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Automated method for measuring the extent of selective logging damage with airborne LiDAR data

L. Melendy [a], S.C. Hagen [a,*], F.B. Sullivan [b], T.R.H. Pearson [c], S.M. Walker [c], P. Ellis [d], Kustiyo [e], Ari Katmoko Sambodo [e], O. Roswintiarti [e], M.A. Hanson [f], A.W. Klassen [g], M.W. Palace [b], B.H. Braswell [a], G.M. Delgado [a]

[a] Applied GeoSolutions, Newmarket, NH, USA
[b] Earth Systems Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, USA
[c] Ecosystem Services Unit, Winrock International, Arlington, USA
[d] The Nature Conservancy, Arlington, VA, USA
[e] Indonesia National Institute of Aeronautics and Space (LAPAN), Jl. Lapan No. 70, Pekayon Pasar Rebo, Jakarta, Indonesia
[f] Development Seed, USA
[g] Tropical Forest Foundation, Bogor, West Java, Indonesia

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ABSTRACT

Selective logging has an impact on the global carbon cycle, as well as on the forest micro-climate, and longer-term changes in erosion, soil and nutrient cycling, and fire susceptibility. Our ability to quantify these impacts is dependent on methods and tools that accurately identify the extent and features of logging activity. LiDAR-based measurements of these features offers significant promise. Here, we present a set of algorithms for automated detection and mapping of critical features associated with logging – roads/decks, skid trails, and gaps – using commercial airborne LiDAR data as input. The automated algorithm was applied to commercial LiDAR data collected over two logging concessions in Kalimantan, Indonesia in 2014. The algorithm results were compared to measurements of the logging features collected in the field soon after logging was complete. The automated algorithm-mapped road/deck and skid trail features match closely with features measured in the field, with agreement levels ranging from 69% to 99% when adjusting for GPS location error. The algorithm performed most poorly with gaps, which, by their nature, are variable due to the unpredictable impact of tree fall versus the linear and regular features directly created by mechanical means. Overall, the automated algorithm performs well and offers significant promise as a generalizable tool useful to efficiently and accurately capture the effects of selective logging, including the potential to distinguish reduced impact logging from conventional logging.

1. Introduction

As the global human population continues to rise, there is an increasing impact on the declining tropical forest regions (Bush et al., 2016; Ryan et al., 2017). These impacts include deforestation, degradation of carbon reserves, and the reduction of biodiversity (Bustamante et al., 2016). With 20% of tropical forests designated as commercial logging concessions (Blaser et al., 2011), management decisions regarding timber harvest play a crucial role in mitigating these impacts (Putz et al., 2012). Efforts to improve management practices in tropical forests have been extensive over the past three decades. Most directly, the primary improvement is the widespread replacement of conventional practices, replete with poor planning on inventory, felling and extraction, with reduced impact practices for the selection and removal of a subset of individual trees within a stand. Practice improvements that reduce the impact of logging on carbon emissions and biodiversity center around planning: the implementation of a detailed skidding plan, a carefully scheduled logging cycle, and a plan to minimize

Abbreviations: ELCH, contiguous areas of **E**xtremely **L**ow **C**anopy **H**eight; NU, contiguous areas with **N**o **U**nderstory; RCH, contiguous areas of **R**educed **C**anopy **H**eight; AA, features identified by the **A**utomated **A**lgorithm; FM, features identified as **F**ield **M**easurements or through aerial photos.

* Corresponding author at: Applied GeoSolutions, 55 Main St., Newmarket, NH 03857, USA.

E-mail address: shagen@appliedgeosolutions.com (S.C. Hagen).

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damage associated with the felling of a tree. The resilience of forest carbon and diversity in these stands is heavily dependent on the implementation of these practices. While logging practices vary substantially across the world's tropical forests, these reduced impact logging techniques are now practiced in many areas (Pearson et al., 2017). But detailed information on the adoption of these practices is still limited.

Tropical forest regions are vast and often difficult to access – so remote sensing tools are likely to be an important component of cost effective logging impact monitoring systems (Chambers et al., 2007; DeFries et al, 2005; Hansen et al., 2008). Even with today's advances in remote sensing technology, the extent of logging impacts across the tropics remains poorly quantified (Asner et al., 2005). Estimates from satellite imagery have shown that the land area affected by logging in the Brazilian Amazon often exceeded the area of annual deforestation in the early 2000s (Asner et al., 2005). Furthermore, reliance on traditional methods such as mill surveys and field reports for estimating logging area and damage is susceptible to under-reporting due to extensive but frequently under-counted illegal logging activity. Research in the last decade indicates as much as 72, 61, and 65% of logging is illegal in the Brazilian Amazon, Indonesia, and in Ghana, respectively (Lawson and MacFaul, 2010), but the spatial location and intensity of illegal logging is entirely unknown and virtually impossible to track without expensive, highly focused studies.

In addition to direct effects on the carbon cycle, logging also affects non-carbon forest ecosystem attributes at a range of time scales, including immediate changes in the forest micro-climate, and longer-term changes in erosion, soil and nutrient cycling, fire susceptibility, as well as potential changes in future tree species structure and composition (Ananda and Herath, 2003; Brouwer, 1996; Cochrane et al., 1999; Holdsworth and Uhl, 1997; Nepstad et al., 1999; Palace et al, 2008a; Pereira et al., 2002; Pinard et al., 1996; Steege et al., 1995). Remote tools, in an integrated framework with field surveys and models, would allow independent oversight of jurisdictional forest management regulations and international greenhouse gas commitments (Alo and Pontius, 2008; Bustamante et al., 2016).

Advances continue in our collective ability to monitor deforestation and forest degradation using remote sensing tools (Frolking et al., 2009; Mitchell et al., 2017). However, uncertainty in satellite-based estimates of land surface features is a function of the length scales of the target features and the spatial and temporal resolution of the satellite sensor (Clark et al., 2004; Palace et al., 2008b). Therefore, small-scale forest impacts on the canopy, such as a single tree fall or an under-canopy skid trail, can be difficult or impossible to detect with moderate spatial resolution imagery where only a small proportion of an imaged pixel is affected by the target feature (Hunter et al., 2015; Read et al., 2003). Additionally, some logging impacts such as the loss of green cover associated with a felled tree are ephemeral, and infrequent repeat observation opportunities over cloudy tropical regions make it challenging to detect selective logging (Pereira et al., 2002; Peres et al., 2006). The earliest techniques employed to map selective logging relied on visual interpretation of Landsat Thematic Mapper (TM) imagery (Watrin and da Rocha, 1992) and annual forest change monitoring products based on moderate resolution optical imagery (Broich et al., 2011). Over the last two decades, large-region evaluation of selective logging has been demonstrated with moderate resolution optical imagery (Asner et al., 2005; Souza et al., 2005), but with uncertainty resulting from sensor limitations.

Recent advances in research efforts to map selective logging in tropical forests involve the use of airborne **Li**ght **D**etection **A**nd **R**anging (LiDAR). LiDAR provides a measurement of the three-dimensional arrangement of trees, branches, and understory vegetation in forests, from the ground to the top of the canopy (Hosoi and Omasa, 2006; Palace et al., 2016). The two-dimensional aggregate of a LiDAR point cloud provides vertical distributions of vegetation, referred to from here on as canopy profiles, which have also been examined to estimate forest biometric properties, such as biomass, stem density, and basal area (Asner et al., 2004; Danson et al., 2007; Hopkinson et al., 2009; Hunter et al., 2015; Kent et al., 2015; Palace et al., 2015; Phua et al., 2016; Sullivan et al., 2014), as well as to delineate individual trees and tree gaps (Ferraz et al., 2016; Lefsky et al., 2007). The characteristics of a canopy profile can provide additional insights into forest conditions and, particularly when considering the proportion of mid-canopy and understory vegetation returns, may be indicative of logging roads, skid trails, and felled trees (Ellis et al., 2016). Several studies have demonstrated that skid trails and logging gaps from felled trees can be identified through the use of LiDAR Relative Density Models (RDM; e.g. Andersen et al., 2014; d'Oliveira et al., 2012; Ellis et al., 2016). While these studies have demonstrated LiDAR can be an effective tool for quantifying logging, recent studies suggest that LiDAR is currently not cost effective for integration into monitoring systems due to the high cost of both acquiring and processing the data (Ellis et al., 2016; Meyer et al., 2013). The development of accurate automated methods for processing LiDAR observations could be of critical value because they would reduce the data processing costs, allowing for more efficient coverage of large areas while providing repeatable and consistent estimates of important land surface attributes. An ability to quantify selective logging and estimate forest degradation proves key in understanding forest resource extraction, quantifying degradation, and aiding the developing sustainable management practices.

In this paper, we focus on new automated methods to map and quantify the extent of selective logging damage at two concessions in Kalimantan, Indonesia. These new methods rely on high spatial density airborne LiDAR data, developed in coordination with field-based measurements, and aerial photos of the extent and impact of selectively logged areas. We present our results in terms of the area of logging features, including skid trails, roads/decks, and gaps associated with felled trees and collateral damage. Assessment of the automated approach is accomplished with a comparison to GPS-based observations and high-resolution aerial photography.

2. Sites and methods

We conducted our study in two regions in Kalimatan, Indonesia on the island of Borneo (Fig. 1). The sites were chosen to represent different levels of terrain ruggedness and logging management approaches. Logging in these two concessions is planned to occur in a 35-year rotation cycle.

Timberdana is a 76,340-hectare concession located in the districts of Kutai Barat and Barito Utara in East Kalimantan (0° 50′47.89″ S, 115° 23′30.03″ E). The 2014 logging block of 801 ha was covered by LiDAR imaging and aerial photos, and sampling of the logging impact was distributed throughout the annual logging area. The 2014 logging block is generally gently to moderately undulating terrain getting progressively steeper and more broken towards the western limits of the block. More than half of the area had been previously logged with the remaining area representing intact, unlogged forest. The company's logging machinery consists of Komatsu D85E-SS-2 crawler tractors typical of the selective logging machinery used elsewhere in Kalimantan. To sell logs on the open market, the company will target select species and individuals with a regular, straight bole and abide by the 50-cm diameter limit as its harvesting criteria. However, the company has not practiced any form of Reduced Impact Logging (RIL) in Timberdana (Fig. 2).