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Future fire emissions associated with projected land use change in Sumatra

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Abstract

Indonesia has experienced rapid land use change over the last few decades as forests and peatswamps have been cleared for more intensively managed land uses, including oil palm and timber plantations. Fires are the predominant method of clearing and managing land for more intensive uses, and the related emissions affect public health by contributing to regional particulate matter and ozone concentrations and adding to global atmospheric carbon dioxide concentrations. Here, we examine emissions from fires associated with land use clearing and land management on the Indonesian island of Sumatra and the sensitivity of this fire activity to interannual meteorological variability. We find ~80% of 2005–2009 Sumatra emissions are associated with degradation or land use maintenance instead of immediate land use conversion, especially in dry years. We estimate Sumatra fire emissions from land use change and maintenance for the next two decades with five scenarios of land use change, the Global Fire Emissions Database Version 3, detailed 1-km^2 land use change maps, and MODIS fire radiative power observations. Despite comprising only 16% of the original study area, we predict that 37–48% of future Sumatra emissions from land use change will occur in fuel-rich peatswamps unless this land cover type is protected effectively. This result means that the impact of fires on future air quality and climate in Equatorial Asia will be decided in part by the conservation status given to the remaining peatswamps on Sumatra. Results from this article will be implemented in an atmospheric transport model to quantify the public health impacts from the transport of fire emissions associated with future land use scenarios in Sumatra.

Keywords: air quality, climate variability, deforestation, fire emissions, land use

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Introduction

Equatorial Asia lost approximately 1% of total forest cover and 2.2% of peatswamp forest cover annually from 2000 to 2010, with estimates as high as 5% per year for lowland Sumatra (Miettinen *et al.*, 2011). Within the Sumatran provinces of Riau, North Sumatra, and Jambi, forest cover declined from 93 to 38% of provincial area between 1977 and 2009. Almost half of this deforestation was attributed to industrial plantation establishment, primarily oil palm and timber plantations, and a further 16% to smallholder agriculture (Miettinen *et al.*, 2012b). Oil palm and timber plantation expansion has played an important role throughout Indonesia over the past few decades (Fig. 1). To the extent that fires are used to establish and maintain these plantations, the associated emissions can impact local and regional air quality, public health, and climate. Fire emissions from Equatorial Asia (mostly from the islands of Sumatra and Borneo) released an average of 128 Tg C per year between 2000 to 2006 (van der Werf *et al.*, 2008), which is of comparable magnitude to Indonesia's emissions from fossil fuel burning, cement manufacture, and gas flaring (Boden *et al.*, 2011). Land-clearing and maintenance fires also release fine particulate matter (Heil & Goldammer, 2001; Marlier *et al.*, 2013), which is dangerous to public health.

High forest conversion rates in Indonesia are particularly problematic with regard to emissions because tropical peatswamps contain rich belowground carbon stocks in addition to aboveground biomass. Indonesian peatswamps alone are estimated to store at least 55 Gt C and are susceptible to fire after drainage (Jaenicke *et al.*, 2008). Recent land use observations indicate that plantations in Sumatra and Kalimantan (Indonesian Borneo) are increasingly established on peatswamps

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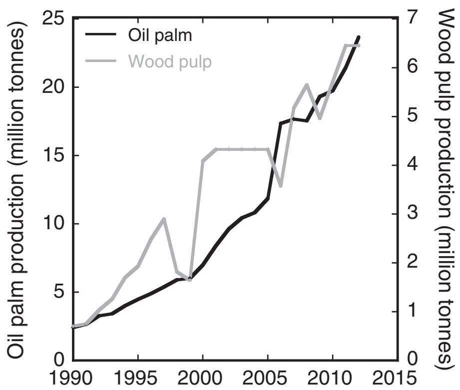

Fig. 1 Oil palm and wood pulp production (in million tonnes) for all of Indonesia from 1990 to 2012 (accessed on 10/1/2013 at http://faostat3.fao.org/faostat-gateway/go/to/home/E).

instead of mineral soils (Miettinen *et al.*, 2011; Carlson *et al.*, 2012). One-fifth of peatswamps in Sumatra, Peninsular Malaysia, and Borneo (3.1 Mha) were converted to industrial plantations by 2010; 62% of these plantations were in Sumatra and mostly consisted of oil palm and pulpwood plantations (Miettinen *et al.*, 2012a). Within Sumatra, Koh *et al.* (2011) estimated that 3.9 Mha of peatswamps were covered by mature oil palm plantations by the early 2000s, dominated by the Riau and South Sumatra provinces.

Logged forests, with reduced canopy cover, are vulnerable to burning due to drier fuels, so fire activity tends to be concentrated in these heavily logged areas and limited in pristine peatswamp forests (Siegert *et al.*, 2001; Dennis & Colfer, 2006; Miettinen *et al.*, 2012b). A case study in Kalimantan found that during the 1997–1998 El Niño, 59% of logged forests were affected by fires vs. 6% of undisturbed forests, and most burned area was concentrated on timber concessions, plantations, agriculture, and fallow land (Siegert *et al.*, 2001). In general, logged forests in Equatorial Asia are not a permanent land cover type. Governments often view logged forests as having low conservation value and tend to reclassify logging concessions, after all commercially valuable timber has been removed, to allow conversion to industrial-scale plantations (Giam *et al.*, 2011; Gaveau *et al.*, 2013). Therefore, logged forests represent an intermediate step on the trajectory of land conversion (with continued habitat destruction) by fire or some other clearing method, as opposed to forest regeneration (Miettinen *et al.*, 2012b). In three study sites in Sumatra, only 20% of logged forests as of the 1970s remained in forest cover by 2010 (Miettinen *et al.*, 2012b). Furthermore, 7.25 of the 7.54 Mha of primary intact Sumatra forests that were deforested over 1990–2010 were logged before being cleared (Margono *et al.*, 2012).

In addition to deliberate land clearing and maintenance fires and the fire-susceptibility of logged forests, fire frequency and intensity have increased recently due to escaped fires, land tenure disputes, resource extraction, lack of fire-fighting capacity, fire use by immigrants, (Dennis *et al.*, 2005). See fig. 1 in Stolle *et al.* (2003) for a conceptual model.

Along with anthropogenic drivers, the magnitude and duration of fire emissions exposure in Equatorial Asia depends on local meteorological conditions, which are strongly influenced by the El Niño-Southern Oscillation (ENSO) (Marlier *et al.*, 2013). Seasonal precipitation controls groundwater levels and the amount of peat available for drying; the risk of intense fires in southern Sumatra and Kalimantan substantially increases when 4 month total precipitation drops below critical 350-mm and 650-mm thresholds respectively (Field & Shen, 2008). During drought stress, trees shed leaves and have lower moisture content (Goldammer, 2006). The effect of the ENSO cycle has been observed in Borneo, where fire incidence can be two to three times higher during strong vs. weak El Niño events (Wooster *et al.*, 2012) and emissions can be up to 30 times higher (van der Werf *et al.*, 2008). Sumatra also experiences higher fire activity during drought conditions, along with a trend of increasing fire emissions over time (rising by ~8 Tg C per year over 2000 to 2006), which could be related to increased clearing rates or intensified droughts (van der Werf *et al.*, 2008).

Previously published projections of land use change in Equatorial Asia predict continued plantation development that could overtake current rates, depending on future economic returns for various crops, the effectiveness of conservation plans, and changes to El Niño. For Equatorial Asia as a whole, one business-as-usual scenario estimates that 6–9 Mha of the total peatswamp area (25 Mha) will be converted to industrial plantations by 2020 (Miettinen *et al.*, 2012a), whereas an estimated 3 Mha of peatswamps in Equatorial Asia were converted by 2010 (Miettinen *et al.*, 2012a). In Northern Sumatra, establishing protected areas in inaccessible upland forests is predicted to offer smaller reductions in anticipated deforestation by 2030 than protecting a more diverse mix of landscapes, including lowland forests that have an inherently higher risk of conversion to high-revenue plantations due to accessibility and proximity to roads (1313 km^2 vs. 7824 km^2 in avoided deforestation) (Gaveau *et al.*, 2009). Several studies have focused on Kalimantan, where 1.1 Mha of peatswamp forest loss in the Central Kalimantan province (roughly half of the current area) is projected to occur by 2020 (Fuller *et al.*, 2011). Carlson *et al.* (2013) found a 278% increase in oil palm plantations in Kalimantan from 2000 to 2010 (62% of which involved deforestation),

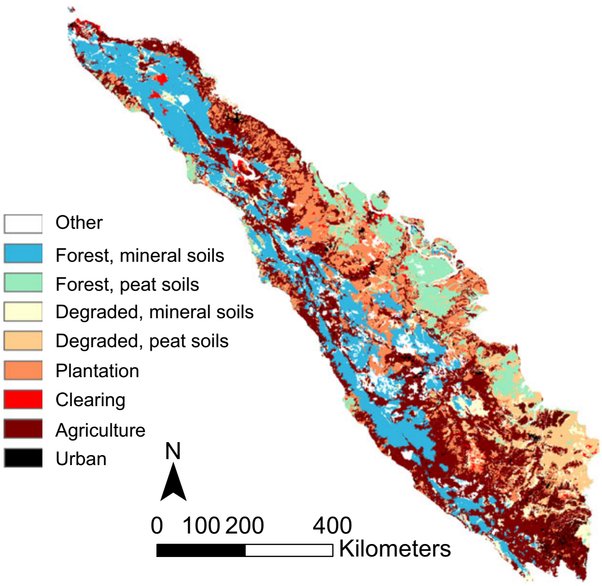

Fig. 2 2006 baseline land use map for Sumatra from the Indonesian Ministry of Forestry (MoF). Classes have been aggregated to 1-km^2 resolution and grouped according to Table 1.

despite 79% of government leases for plantations still remaining undeveloped. If all of these leases are developed using fire, oil palm expansion in Kalimantan will contribute 22% of Indonesia's total CO_2 emissions in 2020 (Carlson *et al*., 2013). In recent oil palm projections from 2010 to 2050 in Indonesia, Malaysia, and Papua New Guinea, net cumulative carbon emissions from land use conversion and peat oxidation are estimated at 15 Pg CO_2 by 2050 under business-as-usual circumstances, with 77% of emissions from drainage of peat on existing or new plantations (Harris *et al*., 2013). Understanding the magnitude and spatial distribution of fire emissions associated with land use change (including oil palm expansion) are important for identifying strategies to mitigate the impact of fires on both climate and public health.

In this article, we study past drivers of fire emissions to project future fire activity for the island of Sumatra, which has experienced rapid deforestation due to large-scale plantation development (Miettinen *et al*., 2011) and is located near dense population centers. We build upon prior works by combining spatially explicit economic models of future land use change with detailed estimates of the associated fire emissions. Specifically, we ask: (i) How are fire emissions in Sumatra associated with different land use management and transitions, (ii) How does interannual meteorological variability impact these observed relationships, and (iii) What are the projected emissions associated with future land use change scenarios for Sumatra? To address these questions, we synthesize information from multiple disciplines, including land use mapping, satellite fire observations, and economic-based land use change modeling. The emissions inventories created in this study will be used in future research with a high-resolution atmospheric chemical transport model to estimate public health impacts resulting from the transport of these emissions.

Materials and methods

We examined patterns of fires and past land use change to predict future fire emissions associated with several land use change scenarios for Sumatra. Our approach relied on six datasets: (i) 1-km^2 land use classifications in 2006 and 2009, (ii)

Table 1 Nine land use classes used in this analysis (left column) along with the original 21 land use classes (right column) from the Indonesian Ministry of Forestry (MoF) 2006 and 2009 classification maps (MoF, 2011)

Land use/land cover	Original MoF land use/land cover types
Forest, mineral soils	(i) Primary dryland forest, (ii) secondary dryland forest, (iii) primary mangrove forest, and (iv) secondary mangrove forest
Forest, peat soils	(i) Primary swamp forest and (ii) secondary swamp forest
Degraded land, mineral soils	(i) Savanna and (ii) bush scrub
Degraded land, peat soils	(i) Swamp and (ii) scrub and bush swamp
Plantation	
Established	(i) Timber plantation* and (ii) other plantation†
Clearing	(i) Defined as cleared land, logging for saw logs, or plantations
Agriculture	(i) Nonrice agriculture with mixed bush, (ii) nonrice agriculture, and (iii) rice agriculture
Urban‡	(i) Defined as 50% mix crop and bush; 50% developed
Other§	(i) Cloud, (ii) water, (iii) beach, and (iv) other

*Mix of logging: 50% saw logs and 50% pulp.
†Weighted average mix of top five tree crops by area and can vary by location; includes oil palm.
‡Considered static in this analysis.
§Not included in this analysis.

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biophysical and economic productivity information for each 1-km^2 pixel, (iii) 0.25° × 0.25° Global Fire Emissions Dataset version 3 (GFED3) for 2005 to 2009, (iv) 1-km^2 Moderate Resolution Imaging Spectroradiometer (MODIS) fire radiative power (FRP) observations for 2005–2009, (v) MODIS Collection 5.1 Direct Broadcast Monthly Burned Area Product (BAP) (MCD64A1), and (vi) five scenarios of projected 1-km^2 land use at 3-year intervals until 2030. The role of each data set is described below.

Past land use observations

30-m^2 land use classification maps of Sumatra for 2006 and 2009, based on Landsat and SPOT satellite observations, were produced by the Directorate of Forest Resources Monitoring and Inventory of Indonesia's Ministry of Forestry (MoF) (MoF, 2011). The 2006 classification map was based on satellite images from 2005 and 2006 and the 2009 map included satellite images from 2009. MoF land use classification and zoning maps have been used by several previous studies (Dennis & Colfer, 2006; Broich *et al*., 2011; Gaveau *et al*., 2012; Margono *et al*., 2012; Romijn *et al*., 2013). Accuracy is estimated at >90% for the forest classes based on ground validation and local knowledge (Margono *et al*., 2012 & citations within). We simplified the MoF land use maps by re-scaling to 1-km^2 resolution by assigning the most dominant land use class (Table S1) and condensing the original 21 land use classes to 9 (Fig. 2, Table 1). Selected examples of Landsat satellite data and corresponding MoF land use maps are shown in Figure S1. To translate 2006–2009 land use change information into a fire emissions inventory, we needed to determine which transitions were likely driven by fire and in what month and year these transitions occurred, which is described in the next step.

Past fires and emissions

Past land use and fire. We associated the 2006–2009 land use transitions with concurrent GFED3 emissions. GFED3 is a monthly, 0.25° × 0.25° gridded fire emissions product that combines satellite observations of burned area with a biogeochemical model to estimate trace gas and aerosol emissions. Global average uncertainty is estimated at 20%, but is higher in Equatorial Asia because of uncertainties related to fuel consumption in peat areas and small fires that can be missed by the burned area detection algorithm. We addressed the latter with a correction factor for the contribution of small fires, as described below. GFED partitions emissions among general fire types, including grassland, deforestation, peat, agricultural waste, forest, and woodland (van der Werf *et al*., 2010). However, there are many 1-km^2 land use classes and transitions within each 0.25° × 0.25° grid cell, which comprises more than 700 1-km^2 pixels. This density of data necessitated an intermediate step with finer spatial information on fire activity before attributing GFED3 emissions to detailed land use change.

For this intermediate step, we overlaid daily 1-km^2 observations of FRP onto the land use maps. FRP is the rate of electromagnetic energy released by a fire, from MODIS Aqua and Terra (MOD14A1 + MYD14A1 products). FRP is related to the rate of fuel consumption and can substitute for estimates of burned area, biomass density, and combustion completeness, although there are uncertainties regarding the partitioning of heat loss among various mechanisms and how this varies with fuel and fire type (Wooster *et al*., 2005). Fires in tropical ecosystems tend to peak in the afternoon (Giglio, 2007), but we summed FRP detected by both Terra and Aqua to capture a broader observational time period (local overpass times of 10:30 hours and 1:30 hours). By overlaying FRP with land use transitions (Table 2), we could determine which transitions were associated with coincident fire observations and the month-to-month variability in peak fire activity within each transition type. We could also estimate the proportion of (i) fires observed during land use conversion, (ii) maintenance fires observed in stable classes, and (iii) unintentional fires that do not increase the economic returns of a given land parcel. For each month, we summed the maximum daily FRP from Aqua and Terra detected within each land use transition class

Table 2 Area (in 100 km^2) for the 7 modeled land use classes in 2006 (rows) and 2009 (columns). Refer to Table 1 for descriptions of land uses within each class. Urban areas in 2006 or 2009 were combined, with a total area of 8805 km^2, and the 'Other' class has been omitted. Italicized areas represent implausible transitions (such as forest on peat soils to forest on mineral soils)

	2009 Land Use							
					Plantation			
2006 Land Use	Forest, Mineral	Forest, Peat	Degraded, Mineral	Degraded, Peat	Established	Clearing	Agriculture	Total
Forest, Mineral	836.5	*3.3*	19.1	*0.7*	7.6	6.9	20.0	894.1
Forest, Peat	*0.3*	282.6	*1.5*	19.5	15.2	22.0	2.8	343.8
Degraded, Mineral	20.5	*4.1*	232.0	*4.3*	8.6	2.1	32.3	303.9
Degraded, Peat	*1.2*	14.1	*2.8*	283.9	8.3	5.0	10.6	326.0
Plantation								
Established	3.6	2.4	13.0	4.5	551.4	11.9	28.9	615.7
Clearing	1.3	0.9	10.5	1.8	11.5	46.7	6.5	79.1
Agriculture	18.2	3.7	42.4	10.4	31.8	8.8	1326.6	1441.9
Total	881.5	311.0	321.2	325.2	634.5	103.6	1427.6	

(such as peat forests to agriculture) and GFED grid cell. Our observational window was January 2005 to December 2009 to cover the entire range of satellite data used in the MoF classification maps.

With this information on finer scale fires and land use transitions, we then incorporated 0.25° × 0.25° GFED3 emissions. First, we applied a correction factor to GFED3 for small fires that may have been missed in the baseline 500-m × 500-m burned area datasets used in developing GFED3. In Equatorial Asia, this correction increased 2001–2010 average fire carbon emissions by 55% (Randerson *et al*., 2012), which reflects the large proportion of small burn scars (<25 ha) that have been mapped in Equatorial Asia (Miettinen & Liew, 2009). Each 0.25° × 0.25° GFED3 grid cell can include fire-driven land use transitions, fires that result in stable land use types, and/or transitions not associated with fires. To keep the transitions without coincident fire observations from contributing to fire emissions (such as manual clearing), we allocated monthly GFED fire emissions in proportion to the monthly sum of daily 1-km^2 FRP observations within the 0.25° grid cell for each land use transition type, so that only land use pixels associated with FRP observations could contribute to our estimated GFED emissions for each land use transition. If no FRP was observed for a specific land use transition within a GFED grid cell, estimated emissions would be higher for other land use transitions with fire observations within that cell. If no FRP was observed in a grid cell with nonzero GFED emissions, then this cell would have no emissions in our downscaled product, though this effect was small (see Results). The downscaled estimates of GFED3 fire emissions were per 1-km^2 per month, for each transition type (49 possible transitions from 7 classes – not including the urban or other classes). When we applied the downscaled estimates to future scenarios, we used the Sumatra-wide average and assumed that fires observed for each transition in the past remains constant in the future.

Interannual variability in emissions. The strong interannual variability in dry season precipitation was also reflected in total fire emissions (Table 3). We quantified the difference in emissions during a representative dry year and wet year (2006 and 2010, respectively) to appropriately consider this interannual variability in our future emissions estimates. We selected 2010 for this analysis because it is the first year after our 2009 land use map so we could assume that all of the documented land use change had already occurred. Burned area and active fire products have different strengths and weaknesses: burned area is more affected by cloud cover, but the signal can persist for longer, whereas active fire detections are more dependent on fires coinciding with the satellite overpass. To build on the strengths of each approach to measuring fire extent, we created a fire-affected area mask by combining the MCD64A1 data and FRP information, for 2006 and 2010. Likely owing to the extensive cloud cover in this region, BAP pixels increased the fire mask extent from the FRP data by <1% for each year. By analyzing these results with land use types and transitions, it was possible to obtain a more nuanced understanding of the differences in emissions between dry and years across different land use transitions.

Future fires and emissions

Future land cover scenarios. We created 1-km^2 land use maps for Sumatra from 2009 to 2030, with 3-year time steps, with an estimated land use change random utility model (RUM). A land use change RUM assumes that observed land use change was largely driven by land users' desire to maximize the expected net monetary returns (gross revenues less production costs and any land use conversion costs) at each time step (Plantinga, 1996; Lewis *et al*., 2011; Lawler *et al*., 2014). However, this primary objective can be attenuated by several factors, which in Sumatra include: (i) plantation or logging concessions and protected land status, which make conversions to untargeted land uses very costly economically (potentially also in legal and social terms) and (ii) unobserved personal preferences and cultural norms for land use that can outweigh economic objectives. The Sumatra land use change RUM is estimated with 2006–2009 Sumatra maps of land use, economic productivity, and land use regulations, and therefore incorporates the aforementioned mitigating factors to the extent that they affected land use change during 2006–2009. See Nelson *et al.* (2014) and the Supplementary Information for more detailed information.

Table 3 July to November average precipitation (in mm month^{-1}) and total emissions (in Tg DM yr^{-1}) over the Sumatra land area. Fire-affected area in forest (on mineral or peat soils), degraded lands (on mineral or peat soils), and nonforest (plantation, clearing, and agriculture) for 2006 (dry year) and 2010 (wet year), based on 2006 and 2009 land use maps, and 2006 and 2010 fire-affected mask respectively. Precipitation data are from the GEOS-5 assimilated meteorology from the NASA Global Modeling and Assimilation Office (GMAO)

Year	Precipitation (mm month^{-1})	Emissions (Tg DM yr^{-1})	Fire area in forests (km^2)	Fire area in degraded lands (km^2)	Fire area in nonforest (km^2)
2005	85.6	56.0			
2006	65.2	209.7	7.24E+03	1.28E+04	1.72E+04
2007	81.9	26.2			
2008	86.7	46.9			
2009	77.8	69.1			
2010	94.6	14.1	2.60E+03	1.34E+03	4.47E+03

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Because the incorporation of unobserved preferences and norms for land use is accomplished with a random variable, estimated RUMs give probabilistic results. For example, with the estimated Sumatra RUM and 2006–2009 land use productivity and regulation (i.e., concession and protected status) data for a 1-km^2 peatswamp forest in 2006, we are able to calculate the statistical likelihood of the parcel remaining in peatswamp forest or converting to other land uses by 2009. After we had calculated these expected 2006–2009 land use change probabilities for all 7 modeled economic land uses in each Sumatra parcel, we calculated average transition probabilities for parcels in the same district, with the same 2006 land use, the same soil quality, and the same 2006 regulation category. With these estimated parcel-level transition matrices, we predicted the 2009 map from the observed 2006 map, and then every 3 years until 2030, where the transition probability vector assigned to each parcel at time step $t + 1$ was determined by its land use, soil quality category, land use regulation category, and district at time t. To calculate the areal mix of land use types in each GFED grid cell at each time step t, we overlaid the 0.25° × 0.25° GFED grid on the 1-km^2 estimated land use maps. Finally, urban land use in either 2006 or 2009 was considered static; parcels classified as 'Other' in 2006 or 2009 were dropped from further analysis. See Nelson *et al.* (2014) and the Supplementary Information for more detailed information.

The case described above creates a business-as-usual 2009–2030 trajectory of land use, which we refer to as the 'Stable Prices' scenario because we use the observed economic and land use regulations from 2006 to 2009 to create the transition matrices. Therefore, land use maps out to 2030 represent expected land use change if real net returns to land use, land use regulation, and other unobserved land use determinants from the 2006 to 2009 era remained spatially and temporally unchanged until 2030 (Table 4).

We also estimated the future land use scenarios for Sumatra with alternative 2009–2030 landscape conditions. For example, under the 'High Oil Palm' scenario, we increased the gross returns for the land use categories that include oil palm plantations by 30% compared to those used in the 'Stable Prices' scenario. This scenario reflects the upward trend in oil palm prices observed since 2009 (FAOStat, 2013). Then, using the previously estimated RUM (which is a function of market prices), the 2006 land use map, the *modified* price data, and all other observed 2006–2009 landscape conditions, we constructed new 2006–2009 transition matrices, with each set of parcels grouped according to 2006 land use, soil quality, land use regulation category, and district. These transition matrices, along with the observed 2006 land use map, then formed the series of 2009–2030 'High Oil Palm' scenario maps (Table 4). Under the 'National Spatial Plan' scenario, we modified the 2006–2009 zoning and concession map according to government documents that detail the Indonesian government's plan for limited and unrestricted production forests, cultivated areas, urban uses, and conservation areas. All other 2006–2009 landscape conditions were left unchanged. Then, as before, we used the previously estimated RUM, the 2006 land use map, and the modified data set of 2006–2009 conditions to calculate land use transition probability matrices and then projected land use out to 2030 in 3-year time steps.

Other alternative scenarios we considered when estimating trajectories of land use for every 3 years from 2009 to 2030 include 'Green Vision' and 'Green Vision with Peat Protection' (Table 4). Under 'Green Vision,' 2006 to 2009 zoning maps were modified according to a sustainable development plan focused on ecosystem conservation endorsed by the Indone-

Table 4 Description of future scenarios and associated assumptions about future trends in land use zoning, economic returns, and tax or subsidy policies

Scenario	Description
Stable prices	Assumes market, economic, political, and social conditions observed from 2006 to 2009 in Sumatra, Indonesia, and globally continue until 2030.
National spatial plan	Re-zones Stable Prices scenario using Indonesian government spatial plan, which includes conserved forests, working forests that cannot be cleared, and unrestricted zoning classes. New urban areas are added in 2009 since we do not have information on how these areas will be implemented over time. This plan was established by Government Regulation Act No. 26 2007 and Act. No. 26 2008, which established the National Spatial Plan (RTRWN) and were developed by the Ministry of Public Works (Kementerian Pekerjaan Umum).
Green vision	Implements World Wildlife Fund sustainable development plan, which changes zoning for different land uses to conserve forested areas. Incorporates leakage effects by increasing revenues in areas where agriculture or plantation conversion is permitted.
Green vision with peat protection	In addition to Green Vision scenario described above, also places all forest or degraded areas on peat soils (as of 2006) in protected area zones and blocks fire incidence in these areas.
High oil palm	Sets real commodity prices for commodities produced on land classes that contain oil palm higher than the 2006-2009 observed prices. The sub-classes that contain oil palm are other plantation and nonrice agriculture with mixed bush. The clearing land use class also contains oil palm. We multiplied 2006-2009 real commodity prices for commodities produced by each of these subclasses and the clearing land use by 30%. Expected prices used for RUM estimation occurred during the most recent global recession, so this scenario mimics market prices more consistent with current conditions.

Table 5 Proportion of pixels within each transition class associated with at least one MODIS FRP observation over 2005–2009. Rows are 2006 classes and columns are 2009 classes. Refer to Table 1 for class names and Table 2 for areas within each transition. The fire proportion in the urban class was 0.10

	2009 Land use							
					Plantation			
2006 Land use	Forest, Mineral	Forest, Peat	Degraded, Mineral	Degraded, Peat	Established	Clearing	Agriculture	Mean
Forest, Mineral	0.08	0.29	0.19	0.20	0.42	0.58	0.25	0.32
Forest, Peat	0.19	0.22	0.49	0.43	0.46	0.79	0.45	0.43
Degraded, Mineral	0.13	0.19	0.27	0.47	0.28	0.46	0.22	0.29
Degraded, Peat	0.33	0.19	0.41	0.42	0.36	0.55	0.26	0.36
Plantation								
Established	0.24	0.38	0.22	0.37	0.19	0.41	0.16	0.28
Clearing	0.26	0.48	0.21	0.45	0.36	0.44	0.29	0.36
Agriculture	0.13	0.26	0.13	0.28	0.14	0.29	0.19	0.20
Mean	0.21	0.29	0.27	0.37	0.32	0.50	0.26	

sian Ministry of Environment, Ministry of Public Works, Ministry of Forestry, and Ministry of Home Affairs, which rezones areas in Sumatra into important conservation areas, production areas with certification principles for sustainable development, and unrestricted development (Roosita *et al*., 2010). All other 2006 to 2009 landscape conditions were left unchanged. The 'Green Vision with Peat Protection' is similar to 'Green Vision' scenario, but provides protected status to all parcels with peatswamp in 2006 and assumes that any remaining conversion in these areas occurs without fire.

Future fire emissions. We applied the 1-km^2 estimates of observed fire emissions for each land use transition to the future scenarios. We first normalized total GFED emissions created by each type of land use transition by the area observed from 2006 to 2009 (Table 2). Although some future transitions will likely occur without fires (Table 5), we applied the average emissions per unit area to the predicted area of all individual land use changes within the 0.25° GFED grid cell. We matched our more detailed fire types from land use transitions to one of the six GFED fire types (van der Werf *et al*., 2010). Forests or degraded land on peat soils were considered peatland fires; degraded land on mineral soils, clearing, or urban were considered savanna fires, plantation was considered woodland fires; and agriculture was considered agricultural waste burning. Following van der Werf *et al*. (2010), we considered all tropical forest fires (on mineral soils) to be deforestation fires.

There is a highly nonlinear relationship between fire emissions and dry season precipitation in this region (van der Werf *et al*., 2008); Table 3 shows the interannual variability between 0.5° dry-season precipitation and observed GFED3 emissions (including small fires) for 2005 to 2010. We used this observed variability to understand how the contribution of different fire types could vary interannually with future meteorology. The influence of near-term climate change on Equatorial Asia on this short a timescale is uncertain (Collins, 2005; Christensen & Kanicharla, 2014), and we do not include its effects. Instead we assume that the mean and variability of the meteorology observed during our 2005 to 2009 training period continues until 2030.

Results

Past land use transitions

We estimated the role of fire in specific land use transitions by counting how many pixels within each transition class were associated with at least one fire observation over the 2005 to 2009 period (Table 5). This allowed us to observe which original 2006 land use classes had coincident fire observations during transitions to other land use classes, as well as which final land use classes in 2009 had corresponding fire observations. The 2006 land uses associated with the highest average proportion of fire observations were forests, degraded land on peat soils, and clearing, all of which had mean proportions above 30%. Compared with all 2009 classes, the clearing class had the highest mean incidence of observed fires (50%), calculated by averaging all 2006 land uses that resulted in clearing by 2009.

MODIS FRP coincident with land use transitions varied among different land use classes and over time. The monthly time series of summed FRP (from Terra and Aqua) for all of Sumatra is shown in Fig. 3 for transitions originating in each land use class. The highest FRP observations were observed in forest or degraded land on peat soils. Forest on peat soils had the highest FRP activity observed in early 2005 that corresponded with pixels transitioning to clearing over 2006 to 2009, as well as moderate FRP activity that corresponded with stable (nontransitioning) forest areas. Stable degraded land on peat soils showed consistent peaks

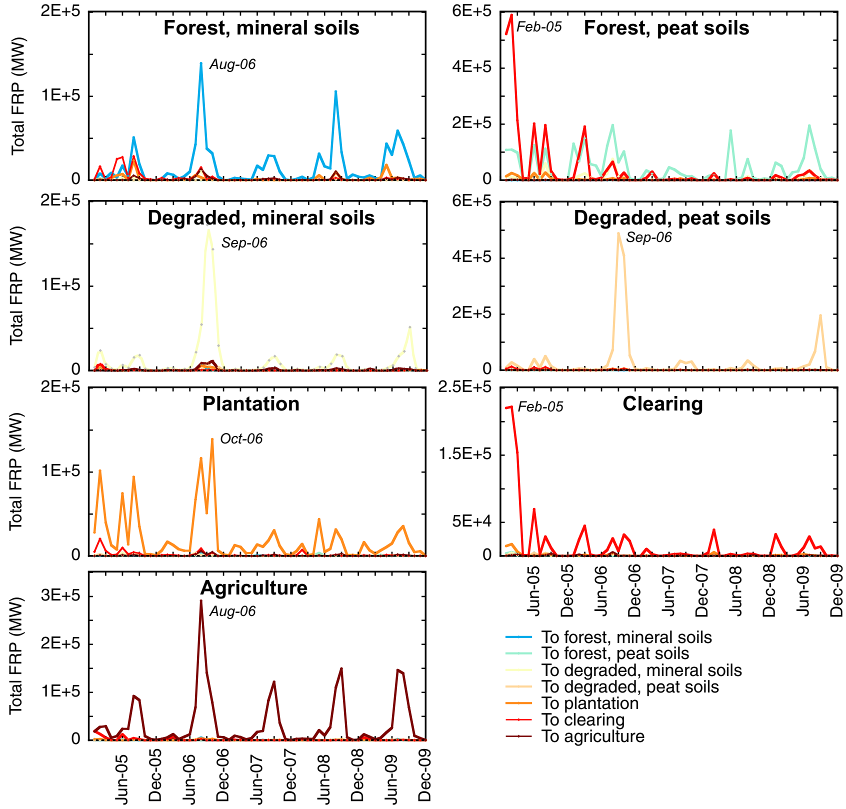

Fig. 3 Monthly sum over Sumatra of maximum FRP (Aqua + Terra) originating in each land use class (as indicated by title at the top of each plot) for January 2005 to December 2009. Note that stable land use transitions remain within the same land use class (Agriculture to Agriculture, for example). Date on each plot indicates the month and year of maximum observed FRP over the 5-year period.

each year during August to October, with an absolute peak during the dry conditions of 2006. Forest and degraded lands on mineral soils and agriculture also exhibited August to October peaks, with absolute maxima in 2006. Established plantation and clearing had relatively low FRP totals. We observed high FRP values in early 2005 in the forest on peat soils and clearing classes. Overall, Fig. 3 reveals three aspects of our FRP downscaling approach: (i) FRP variations by transition, with higher observed FRP in fuel-rich peatswamp fires, (ii) interannual and monthly variations in the magnitude of FRP, and (iii) specific land use groupings exhibiting a higher FRP observations during land use transitions instead of stable land use (forest on peat soils to clearing).

As expected, higher fire-affected area was observed in the dry vs. wet year (2006 vs. 2010) (Fig. 4). The areas reported in Fig. 4 likely overestimated the absolute areas because we summed whole 1-km^2 pixels that were flagged in either the burned area maps or FRP data (no fractional fire-affected area). However, we were interested in the relative changes between the 2 years. When stratified by land use transition, we found that a greater proportion of fire-affected area in 2006 occurred in areas that transitioned from classes unassociated with agricultural production (especially degraded lands on peat soils) than was observed in 2010. In 2010, there was a higher proportion of the total fire-affected area in areas associated with productive land uses (including plantation, clearing, and agriculture). This result suggested that higher emissions observed in dry years are more associated with unintentional fires, as indicated by greater correlation with burned areas transitioning to nonproductive land use types, or fires that do not directly result in conversion to productive use within our observational time period (Table 3).

Fire emissions from land use transitions

Total GFED emissions downscaled by MODIS FRP values indicated both interannual and monthly variation (Fig. 5). Annual emissions for all of Sumatra mirrored the original GFED with small fire emissions that were described in Table 3. Figure 5a shows that most emissions were observed during the dry conditions of 2006, as well as the enhanced contribution of specific land use classes, especially carbon-rich degraded land on

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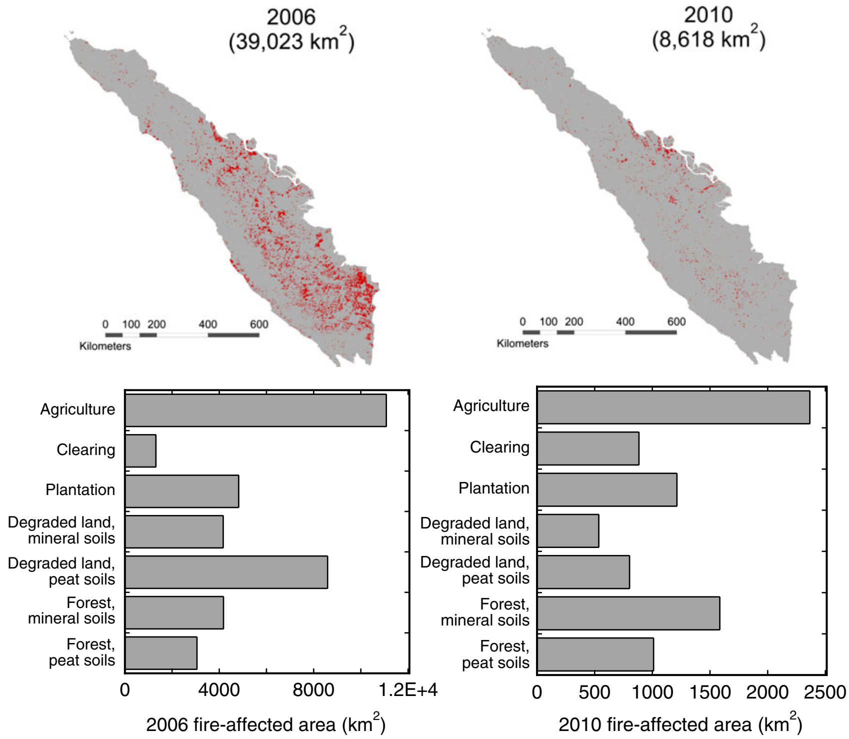

Fig. 4 Annual fire-affected mask from MODIS burned area product and active fire detections for 2006 (representative dry year) and 2010 (representative wet year). Area (km^2) from the fire-affected mask is partitioned into land use classes described in Table 1. Left column represents 2006 (transitions from 2006 land use), right column represents 2010 (transitions to 2009 land use).

peat soils. These totals show the emissions originating in these seven land use classes and transitioning to any other class. Emissions from degraded land on peat soils contributed more than 40% of total emissions during 2006, but a smaller fraction of total emissions during wetter years (like 2005). Emissions from plantations showed the least interannual variability. A large proportion of emissions were not associated with land use transitions observable over our time period (Fig. 5c), but forests on peat soils had the largest proportion of emissions transitioning to another class (clearing). Our estimates of future burning assume that nontransition emissions continue at the same levels as observed during 2005–2009.

Sumatra-level emissions for all years (2005–2009) within a given month showed the strong variability over the course of the year in overall fire activity and fire type (Fig. 5b). Both the bulk of emissions and the contribution of peatswamp fires peaked during August, September, and October. Emissions from agricultural and established plantation areas also peaked during these months, and burning in the clearing class contributed the most during September and October. Overall, these results indicated that degraded lands on mineral or peat soils were the most vulnerable during the summer months of dry years.

Future emissions from land use change

The trends in total area within each land use class demonstrates the power of land use policies to influence future development, as well as the sensitivities of the RUM model to the economic and policy assumptions implemented in each scenario (Fig. 6). Forests on mineral soils showed equally large increases with the 'Green Vision' and 'Green Vision with Peat Protection' and the strongest declines in the 'High Oil Palm' scenario (Fig. 6a). Similar trends were observed for forests on peat soils (Fig. 6b), except that the 'Green Vision with Peat Protection' scenario had much larger gains. Degraded lands on mineral soils (Fig. 6c) declined in all scenarios, with the steepest decline in the 'High Oil Palm' scenario. The 'Stable Prices' and 'National Spatial Plan' also exhibited slight recovery after 2018. All scenarios showed declines in degraded land on peat soil area (Fig. 6d), with the largest changes in the 'High Oil Palm' and 'Green Vision with Peat Protection' scenarios. Plantation area (Fig. 6e) increased in all scenarios except for 'Green Vision with Peat Protection.' Trends in the clearing class (Fig. 6f) were similar for all scenarios except the 'High Oil Palm' scenario, with fivefold increases in area. Agricultural area (Fig. 6g) had slight gains in the 'Stable Prices' and

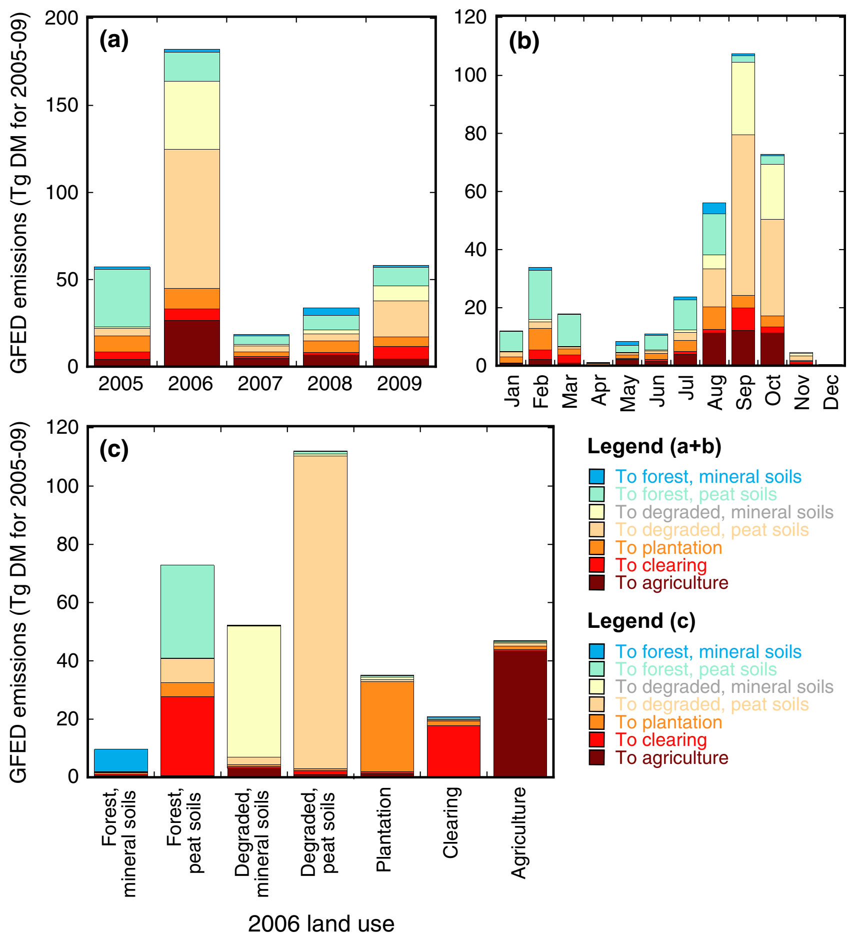

Fig. 5 Sum of total Sumatra fire emissions for 2005–2009 (in Tg DM) from FRP-downscaled GFED emissions for land use classes described in Table 1. (a) Annual sum, (b) Sum for all years within a given month, and (c) Emissions coming from original land use groupings in 2006 (*x*-axis) to land use groupings in 2009 (bars).

'High Oil Palm' scenario, with declines in the other three scenarios.

Figure 7a shows the percentage of forest cover (on mineral or peat soils) for each 0.25° × 0.25° grid cell, for the same scenarios described above. All five scenarios indicated that most of the projected remaining forest was in the western part of Sumatra (mostly forests on mineral soils at high elevations). There were varying degrees of remaining forest (mostly on peat soils) in the eastern part of Sumatra; the lowest forest cover was in the 'High Oil Palm' scenario and the highest in the 'Green Vision with Peat Protection' scenario. The 'Green Vision' scenario also had higher retention of forests in eastern Sumatra, but since fires could still occur in these areas, fire emissions remained high (Fig. 7b).

Cumulative total emissions (2009–2030) showed that the eastern part of Sumatra dominated fire emissions over the next two decades due to emissions from peat areas, which contributed to the bulk of emissions in all scenarios (Table 6). Our three-yearly estimates assumed that meteorological conditions over our observational period were representative of the next two decades. The highest total emissions (3189 Tg DM from 2009 to 2030) were projected in the 'High Oil Palm' scenario due to the increased contribution of fires from the clearing class (including initial stages of plantation development), in addition to fires in peat areas. The 'National Spatial Plan' and 'Stable Prices' scenarios followed with similar totals of 2723 and 2733 Tg DM in cumulative emissions respectively. The 'Green Vision' scenario had slightly lower emissions (2580 Tg DM from 2009 to 2030), with differing reduced contributions from degraded land and clearing. The 'Green Vision with Peat Protection' scenario had the lowest total emissions, 1320 Tg DM. Emissions time series for the next two decades showed the stark contrast between the 'High Oil Palm' and 'Green Vision with Peat Protection' scenarios (Fig. 8).

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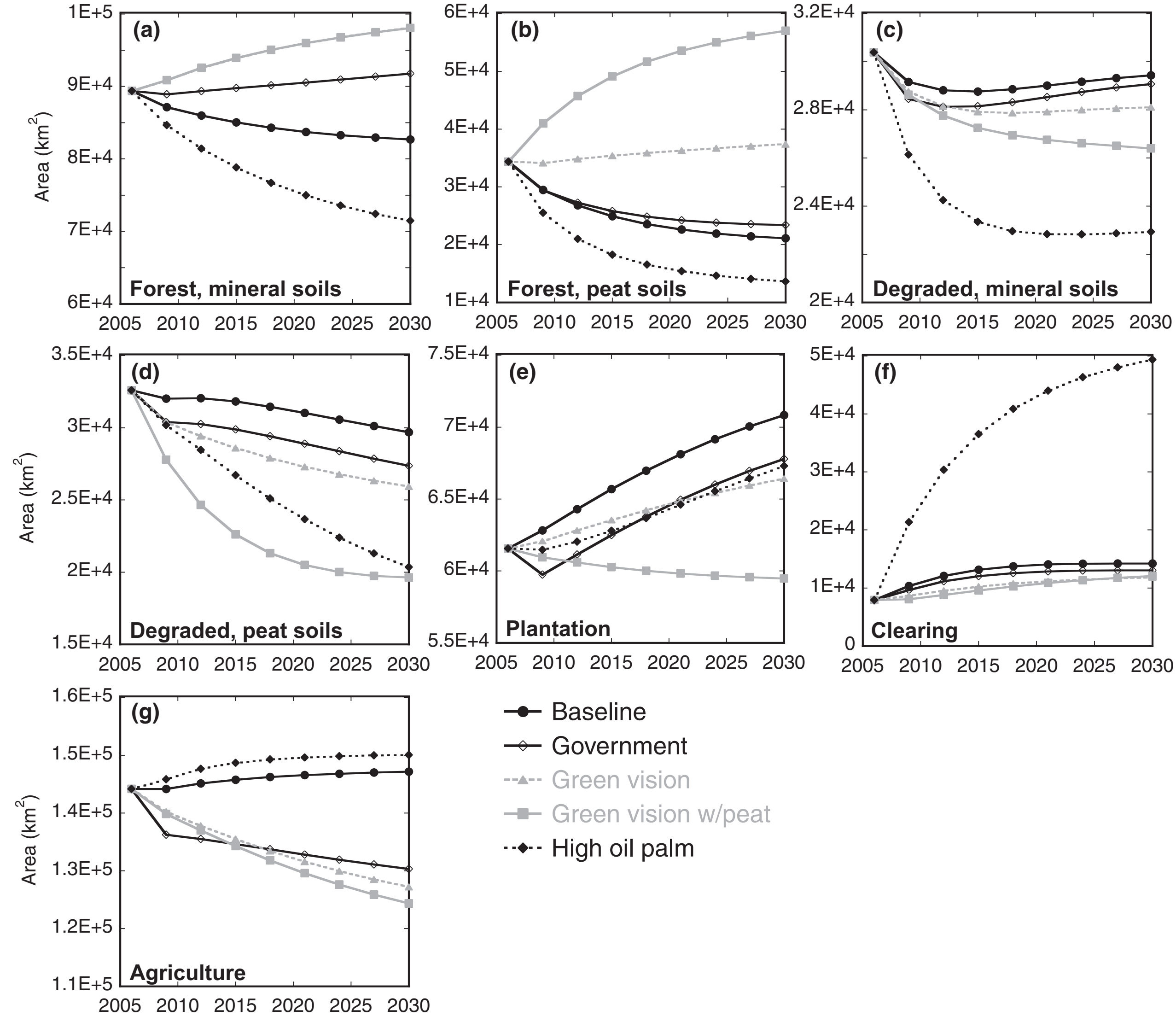

Fig. 6 Total area (km^2) for Sumatra within each land use class, for 2006 to 2030: (a) Forest on mineral soils, (b) Forest on peat soils, (c) Degraded on mineral soils, (d) Degraded on peat soils, (e) Plantation, (f) Clearing, and (g) Agriculture. Future scenarios as defined in Table 4. Note change in scale of *y*-axis and that 2030 refers to start of final three-year timestep.

In Fig. 9, the three-yearly emissions from the 'High Oil Palm' scenario were partitioned into an annual time step, which illustrated the strong impact that applying interannual variability in meteorology can have on peak annual emissions totals. Here, we repeated the 2005 to 2009 meteorology for the next two decades and allowed the contributions of each fire type to vary according to the proportions of each fire type per year, as observed in Fig. 5. (These relationships were also supported by our analysis of burned area in Fig. 4.) For example, for the 2009 to 2011 time period, we assigned meteorological conditions for 2009, 2005, and 2006, in that order. We then calculated the proportion of emissions that each year would contribute if that sequence of meteorology had occurred in the past, and scaled the 2009 to 2011 estimated three-yearly total accordingly. In Fig. 9a, spikes in emissions estimates could change estimated population exposures to fire emissions, as opposed to the constant emissions in Fig. 9b. The sum of all types of fire emissions is shown in Fig. 9c, for constant three-yearly emissions and partitioning these same emissions into an annual time step using 2005 to 2009 meteorology. While we do not expect present-day meteorological conditions to continue into the future, these years offer a feasible representation of the interannual variability in meteorology and its effect on emissions. Planned future work will include sensitivity cases to test the effect of different meteorological conditions.

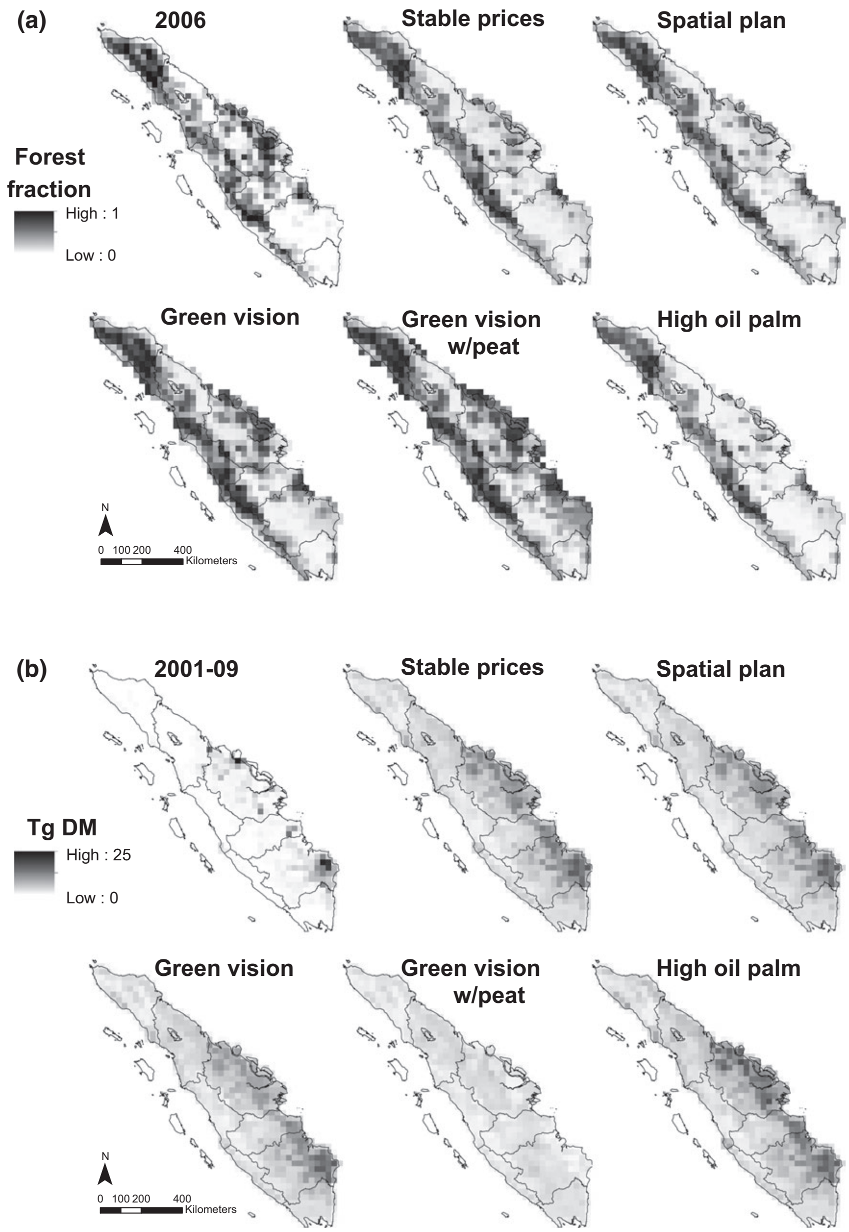

Fig. 7 (a) Fraction of forest cover – here defined as forest on mineral or peat soils – remaining in 2030 for five future scenarios (i) Stable Prices, (ii) National Spatial Plan, (iii) Green Vision, (iv) Green Vision with Peat Protection, (v) High Oil Palm, and (b) Cumulative total fire emissions for 2009–2030 (in Tg DM). Darker colors represent greater forest fraction in (a) and higher emissions in (b). Note that 2030 refers to the start of the final three-year timestep.

Sensitivity analysis

Data limitations and the need to simplify a complex coupled biophysical and social system led to several modeling assumptions and decisions that could significantly affect modeled results. Here, we acknowledge potential problems and examine the impact of some of the assumptions and simplifications on modeled results. First, although the MoF land use maps were crucial tools in this analysis, they did not have specific dates associated with the satellite images used for the classification process. We therefore extended our temporal window from 2005 to 2009 to capture the full range of potential fire emissions associated with land use transitions. Second, the agriculture and plantation land use classes aggregated many crop types and land management styles. Therefore, the economic productivity and fire management practices assigned to a parcel in these land uses represented the general productivity and fire management for land uses of that type in that

Table 6 Cumulative total fire emissions (in Tg DM), by fire type, for five future scenarios over 2009–2030 (description of scenarios in Table 4). Emissions from the 'Other' land use class were omitted from the future analysis as this included cloud cover and water in the MoF land use maps. Note that 2030 refers to the start of the final three-year timestep

Land use class	Stable prices	Spatial plan	Green vision	Green vision w/ peat protection	High oil palm
Forest, Mineral Soils	71	73	75	75	71
Forest, Peat Soils	415	412	450	0	460
Degraded, Mineral Soils	386	379	374	362	318
Degraded, Peat Soils	865	808	776	0	712
Established Plantation	300	286	291	275	288
Clearing	291	268	238	234	925
Agriculture	381	351	353	349	391
Urban	24	146	24	24	24
Total	2733	2723	2580	1320	3189

portion of Sumatra. Instead of the individual 1-km^2 parcel scale, our model is better analyzed at a coarser spatial grain (like the 0.25° × 0.25° GFED grid), where generalizations by land use type are much more representative. Third, attributing fire emissions to specific land use transitions may be impacted by errors in the MoF classification maps; further research is needed to understand how these errors may have changed our estimates.

In the emissions analysis that used FRP to downscale GFED emissions, there were several potential sources of error. Since it is not possible to have monthly resolution land use maps covering all of Sumatra due to near-constant cloud cover in this region, we overlaid FRP and associated emissions data on the longest possible time period of land use change, 2005 to 2009. We tested the sensitivity of this assumption by assuming that only January 2006 to December 2008 fires were relevant to the land use change maps, and found 32% lower cumulative emissions estimates (Table S2). Also, satellite overpasses may have missed fires or not coincided with the peak burning time, leading to underestimates of the contributions of the 1-km^2 pixels to 0.25° GFED emissions. We partially addressed the latter problem by combining MODIS Aqua and Terra FRP observations. Our downscaling approach did not capture all monthly GFED emissions (Figure S2); some emissions were missed if there were no MODIS FRP observations within a GFED grid cell, such as when fire emissions were estimated in the GFED product through the burned area algorithm. If we scale our 1-km downscaled emissions estimates to match the monthly 0.25° GFED totals, our cumulative emissions estimates were 5% higher (Table S2).

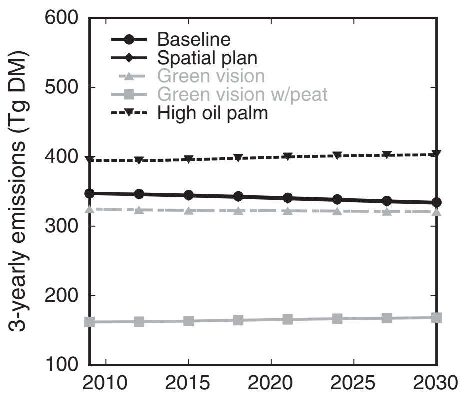

Fig. 8 Total emissions (in Tg DM per 3 year timestep) for each scenario from 2009 to 2030. Note that 2030 refers to the start of the final three-year timestep.

Peatswamp emissions were found to drive the majority of emissions in our future scenarios. Peat burning depth ranges from 0 to 50 cm in the GFED model for Indonesia, and was scaled according to soil moisture and fire persistence (van der Werf *et al.*, 2010), with a 30 cm average that compared well with a recent LIDAR study, which estimated an average peat burning depth in Central Kalimantan of 0.33 ± 0.18 m (Ballhorn *et al.*, 2009). We also addressed underestimates by GFED of Equatorial Asian fire emissions with the new dataset that quantifies the contribution of small fires (Randerson *et al.*, 2012).

We created five future scenarios to show how different economic and policy assumptions affected our emissions estimates. The similar totals between the 'Stable Prices,' 'National Spatial Plan,' and 'Green Vision' scenarios (2580–2733 Tg DM from 2009 to 2030) indicate that zoning changes proposed under the two spatial plans would do little to affect overall emissions. Instead, relatively drastic changes in protection of peatswamp areas ('Green Vision with Peat Protection' scenario) and market prices ('High Oil Palm' scenario) were found to affect emissions much

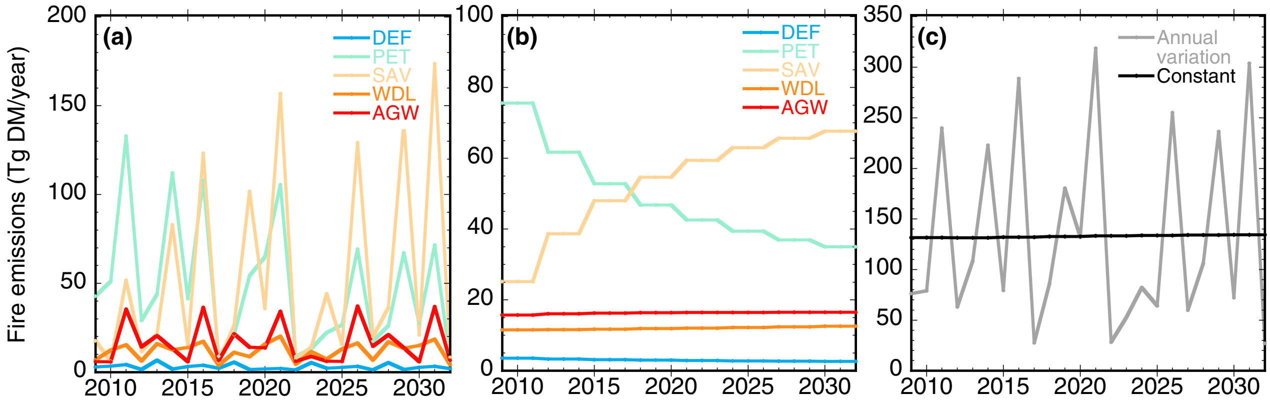

Fig. 9 Emissions by fire type (Tg DM) for the High Oil Palm scenario when: (a) partitioned according to relationships between fire emissions and meteorology observed over 2005–2009, (b) assumed to be constant over each three-year time step. Panel (c) shows the sum of all fire types from (a) and (b). Fire type groupings are as defined in text, with DEF = deforestation, PET = peatland, SAV = savanna, WDL = woodland, and AGW = agricultural waste.

more profoundly. Although the 30% increase in oil palm and other nontimber plantation commodity prices assumed in the 'High Oil Palm' scenario may seem extreme, recall that the period 2006 to 2009 were global recession years, and prices for many globally traded plantation commodities were lower than normal at the time. In a postrecession global economy, 30% higher palm oil and other plantation commodity prices, as observed since 2009, are plausible (FAOStat, 2013). All told, our five land use change scenarios offer realistic bounds on the Sumatra's 2009 to 2030 emission trajectory.

As described above, the land use transition matrices for all scenarios were generated with an estimated land use change RUM and a set of 2006 to 2009 conditions, either the observed ('Stable Prices') or with modifications. When we estimated the land use change RUM, we used only a subset of 7556 Sumatra parcels and their related 2006 to 2009 data; the maximum-likelihood routine used to estimate the model did not converge to a solution when we included all Sumatra parcels. The results presented above are based on a random sample of parcels. As part of a sensitivity analysis, we estimated the alternative RUM using a sample of 4309 evenly spaced parcels separated by 10-km. This exercise verified that expected emission projections were not highly sensitive to our sampling method. For example, cumulative 2009 to 2030 emissions for the 'Stable Prices' scenario were 2733 and 2767 Tg DM when the RUM was estimated with the randomly chosen and evenly spaced parcels respectively (Table S3). This result represents a 1.2% difference in cumulative emissions. Second, we were interested in determining whether unexplained local spatial processes on the landscape affected our model results. If the standard errors of the estimated model coefficients based on the evenly spaced sample are consistently higher than those from the random sample then we can conclude that the RUM estimated with the random sample is affected by spatial autocorrelation. As expected, the model estimate with the random set of parcels did show some evidence of spatial autocorrelation (see Nelson *et al.*, 2014). The ramification of this spatial autocorrelation is that the p-values associated with variables from the RUM estimated with the random subset of parcels are higher than reported. However, given that the sampling method does not affect the output of interest – predicted land use maps – best statistical practice always recommends a random sample over a nonrandom sample when ambivalent over the selection.

For the 'National Spatial Plan,' 'Green Vision,' and 'Green Vision with Peat Protection' scenarios described above, the various land use regulation plans increased the area of protected forests (on mineral soils, peat soils, or both). In our primary analysis above, we assumed markets did not react to changes in the supply of unprotected forests. However, it is likely that the Sumatran land market and its economic actors would react to the changes wrought by a new zoning plan. First, many forest parcels that were developed under 'Stable Prices' would now be zoned for protection. This rezoning would stop most of the business-as-usual conversion on the newly conserved parcels. Land developers would then have to look elsewhere for unprotected, convertible forest, which would include unprotected forest areas left intact under the 'Stable Prices' scenario. (This spatial displacement of development is known as policy leakage.) That these sites were left alone under the 'Stable Prices' scenario

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indicates that they are not as productive or cost-effective as some of the newly protected forests. Furthermore, the increase in protected forest means that developers of land would be competing over a scarcer supply of unprotected forest, leading to higher land rents across Sumatra. The conversion of less productive land and higher land rents means that commodity production costs on converted land would generally be higher under the various alternative zoning plan scenarios than they are under the 'Stable Prices' scenario. Producers would attempt to pass increased production costs onto consumers by charging higher prices for the products they create. However, producers of goods that are sold on a global market would be less successful at passing this price change to consumers than producers of goods that face less import competition (local goods). Finally, as market prices increase so would the gross revenues from managed forest and agriculture.

Because policy leakage mitigates the environmental improvements generated by protective land use regulations, modeling leakage is essential to accurately assessing for the impact of a land use policy. Unfortunately, without a model of the Indonesian economy and its place in the global economy we cannot predict how much policy leakage might occur under each alternative land use regulation scenario. Instead, we investigated to what degree the emission benefits of a land use regulation policy would change if leakage were extreme enough that forest protection generated by a policy without leakage was halved. For example, the 'Green Vision' scenario increases 2030 forest area by 30.6% relative to the 'Stable Prices' scenario but 'extreme' leakage would mean that this overall increase in forest area was instead approximately 15%. To spatially allocate this leakage in an economically coherent manner, we increased forest and agricultural product market prices, and thus gross revenues for the various managed forest and agricultural land uses, such that the increase in forest area was only 16% compared to the 'Stable Prices' scenario. With this modification, the forest stands that remain unprotected under the 'Green Vision' scenario and that were almost productive enough to be converted to managed forest or agricultural uses under the 'Stable Prices' scenario were likely converted. In the 'Green Vision' scenario, a halving of forest area by 2030 required a 17.5% increase in the real prices of local goods and a 12% increase in the real price of globally traded goods as of 2009.

In Table S4, we present the real price increases necessary to reduce additional forest conservation by half under each alternative zoning scenario. By adding extreme leakage to both the 'Green Vision' and 'National Spatial Plan' scenarios, 2009 to 2030 fire emissions were ~40 Tg DM greater than under the scenarios without leakage. For the 'Green Vision with Peat Protection,' cumulative 2009 to 2030 fire emissions with leakage added 76 Tg DM compared to no leakage effects. Implementation of a policy that rezoned land use for a significant portion of Sumatra would generate forest conversion leakage. Here, we have put bounds on the potential leakage for the rezoning scenarios that we have considered. [A 50% leakage rate is extreme; see Busch *et al.* (2012) for a more on policy-driven forest conversion leakage in Indonesia]. If Indonesian policymakers were to implement one of our scenarios, it would be critical to conduct a more thorough leakage analysis given the potential emission ramifications.

Discussion

An often-ignored issue in tropical land use policies is the public health impact of emissions from fire-driven deforestation. We examined how different market conditions and land use policies to protect natural forests and limit agriculture, forestry, and plantation growth affect predicted trajectories of fire-based emissions from Sumatra (Fig. 6). As illustrated in Fig. 7 and Table 6, the examined land development strategies in Sumatra were associated with varying patterns of forest conservation and potential associated fire emissions from burning. Our analysis makes it clear that cumulative emissions out to 2030 will remain high, regardless of the amount of protection for forests on mineral soils, unless strong protections for peatswamp areas are also implemented. Across the four scenarios that do not include broad peatswamp conservation, we found a range of 2580 to 3189 Tg DM of cumulative emissions from 2009 to 2030, with peatswamp fires contributing 37–48% of total emissions. When peatswamp areas were protected, 2009 to 2030 cumulative emissions decreased to 1320 Tg DM. These ranges indicated that fire emissions associated with our scenarios are less sensitive to the various economic and policy assumptions than to fires in peatswamp areas with high fuel loads. Compared with the business-as-usual cumulative emissions estimate from land use conversion and peat oxidation of ~2000 Tg DM (converted from reported CO_2 units) for Sumatra by 2050 from Harris *et al.* (2013), our range of 2580–3189 Tg DM by 2030 (in our scenarios without peat protection) is higher. This can be attributed to including emissions from peat fires, considering conversion to land uses other than oil palm plantations, and incorporating emissions from fires that do not result in immediate conversion.

Our results can inform policy makers in several ways. First, our work reveals the stark contrasts in the consequences of different possible scenarios of future fire activity. We do not expect the economic and cultural conditions observed from 2006 to 2009 in Sumatra to remain constant until 2030, so it is unlikely that our alternative scenario projections will exactly predict the future. For example, our model of land use change does not consider how shifts in land use would impact commodity prices over time and how these changes in turn would feedback into land use decisions (Lawler *et al.*, 2014). However, we believe that the value in our analysis lies in quantifying the relative differences between scenarios. For example, if Indonesian policymakers were considering instituting the 'Green Vision with Peat Protection' scenario in Sumatra over the next several years, a comparison with the 'High Oil Palm' scenario would give policymakers a general sense of the range of emissions reductions that could be expected over the next two decades. We are confident in the policy relevance of the relative results, despite an uncertain future, because macroeconomic and cultural changes on the landscape over time would generally affect scenario results in a similar fashion, thereby largely preserving the relative differences in scenarios.

Second, detailed information on how specific land use transitions were associated with fire (Figs 3 and 5, Table 5), along with the most vulnerable times for fire activity, could be used to inform on-the-ground policies to restrict burning. While a zero burn policy does not give smallholders alternative methods to clearing land, identifying low risk conditions for burning that help contain fires could reduce the impact (Dennis *et al.*, 2005). For example, the contribution of emissions from peatswamp forests and degraded areas peaked in drier years (such as 2006) and during the driest part of the year (September and October). We find that the majority of emissions were not from forest conversion directly, but from fires in highly susceptible degraded areas, which might be unintentional or related to the initial stages of the clearing process. This confirmed previous findings that fires in Sumatra are concentrated in degraded land use types and limited in intact natural ecosystems (Margono *et al.*, 2012; Miettinen *et al.*, 2012b) and protecting these areas from ignition sources is crucial for emissions reductions.

Third, our findings can be used to investigate the consequences of different land use scenarios on human health. Our research is part of a larger project that will quantify local and transboundary public health benefits associated with ecosystem conservation in Sumatra. To appropriately compare with the economic benefits of plantations, the full value of ecosystem services provided by forests will be undervalued without accurate quantification of the public health costs associated with exposure to emissions from deforestation and degradation fires. (Other important costs not considered here include depleted carbon stocks, biodiversity declines, and water quality (Naidoo *et al.*, 2009; Bhagabati *et al.*, 2012)). The future fire emissions inventories described in this study will be used in an atmospheric transport model to simulate future exposure to transported fire emissions and associated public health impact. In these simulations, it is imperative to consider the interactions between future fire emissions and future meteorological conditions (Fig. 9). Our three-yearly emissions estimates assumed that the observed meteorological variability from 2005 to 2009 continues until 2030; we will test the sensitivity at the annual level by partitioning emissions according to different combinations of meteorological conditions. For example, a strong drought year followed by two wetter years would be expected to concentrate fire-driven land use change in the first year with less change attributed to the following 2 years. Finally, the approach taken by this paper can be extended to other parts of Indonesia that constitute the frontier of plantation development, especially Kalimantan and Papua, and to land use fires in other parts of the world.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Description of the methods used to estimate future land use change scenarios, examples of land use classifications with corresponding satellite data, and sensitivity analyses.
Figure S1. Examples of Landsat images (left) and corresponding Ministry of Forestry (MoF) land use classification maps (right) at 30-m and 1-km resolution, respectively, for a range of landscapes. Each landscape is shown for 2006 (top) and 2009 (bottom). The legend defines the MoF land use types. The sample landscapes are dominated by (a) mixed plantation, clearing, agriculture, and degraded land on peat soils, (b) forest on peat soils, (c) forest on mineral soils, plantation, clearing, and degraded land, (d) plantation, urban, and degraded lands, (e) forest on peat soils with a mix of agriculture, plantation, and degraded lands, and (f) plantation, clearing, and remaining forest on peat soils. The forest in (e) experienced active burning in 2006.
Figure S2. Total Sumatra monthly emissions (in Tg DM) for 2005–2009 for observed 0.25° GFED data (white) and for the downscaled 1-km emissions (gray).
Table S1. Change in proportion of each land use transition in Sumatra for 1-km land use maps relative to 30-m land use maps (as % of Sumatra total land area for each transition class), after assigning the dominant land use type when rescaling. Rows represent 2006 land use classes and columns represent 2009 land use classes. 'ther' includes MoF water, beach, clouds, and other classes.
Table S2. Sensitivity for cumulative 2009 to 2030 total fire emissions (in Tg DM), by fire type, for Stable Prices scenario: (i) As presented in main results, (ii) Overlaying 2006–2008 FRP only (instead of 2005–2009 in main results), (iii) Scaling monthly emissions totals from our downscaled 1-km2 product to match observed monthly 0.25° GFED totals.
Table S3. Stable Prices scenario sensitivity analysis: (i) Random: 2030 land use allocation and 2009–2030 cumulative emissions presented in the main text, and (ii) Grid: 2030 land use allocation and 2009–2030 cumulative emissions if the land use change RUM had been parameterized with a gridded sample of parcels instead of a random sample of parcels.
Table S4. Additional forest area conserved emissions impacts (relative to 'Stable Prices' scenario) with no leakage and 'extreme' leakage. Forest area is the sum of forest on peat soils and forest on mineral soils. By 'extreme leakage' we mean a halving in additional forest cover (compared to 'Stable Prices') associated with a land use regulation policy due to displaced land use conversion. We assumed goods produced on nonrice agriculture with brush and nonrice agriculture fields were mostly traded in local markets with limited import competition and all other goods were traded in more global markets.