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Monitoring selective logging in western Amazonia with repeat lidar flights

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ABSTRACT

The objective of this study was to test the use of repeat flight, airborne laser scanning data (lidar) for estimating changes associated with low-impact selective logging (approx. 10–15 m^3 ha^{-1} = 5–7% of total standing volume harvested) in natural tropical forests in the Western Brazilian Amazon. Specifically, we investigated change in area impacted by selective logging, change in tall canopy (30 m+) area, change in lidar canopy structure metrics, and change in above ground biomass (AGB) using a model-based statistical framework. Ground plot measurements were only available from the time of the 2010 lidar acquisition. A simple differencing of the 2010 and 2011 lidar canopy height models identified areas where canopy over 30 m tall had been removed. Area of tall canopy dropped from 22.8% in 2010 to 18.7% in 2011, a reduction of 4.1%. Using a relative density model (RDM) technique the increase in area of roads, skidtrails, landings, and felled tree gaps was estimated to be 17.1%. A lidar-based regression model for estimating AGB was developed using lidar metrics from the 2010 lidar acquisition and corresponding AGB ground plot measurements. The estimator was then used to compute AGB estimates for the site in 2010 and 2011 using the 2010 and 2011 lidar acquisition data, respectively. A model-based statistical approach was then used to estimate the uncertainty of the changes in AGB between the acquisitions. Change in RDMs between lidar acquisitions was used to classify each 50 m cell in the study area as impacted or non-impacted by logging. The change in mean AGB for the entire study area was −9.1 Mg ha^{-1} ± 1.9 (mean ± SD) (*P*-value < 0.0001). The change in mean AGB for areas newly impacted in 2011 was −17.9 ± 3.1 Mg ha^{-1} (*P*-value < 0.0001) while the change in mean AGB for non-impacted areas was significantly less at −2.6 ± 1.1 Mg ha^{-1} (*P*-value = 0.009). These results provide corroborating evidence of the spatial extent and magnitude of change due to low-intensity logging in tropical forests with heavy residual canopy cover.

1. Introduction

Selective logging of high value timber is an important land use in the Brazilian Amazon (Asner et al., 2005) and in other tropical regions (Curran et al., 2004; Wright, 2010). At the beginning of this century, the area of Brazilian forest subjected to selective logging was similar to the area deforested (Asner et al., 2005). Both deforestation (INPE, 2013) and logging activities (Pereira, Santos, Vedoveto, Guimarães, & Veríssimo, 2010) have declined at similar rates in the Brazilian Amazon but despite these declines both activities still affect several thousand square kilometers of forest area every year.

Reducing Emissions from Deforestation and Forest Degradation (REDD) has been proposed as a means to mitigate carbon dioxide emissions (Angelsen, 2008). Gross carbon dioxide emissions from tropical deforestation (excluding regrowth and carbon losses from peat and mineral soil) accounted for approximately 0.8 Pg-C (1 Pg = 1015 g) during the period 2000 to 2010 or approximately 10% of global anthropogenic carbon dioxide emissions (Baccini et al., 2012; Harris, Brown, Hagen, Baccini, & Houghton, 2012; Harris, Brown, Hagen, Saatchi, et al., 2012). The carbon released from forest degradation is highly uncertain because both the area affected and carbon loss through degradation are poorly quantified. In Brazil, logging, an important degradation pathway, may have emitted as much as 0.1 Pg-C y^{-1} from 1999 to 2002 (Asner et al., 2005).

Logging damage is generally quantified not in carbon terms but rather in terms of ground damage and canopy damage either as a proportion of area logged or on a per tree harvested basis (Pereira, Zweede, Asner, & Keller, 2001, 2002; Picard, Gourlet-Fleury, & Forni, 2012). Carbon dioxide emissions from logging depend on the original forest carbon stocks, the intensity of logging, the quality of the logging management, and the rate of recovery following logging (Keller, Asner, Silva, & Palace, 2004;

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Keller, Palace, Asner, Pereira, & da Silva, 2004; Pinard & Putz, 1996). Because adequate field sampling of remote logged forest areas is costly and difficult (d'Oliveira, Reutebuch, McGaughey, & Andersen, 2012), we have few data on carbon losses caused by logging and as such a great uncertainty regarding the potential for carbon mitigation for REDD by improved management of tropical selective logging.

Prompted by the international Governor's Climate and Forests Task Force, the Brazilian State of Acre is implementing a sustainable development policy that aims to promote integrated forest management, where the native forests are providers of products (timber and non-timber) and environmental services. The main objective is to aggregate value to the standing forest, avoid deforestation and mitigate the climatic change effects of forest destruction and degradation. This policy permits Acre to participate in REDD carbon markets. In 2010 Acre enacted a law to create the State System of Incentives for Environmental Services (SISA). SISA establishes the legal and institutional framework for planning, monitoring, and marketing carbon credits associated with sustainable forest management practices (Acre State, 2010; Acre. Governo Do Estado Do Acre, 2012). Economical, rapid, and reliable methods for measuring carbon changes over large areas of managed forests would assist Acre State with monitoring SISA efforts.

In remote forest areas, where ground-based monitoring of forest carbon stocks is costly and difficult, lidar may be a valuable tool for estimation of forests carbon stocks, carbon stock changes, and forest degradation through logging. Many studies have demonstrated that small-footprint airborne lidar systems can be used to estimate above ground biomass (AGB) in forest types ranging from boreal to tropical (e.g., Andersen, Strunk, & Temesgen, 2011; Asner et al., 2010, 2011, 2012; Beets et al., 2011; d'Oliveira et al., 2012; Gobakken et al., 2012; Gonzalez et al., 2010; Hudak et al., 2012; Koch, 2010; Li, Andersen, & McGaughey, 2008; Næsset, 2011; Næsset & Gobakken, 2008; Nyström, Holmgren, & Olsson, 2012). There are limited studies on the estimation of structural and biomass change in temperate forests using lidar data (Bollandsås, Gregoire, Næsset, & Øyen, 2013; St-Onge & Vepakomma, 2004; Yu, Hyyppa, Hyyppa, & Maltamo, 2004) and even fewer in tropical forests (Dubayah et al., 2010; Kellner, Clark, & Hubbell, 2009; Meyer et al., 2013), these studies focus on unmanaged tropical forests. Almost no effort has been made to investigate the use of airborne lidar to detect selective logging in tropical forests. Weishampel, Hightower, Chase, and Chase (2012) compared lidar estimates of canopy gaps with Landsat estimates of deforestation for the Caracol Archaeological Reserve in Belize and concluded that lidar can be used as a tool for monitoring fine-scale canopy changes in areas affected by selective logging.

In a study conducted in Antimary State Forest (FEA), Acre State, Brazil, d'Oliveira et al. (2012) used lidar data to map forest biomass in areas of low-intensity selective logging. Using near-ground lidar return density, rather than overstory canopy gaps, d'Oliveira et al. (2012) successfully mapped roads, skid-trails, landings and tree gaps under heavy residual canopy. In 2011, selective logging of the FEA study site was completed and a second lidar dataset was acquired. Our current study adds a temporal dimension to the predecessor study by use of lidar data collected in May–June 2010 (prior to logging in the northern two-thirds of the area) and in November 2011 after selective logging operations had been completed. We investigate how lidar acquired before and after logging can be used to quantify changes in canopy structure and AGB, both over the entire study area and specifically in areas affected by selective logging, thereby complementing the work of d'Oliveira et al. (2012). The objectives of the follow-up study herein reported were to: 1) investigate changes in lidar canopy structure metrics used in AGB estimation that were observed between lidar acquisitions; 2) demonstrate how a lidar model-based approach can be used to estimate change in AGB associated with low intensity selective logging; and, 3) demonstrate how changes in area of logging roads, skidtrails, landings, and large tree gaps can be mapped using relative density models (RDM).

2. Materials

2.1. Study site

The study area is located in FEA, 90 km northwest of the city of Rio Branco, Acre State, Brazil. It is a 1000 ha block of mature tropical forest from natural origins. In the study area there are predominately two types of forest: dense tropical forests with uniform canopy and emergent trees and open tropical forests with large occurrence of lianas and palm trees. The area has rolling topography with annual precipitation of 2000 mm. Under a management plan administered by Acre State Government a volume of approximately 10–15 m^3 (approximately 12–18 Mg ha^{-1} AGB) of merchantable timber was harvested throughout the entire site using selective logging methods (d'Oliveira et al., 2012). At the time of the first lidar acquisition (29 May, 2–3 June 2010), most of the roads and skidtrails had been built and the majority of the trees planned for harvest had been felled in the southern one third of the study area. By the time of the second lidar acquisition (29 November 2011), road building and selective logging operations had been nearly completed throughout the entire study area.

2.2. Field data and biomass calculations

A forest inventory was conducted in May 2010 immediately before the first lidar flight. The inventory used a systematic random sample (SRS) with plots that were nominally 50 m × 50 m in size, evenly distributed along ten lines with a total of 50 sample plots and a total sampled area of 12.5 ha or 1.25% of the total study area (Fig. 1). All plants greater than 10 cm diameter at breast height (DBH) were labeled, measured and identified. Oven-dry AGB (Mg) was estimated for each plot using an allometric equation developed for a similar forest in the southern Amazon (Nogueira, Fearnside, Nelson, Barbosa, & Keizer, 2008).

$$AGB = \exp(-1.716 + 2.413{*}Ln(\text{DBH}))/1000.$$

AGB includes bark, bole, branches, foliage, and flowering materials above the ground surface. AGB in the ground plots varied from 96.9 to 493.6 Mg ha^{-1} (mean 230.9 ± 10.5 SE). Details of plot location, layout, measurement protocols, and range of observed AGB are found in d'Oliveira et al. (2012).

2.3. Lidar data sets

Two high-density discrete return lidar datasets were collected over the study site. Both datasets were acquired by the same lidar vendor using the same lidar sensor and with similar sensor settings and flight parameters (Table 1). The 2010 dataset had a pulse density of 25 m^{-2} and above ground flying height of 500 m, compared to 14 m^{-2} and 600 m for the 2011 data. For both acquisitions, the lidar vendor delivered LAS point files, filtered ground point files, and 1-m resolution bare earth digital terrain models (DTM). The expected positional accuracy (1 σ) of the lidar measurements is approximately 0.1 m horizontal and 0.12 m vertical (Optech Inc., 2008).

Many studies have documented that changes in sensor model, sensor settings, flight parameters, and seasonal foliage status (leaf-on; leaf-off) can cause changes in computed lidar metrics (Chasmer, Hopkinson, Smith, & Treitz, 2006; Goodwin, Coops, & Culvenor, 2006; Hopkinson, 2007; Magnussen, Næsset, & Gobakken, 2010; Magnusson, Fransson, & Holmgren, 2007; Morsdorf, Frey, Meier, Itten, & Allgöwer, 2008; Næsset, 2009). Fortunately, in this study, with the exception of pulse density, sensor and flight, parameters were very similar between the 2010 and 2011 lidar datasets. Magnussen et al. (2010) concluded that when pulse density is greater than approximately 1 m^{-2}, effects on computed lidar metrics should be very limited and calibration