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Fire activity in Borneo driven by industrial land conversion and drought during El Niño periods, 1982–2010

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ABSTRACT

Tropical rainforests, naturally resistant to fire when intact, are increasingly vulnerable to burning due to ongoing forest perturbation and, possibly, climatic changes. Industrial-scale forest degradation and conversion are increasing fire occurrence, and interactions with climate anomalies such as El Niño induced droughts can magnify the extent and severity of fire activity. The influences of these factors on fire frequency in tropical forests has not been widely studied at large spatio-temporal scales at which feedbacks between fire reoccurrence and forest degradation may develop. Linkages between fire activity, industrial land use, and El Niño rainfall deficits are acute in Borneo, where the greatest tropical fire events in recorded history have apparently occurred in recent decades. Here we investigate how fire frequency in Borneo has been influenced by industrial-scale agricultural development and logging during El Niño periods by integrating long-term satellite observations between 1982 and 2010 – a period encompassing the onset, development, and consolidation of its Borneo's industrial forestry and agricultural operations as well as the full diversity of El Niño events. We record changes in fire frequency over this period by deriving the longest and most comprehensive spatio-temporal record of fire activity across Borneo using AVHRR Global Area Coverage (GAC) satellite data. Monthly fire frequency was derived from these data and modelled at 0.04° resolution via a random-forest model, which explained 56% of the monthly variation as a function of oil palm and timber plantation extent and proximity, logging intensity and proximity, human settlement, climate, forest and peatland condition, and time, observed using Landsat and similar satellite data. Oil-palm extent increased fire frequency until covering 20% of a grid cell, signalling the significant influence of early stages of plantation establishment. Heighted fire frequency was particularly acute within 10 km of oil palm, where both expanding plantation and smallholder agriculture are believed to be contributing factors. Fire frequency increased abruptly and dramatically when rainfall fell below 200 mm month^{-1}, especially as landscape perturbation increased (indicated by vegetation index data). Logging intensity had a negligible influence on fire frequency, including on peatlands, suggesting a more complex response of logged forest to burning than appreciated. Over time, the epicentres of high-frequency fires expanded from East Kalimantan (1980's) to Central and West Kalimantan (1990's), coincidentally but apparently slightly preceding oil-palm expansion, and high-frequency fires then waned in East Kalimantan and occurred only in Central and West Kalimantan (2000's). After accounting for land-cover changes and climate, our model under-estimates observed fire frequency during ca. 1990–2002 and over-estimates it thereafter, suggesting that a multi-decadal shift to industrial forest conversion and forest landscapes may have diminished the propensity for high-frequency fires in much of this globally significant tropical region since ca. 2000.

1. Introduction

Humid tropical forests, naturally resistant to burning when intact, are increasingly subject to destructive landscape fires driven by agricultural expansion, forest disturbance, and potentially climate change (Cochrane, 2009; Krawchuk et al., 2009; Jolly et al., 2015). Borneo is exemplary in this respect, as there, significant periodic declines in precipitation during El Niño events associated with the

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positive phase of the El Niño Southern Oscillation (ENSO) climatic phenomenon have repeatedly coincided with what are generally regarded as the largest recorded tropical biomass burning events following forest degradation and agricultural development (Malingreau et al., 1985; Liew et al., 1998; Barber and Schweithelm, 2000; Siegert et al., 2001; Page et al., 2002; Field et al., 2009). Climatic projections anticipate variable, generally increasing trends in annual precipitation, but also increases in seasonal drought indices and a three-fold increase in the number of days of extreme fire danger per annum in fire-prone regions of Indonesia (Herawati and Santoso, 2011). Projections of increasingly frequent or extreme ENSO phenomena (Cai et al., 2014) and more pronounced ENSO-driven periodic precipitation reductions across the western Pacific (Power et al., 2013) presumably extending to Borneo could compound such trends and, by extension, recurrent fire activity. The 2015/16 El Niño event ranked alongside the 1997/98 and 1982/83 events in terms of extreme sea-surface temperature anomalies (Null, 2016); yet, whilst extreme by any standard (Field et al., 2016; Huijnen et al., 2016; Tacconi, 2016), observations to date suggest that the 2015/16 fires did not occur at the unprecedented scales of these historic events suggesting changing relationships between landscape fire activity, land change, and climate, as well as between precipitation and El Niño events.

Industrial-scale forest extraction, degradation, and agricultural conversion have been advanced as principal drivers of landscape burning in Borneo exacerbated by El Niño events (Leighton, 1984: 132; Lennertz and Panzer, 1984; Malingreau et al., 1985; Woods, 1989; Wirawan, 1993; Gellert, 1998; Dennis and Colfer, 2006). Despite pronounced El Niño droughts over the 19th and 20th centuries (Walsh, 1996) and gradual declines in precipitation since the mid-20th century (Malhi and Wright, 2004), major El Niño fire events appear not to have occurred in Borneo until 1982/83 (Field et al., 2009), ~10 years after industrial logging commenced and alongside 'transmigration' agricultural settlement (Dennis and Colfer, 2006; Gaveau et al., 2014a). Concerns over historical, ongoing and planned forest exploitation and conversion are heightened by the potential for intensifying El Niño events. Of particular concern are feedbacks between fire activity and forest degradation, such as that due to timber extraction and agricultural activities. Relative to intact forests, perturbed forests appear more prone to fire occurrence and, once burned, become still more fire-prone, so that increasingly recurrent fires in such forests may maintain them in degraded, low-vegetation states (Cochrane et al., 1999; Nepstad et al., 1999; Siegert et al., 2001; Cochrane and Laurance, 2002, 2008; Dennis and Colfer, 2006). Such feedbacks have apparently converted vast areas of intact and selectively-logged forest to scrublands and fern fields in Borneo since the 1970s (Hoscilo et al., 2011; Gaveau et al., 2016b). In one region of East Kalimantan, many forests that burned in logged forests in 1982/83 burned again in degraded forests in 1997/98, and ultimately 70% of forests initially damaged by fire and drought in 1983 were reportedly non-forest by 2000 (Dennis and Colfer, 2006), reflecting the biophysical effects of recurrent fire as well as opportunistic oil-palm and timber plantation establishment over 'degraded' forests (Schindele et al., 1989). Plans to greatly expand oil-palm and timber plantations (Verchot et al., 2010; Miettinen et al., 2012a; Jakarta Post, 2014) as well as logging operations to a lesser extent in perturbed landscapes may thus threaten forest loss more widely by intensifying future fire regimes. In Sumatra, where oil palm and timber plantations on peatlands are more extensive than in Borneo, major landscape fires may no longer be confined to El Niño events (Gaveau et al., 2014b).

Shifts in El Niño – fire activity in Borneo over the last 40 years undermine historical generalisations regarding the drivers of fire reoccurrence and thus our ability to anticipate future trends. Following the 1982/83 El Niño, surveys overwhelmingly found logged or 'disturbed' lowland forests to be the most extensively burned land covers, absolutely and relatively, with 58–88% of their total area burned (Lennertz and Panzer, 1984; Leighton and Wirawan, 1985; Schindele et al., 1989; Gellert, 1998). Smallholder 'slash-and-burn' agriculture was widely considered the primary ignition source (Dennis, 1999). By the 1997/98 El Niño, recently established industrial oil-palm and timber plantations provoked new dynamics (Dennis, 1999). Estimates of burned plantation areas vary widely, from negligible to half of the area of burned logged/disturbed forests (Fuller and Fulk, 1998; KLH, 1998; Legg and Laumonier, 1999; Siegert and Hoffmann, 2000; Dennis and Colfer, 2006). The burned proportion of plantations similarly varied from the negligible to 66%, often exceeding proportions for logged/disturbed forests (Siegert and Hoffmann, 2000; Siegert et al., 2001; Dennis and Colfer, 2006). Fires arose extensively in or around plantations, in addition to other land covers (Dennis and Colfer, 2006) and ignition sources grew to include arson by expansionist concessionaires and aggrieved smallholders (Potter and Lee, 1998; Tomich et al., 1998; Dennis, 1999). Accelerated plantation expansion (Miettinen et al., 2012a,b) and the decline of logging (Gaveau et al., 2014a) and agricultural transmigration programs (Potter, 2012) following decentralisation over the 2000s has quite possibly shifted patterns of El Niño fire patterns once again.

Improved understanding demands ampler spatial and temporal scales of observation than has been the case to date. Whilst important for highlighting major trends, prominent generalisations, such as that "recurrent fires will lead to a complete loss of Borneo's lowland rainforests" because 59% of observed logged forests burned in 1997/98 and some of these burned previously in 1982/83 (Siegert et al., 2001), rest somewhat tenuously on short observation periods (e.g., 2–3 months, or one inter-annual comparison) and/or analysis of relatively small geographic areas (typically severely-burned and widely degraded parts of fire-prone East Kalimantan). Further, most analyses focus only on the 1997/98 El Niño, for which exceptional drought greatly exacerbated burning across all land covers to such an extent that insight regarding fire reoccurrence are of uncertain generality (Tacconi, 2003: 6; Dennis and Colfer, 2006). Syntheses of trends underlying fire activity across individual El Niño events are frustrated by inconsistent, incomplete and uncertain surveys of burned land covers (e.g., KLH, 1998; Siegert and Hoffmann, 2000; Siegert et al., 2001; Langner and Siegert, 2009), which frequently conflate 'degraded' and 'logged' forests. It is also problematic to equate the burned proportion of a land cover with its fire reoccurrence rate, particularly for severe El Niño events. Recurrence rates reflect active land-use strategies and the juxtapositions of land use/covers that propagate or experience burning differently, in addition to the inherent propensity of a given land cover to burn. Observations that 80% of El Niño fire 'hotspots' occurred within logging concessions in Kalimantan over 1997–2006 are thus qualified by the points above as well as by the facts that such forests were not necessarily contemporaneously logged and that they comprised a comparable 68% of the landscape and most of its forest extent (Langner and Siegert, 2009). Exceptional regions, particularly Malaysian Borneo, which has been widely perturbed and heavily logged (Bryan et al., 2013; Gaveau et al., 2014a) but which has experienced relatively few large landscape fires during El Niño events (Langner and Siegert, 2009; Wooster et al., 2012), further highlight the problems of generalising from short-term and regionally-confined studies.

Here we comprehensively profile the effects of industrial forest extraction and agricultural development on fire frequency across Borneo during all El Niños occurring over 1982–2010. To do so we derived the longest-term and most complete spatial record of tropical landscape fires and land-use change spaning historical ENSO episodes for a large tropical region insofar as we are aware. Our observations encompass the onset, development, and consolidation of Borneo's industrial forestry and agricultural operations as well as the full diversity of its historical El Niño events. This allows for more confident generalisations of future El Niño-related fire reoccurrence given continued industrial land-cover change.

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