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Mapping the structure of Borneo's tropical forests across a degradation gradient

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ABSTRACT

South East Asia has the highest rate of lowland forest loss of any tropical region, with logging and deforestation for conversion to plantation agriculture being flagged as the most urgent threats. Detecting and mapping logging impacts on forest structure is a primary conservation concern, as these impacts feed through to changes in biodiversity and ecosystem functions. Here, we test whether high-spatial resolution satellite remote sensing can be used to map the responses of aboveground live tree biomass (AGB), canopy leaf area index (LAI) and fractional vegetation cover (FCover) to selective logging and deforestation in Malaysian Borneo. We measured these attributes in permanent vegetation plots in rainforest and oil palm plantations across the degradation landscape of the Stability of Altered Forest Ecosystems project. We found significant mathematical relationships between field-measured structure and satellite-derived spectral and texture information, explaining up to 62% of variation in biophysical structure across forest and oil palm plots. These relationships held at different aggregation levels from plots to forest disturbance types and oil palms allowing us to map aboveground biomass and canopy structure across the degradation landscape. The maps reveal considerable spatial variation in the impacts of previous logging, a pattern that was less clear when considering field data alone. Up-scaled maps revealed a pronounced decline in aboveground live tree biomass with increasing disturbance, impacts which are also clearly visible in the field data even a decade after logging. Field data demonstrate a rapid recovery in forest canopy structure with the canopy recovering to pre-disturbance levels a decade after logging. Yet, up-scaled maps show that both LAI and FCover are still reduced in logged compared to primary forest stands and markedly lower in oil palm stands. While uncertainties remain, these maps can now be utilised to identify conservation win–wins, especially when combining them with ongoing biodiversity surveys and measurements of carbon sequestration, hydrological cycles and microclimate.

1. Introduction

Through the processes of selective logging and agricultural conversion, large areas of tropical forests are being degraded and fragmented worldwide (Blaser, Sarre, Poore, & Johnson, 2011). South East Asia, in particular, has the highest rate of lowland forest loss of any tropical region, with deforestation and logging for conversion to oil palm being flagged as the most urgent threats (Sodhi, Koh, Brook, & Ng, 2004). Conventional logging, widely used in South East Asia, and to a lesser extent 'Reduced Impact Logging' (Pinard & Putz, 1996) reduces aboveground biomass (AGB) through the removal of large trees (Slik et al., 2013), and causes residual damage that includes opening previously dense forest canopies (Pfeifer, Lefebvre, Turner, Cusack, & Khoo, 2015). Resultant decreases in canopy leaf area index (LAI) and fractional vegetation cover (FCover) affect microclimate (Didham & Lawton, 1999; Hardwick et al., 2015), carbon sequestration through photosynthesis and regulation of surface water flows (Douglas, 1999). These changes can affect biodiversity (Edwards et al., 2011; Wilcove, Giam, Edwards, Fisher, & Koh, 2013) and ecosystem functions operating at different trophic levels (Ewers et al., 2015).

Thus, unsurprisingly, detecting and mapping forest degradation is a primary conservation concern, and remote sensing could provide an effective means to achieve this task (Rose et al., 2014). Satellite or airborne sensor data have previously been employed to map deforestation at coarse to fine spatial resolutions from landscape to global scales (Hansen et al., 2013). Sensor-data based forest degradation and change

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maps combined with ground-surveys aid in quantifying degradation impacts on carbon stocks and emissions (Baccini et al., 2012; Harris et al., 2012), as well as on biodiversity (Gibson et al., 2011; Strassburg et al., 2010; Wearn, Reuman, & Ewers, 2012).

Yet, mapping forest degradation using space-borne sensors is challenging in many tropical humid landscapes, not least because of persistent cloud cover. Tree cover maps (Hansen et al., 2013) or simpler maps of vegetation greenness (Pettorelli et al., 2005) do not directly map forest biophysical structure or biomass and struggle to distinguish primary from disturbed forests or agricultural land, including oil palm stands (Tropek et al., 2014). The latter now cover large areas of South East Asian landscapes (Koh & Wilcove, 2008), and are easily confused with forests during image classifications, especially when reaching maturity.

A number of methods can distinguish logged from primary forests (Asner et al., 2005). But, these methods map categories and thus treat the habitat within each land-use as homogenous. Yet, forest canopy structure and biomass can vary considerably within logged and unlogged forests affecting ecosystem processes on a continuous scale. For instance, the intensity of forest disturbance is a key determinant of the carbon (Berenguer et al., 2014; Pfeifer et al., 2015) and biodiversity (Burivalova, Şekercio lu, & Koh, 2014; Gibson et al., 2011) that persists in logged forest. Carbon and biodiversity, in turn, are used to dictate conservation and management priorities at the landscape scale under certification schemes such as the High Carbon Stock and High Conservation Value standards applied to the palm oil industry (Greenpeace International, 2013; RSPO, 2013).

Successfully linking sensor data to actual forest structure data is challenging. Multi-sensor approaches combining airborne LIDAR with satellite data are delivering promising results in estimating canopy gap structure at landscape scales (Asner, 2009; Asner et al., 2010). But despite the decreasing costs of airborne LIDAR data (Asner, 2009), their widespread use is still limited by the need for expensive expert knowledge for data processing, large financial resources to fund planes and flights, and special flying permits that are often hard to obtain in many tropical countries. Spaceborne Synthetic Aperture Radar (SAR) such as ALOS PALSAR overcomes the challenges of persistent cloud cover and atmospheric effects when mapping forest degradation (Woodhouse, Mitchard, Brolly, Maniatis, & Ryan, 2012), with long-wavelength L-Band signals penetrating vegetation canopies and relating to forest biophysical properties (Boyd & Danson, 2005; Lucas et al., 2014). However, costs of Radar imagery are high and availability limited (Joshi et al., 2015). Backscatter starts to saturate at around 100–150 Mg ha^{-1} with errors being introduced largely in ≥150 Mg ha^{-1} forest stands (Robinson, Saatchi, Neumann, & Gillespie, 2013; Mermoz et al., 2015) typical for humid tropical forests with dense canopies. Also, backscattered energy is not only affected by the size and orientation of the structural elements in the vegetation canopy, but also by the moisture content of the vegetation and the underlying soil conditions (Naidoo et al., 2015).

Unlike LIDAR and Radar, moderate to high-resolution satellite images can be obtained for most regions in the world free of charge (e.g. Landsat 8 data via USGS Earth Explorer; SPOT and RapidEye™ data via European Space Agency). Spectral and texture information derived from such images have been exploited by ecologists to map tree cover (Céline et al., 2013), green foliage density (Glenn, Huete, Nagler, & Nelson, 2008), and forest biomass and canopy structure (Castillo-Santiago, Ricker, & de Jong, 2010; Pfeifer, Gonsamo, Disney, Pellikka, & Marchant, 2012; Wang, Qi, & Cochrane, 2005). In addition, tools to process these images are now easily accessible via statistical and spatial analyses software, including freeware such as R Open Source Statistical software (R Development Core Team, 2013) and QGIS Open Source Geographic Information System (QGIS Development Team, 2012), more accessible to management staff in the tropics and elsewhere.

Here, we test whether significant relationships can be found between high spatial resolution optical satellite sensor data and three attributes of forest structure (AGB, LAI, FCover) measured in rainforest and oil palm plantation areas across a degradation landscape in Malaysian Borneo. Satellite imagery was obtained at no-cost from the European Space Agency under Category 1 User Agreement. Forest attributes were collected in permanent vegetation plots (a combined survey area of >12 ha) established across the Stability of Altered Forest Ecosystems (SAFE) Project landscape (Ewers et al., 2011). In particular, we ask: (1) what are the impacts of logging on forest structure more than one decade after logging, and are these impacts spatially homogenous or heterogeneous; and (2) can we reliably detect spatial variability in logging impacts, observed on the ground, using high spatial resolution passive sensor data? Our aim was to identify reliable mathematical relationships that would enable mapping of continuous surfaces of forest and oil palm structure across entire landscapes. This would provide important baseline data for use in the planning and management of future logging and agricultural activities in Borneo's highly threatened forests to minimise their environmental footprints.

2. Methods

2.1. The SAFE degradation landscape

The Stability of Altered Forest Ecosystem (SAFE) Project (4° 38′ N to 4° 46′ N, 116° 57′ to 117° 42′ E; Fig. 1), located within lowland dipterocarp forest regions of East Sabah in Malaysian Borneo, features a gradient of forest disturbance from unlogged primary forest through to severely degraded forest and oil palm plantations (Ewers et al., 2011). SAFE thus reflects Sabah's predominant land use change over the past decades, characterised by industrial harvesting and premature relogging of extensive tracts of once-logged forests and large-scale forest-to-palm conversions (Reynolds, Payne, Sinun, Mosigil, & Walsh, 2011). The region has a tropical climate with high rainfall (>2000 mm/year) and varying terrain topography, although all plots are below 800 m altitude. The geology comprises a mixture of sedimentary rocks including siltstones, sandstones and others that are easily eroded (Douglas, 1999).

Meteorological records from nearby Danum Valley Field Centre, show that the climate in this part of Sabah is aseasonal, with occasional dry spells that are usually associated with El Niño events (Walsh & Newbery, 1999). Recent data from Danum Valley (SEARRP: http://www.searrp.org/danum-valley/the-conservation-area/climate) show that no dry months occurred between September 2011 and January 2013, the period during which our data was collected. This is important, as this could have potentially changed biophysical attributes between time of field measurements and time of satellite data acquisition, as reported for drought-affected areas in evergreen Amazonian forests (Myneni et al., 2007).

193 vegetation plots (25 m × 25 m) with North–South orientation were set out at SAFE in 2010 using a Garmin GPSMap60 device. Vegetation plots were established across the forest degradation landscape according to a hierarchical sampling design as an objective procedure to assess regional forest attributes (Ewers et al., 2011). The design was chosen to ensure unbiased decisions as to where to establish vegetation monitoring plots in the field (Ewers et al., 2011). Plots were located at roughly equal altitude and oriented to minimise potentially confounding factors such as slope, latitude, longitude and distance to forest edges (prior to controlled forest-to-oil palm conversion currently being carried out at SAFE) (Ewers et al., 2011). Plots were distributed among 17 sampling blocks: three oil palm plantation blocks of two different ages (OP1 and OP2 planted in 2006 and OP3 planted in 2000), two primary forest stands (OG1 and OG2), lightly or illegally logged forests inside multi-use or protected areas (OG3 and VJR), twice logged forests (LFE, LF1–LF3) and salvage logged forest (A–F). The latter is forest that has been logged with lifted restrictions on type of tree, size limits and volume in advance of outright conversion to a new land use type such as agriculture (for details on the hierarchical sampling design