilities in the land cover change model may introduce bias, though sensitivity calculations combining the non-forest and plantation classes together had a small effect on emissions estimates (data not shown).

There is also uncertainty associated with the fire emissions analysis. We used a hybrid fire emissions estimation approach based on the strengths of the GFED dataset in combining biogeochemical modeling with burned area and active fire mapping with finer resolution FRP estimates from MODIS. Overall uncertainties for GFED3 are estimated to be 20% globally and higher for Equatorial Asia due to the influence of peat burning (van der Werf *et al* 2010). Previous studies that have compared GFED3 with the National Centre for Atmospheric Research Fire Inventory (FINNv1; Wiedinmyer *et al* 2011) in this region have found comparable deforestation and peatlands emissions but underestimates from GFED3 in agricultural areas. This may be at least partially compensated for by the small fires correction factor applied here to the GFED3 dataset (Randerson *et al* 2012). In addition, this region has substantial cloud cover (less so during the traditional burning season) that may obscure the signal measured by satellites used for land cover mapping, active fire detections, and burned area mapping. Finally, we present the effect of fire emissions on regional smoke concentrations using the GEOS-Chem adjoint model and the 2006 burning season only because atmospheric transport patterns during 2006 were representative of the 2004–2010 mean (Kim *et al* 2015). However, it is possible that other population centers could experience elevated smoke concentrations during other years, as observed by Xian *et al* (2013) with longer smoke lifetimes and anomalous easterlies during 2006, or during other seasons, such as spring burning in Sumatra evident in figure S3.

4. Discussion

Scenario-based estimates of future fire activity can help to assess the relative impact of land cover trends on fire emissions and air quality. In our scenarios, even a doubling of the deforestation and degradation rate did little to affect fire emissions over two decades due to the limited amount of remaining forest, increasing emissions by just 8% compared with *BAU*. Protecting peatlands, as found by Fuller *et al* (2011), was key to drastically reducing the fire emissions burden (59% lower than *BAU*), especially if logged forest or non-forest instead of intact forest. The latter also supports conclusions of Carlson *et al* (2012) and Marlier *et al* (2015), which found that fires associated with direct conversion were much less than uncontrollable fires in non-forested areas. However, our results may be conservative based on recent findings by Gaveau *et al* (2014a) regarding Sumatra during the June 2013 fires, where the extreme susceptibility of non-forested peatlands to fire in non-drought years could suggest an increase in future fire activity in this region. While non-forested or severely degraded peatlands may be overlooked by conservation strategies that focus instead on the benefits of standing forests for carbon storage and/or habitat quality, they require urgent protection from fire in order to protect regional air quality and public health. Our results support efforts to restore degraded peatlands by blocking drainage canals to raise groundwater levels, which would not only reduce carbon dioxide emissions associated with peatland oxidation (Jaenicke *et al* 2010), but would also reduce the susceptibility to fire.

Our results also highlight the potential for continued high fire activity in Kalimantan, which outweighed contributions from Sumatra by a factor of two in cumulative future emissions totals. However, the contribution of emissions from Kalimantan affecting smoke concentrations at the receptor sites considered in this study was lower than Sumatra due to the lower sensitivities determined by meteorological conditions. *BAU* emissions from Kalimantan comprised 1% of the total contribution from both Sumatra and Kalimantan to smoke concentrations in Palembang, 38% in Singapore, and 50% for the population-weighted region despite burning season emissions being higher by a factor of 2.4. Since we focused on the July–November burning season in this study, our estimates are likely conservative because of the potential for additional exposure to emissions during other months. This is the subject of ongoing research.

Our scenarios illustrate that transboundary population centers such as Singapore, as well as the region as a whole, could continue to be affected by fire emissions from both Sumatra and Kalimantan in the coming decades, while the impact on Palembang, a local population center, could continue to be almost entirely affected by Sumatra due to its proximity. Kalimantan emissions likely affect other population

centers in Borneo. In addition, we estimate that protecting peatlands from fire could reduce emissions from Sumatra and Kalimantan, relative to *BAU*, by 60%. This would reduce contributions to smoke concentrations by a factor of three for Singapore, 1.6 for Palembang, and 2.4 for the population-weighted region. Strengthening Indonesia's land use policies to protect peatlands from fire would offer substantial public health improvements for both local populations within Indonesia and transboundary populations throughout the region.

Acknowledgments

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