Forest Ecology and Management 391 (2017) 246–255

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Quantifying uncertainty about forest recovery 32-years after selective logging in Suriname

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ARTICLE INFO

Article history:
Received 24 August 2016
Received in revised form 9 February 2017
Accepted 10 February 2017
Available online 21 February 2017

Keywords:
Reduced-impact logging
Sustainable forest management
REDD+
Timber stocks
Cutting cycles
Allometric models

ABSTRACT

The inclusion of managed tropical forests in climate change mitigation has made it important to find the sustainable sweet-spot for timber production, carbon retention, and the quick recovery of both. Here we focus on recovery of aboveground carbon and timber stocks over the first 32 years after selective logging with the CELOS Harvest System in Suriname. Our data are from twelve 1-ha permanent sample plots in which growth, survival, and recruitment of trees $\geq$15 cm diameter were monitored between 1978 and 2012. We evaluate plot-level changes in basal area, stem density, aboveground carbon, and timber stock in response to average timber harvests of 15, 23, and 46 m^3 ha^{-1}. We use a linear mixed-effects model in a Bayesian framework to quantify recovery time for aboveground carbon and timber stock, as well as annualized increments for both. Our statistical models accounted for the uncertainty associated with the height and biomass allometries used to estimate aboveground carbon and increased precision of annualized aboveground carbon increments by including data from forty-one plots located elsewhere on the Guiana Shield. The probabilities of aboveground carbon recovery to pre-logging levels 32 years after harvests of 15, 23 and 46 m^3 ha^{-1} were 45%, 40%, and 24%, respectively. Net aboveground carbon increment for logged forests across all harvest intensities was 0.64 Mg C ha^{-1} yr^{-1}, more than twice the rate observed in unlogged forests (0.26 Mg C ha^{-1} yr^{-1}). The probabilities of timber stock recovery at the end of the 32-year period were highest after harvest intensities of 15 and 23 m^3 ha^{-1} (with 80% probability) and lowest after the harvest of 46 m^3 ha^{-1} (with 70% probability). Timber stock recovery across all harvest intensities was driven primarily by residual tree growth. Application of the legal cutting limit of 25 m^3 ha^{-1} will require more than 70 and 40 years to recover aboveground carbon and timber stocks, respectively, with 90% probability. Based on the low recruitment rates of the twelve species harvested, the 25 year cutting cycle currently implemented in Suriname is too short for long-term timber stock sustainability. We highlight the value of propagating uncertainty from individual tree measurements to statistical predictions of carbon stock recovery. Ultimately, our study reveals the trade-offs that must be made between timber and carbon services as well as the opportunity to use carbon payments to enable longer cutting rotations to capture carbon from forest regrowth.

1. Introduction

Technological advancements (e.g., development of chainsaws and bulldozers) coupled with growth of global shipping industries and increased demand for tropical timbers during the mid-20th Century led to the degradation of large expanses of tropical forests by unnecessarily destructive logging (Dawkins and Philip, 1998). Concerns about sustained timber production and the environmental degradation caused by bad logging practices motivated research to identify management prescriptions for improved tropical forest management. These logging studies aimed to reconcile tropical timber production with the provision of other ecosystem services, and to ensure continued timber production with economically viable cutting cycles (FAO, 2004; Jonkers, 1987; Nicholson, 1958, 1979; van der Hout, 1999).

The CELOS Harvest System experiments in Suriname, the results of which were recently reviewed by Werger (2011), are among the

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http://dx.doi.org/10.1016/j.foreco.2017.02.026
0378-1127/

oldest on-going studies of improved forest management in the tropics. The CELOS approach involves the selective removal of a few trees per hectare in a manner that minimizes collateral damage to the residual forest and improves recovery of utilizable timber. The specific logging practices employed include: (1) mapping all trees of commercial timber species ≥35 cm measured at 1.3 m above the ground (DBH); (2) selecting trees to be felled to avoid aggregations that would result in large felling gaps; (3) planning and construction of roads and skid trails prior to felling; (4) directional felling to facilitate log extraction; and, (5) winching of logs during extraction and the use of wheeled skidders for long-distance log yarding (de Graaf, 1986; Jonkers, 1987). These practices are common components of what are now referred to as reduced-impact logging (RIL) systems (e.g., Putz et al., 2008). The full CELOS Management System also includes the release of future crop trees from competition through poison girdling of non-marketable stems, but no post-harvest silvicultural treatments were applied in the plots we studied.

Although the primary goal of the CELOS Management System was to sustain timber stocks, reduction in residual stand damage relative to unplanned or conventional logging also has positive effects on standing stocks of forest carbon and rates of post-logging recovery (Pinard and Putz, 1996; Putz et al., 2012; Vidal et al., 2016). By reporting on the post-logging dynamics of aboveground carbon stocks (ACS) and timber stocks, we hope that this study helps inform the management of Suriname's forest for both, the former associated with the country's commitment to climate change mitigation (e.g., REDD+, Intended Nationally Determined Contribution (INDCs) associated with COP12; UFCCC, 2016). In particular, with permanent sample plot data for the first 32-years after logging, we evaluate changes in tree density, basal area, ACS, and timber stocks.

We use permanent sample plot data collected between 1978 and 2012 to build statistical models in a Bayesian framework to predict recovery time and forest stand increments as a function of harvest intensity ($m^3\ ha^{-1}$ of commercial timber). Our Bayesian analytical approach also provided a means to address the long and irregular census intervals that would otherwise result in underestimated aboveground carbon increments (Clark et al., 2001; Sheil and May ,1996; Talbot et al., 2014). Specifically, we include results from previous research on aboveground carbon increments for the Guiana Shield as informed priors to reduce uncertainty in our model predictions (Crome et al., 1996; McCarthy and Masters, 2005; Morris et al., 2013). In addition to leveraging knowledge gained from other studies, our Bayesian approach enabled us to propagate uncertainty associated with our height and biomass allometries into our ACS recovery predictions.

2. Methods

2.1. Study site

The experimentally logged plots are in a 1150 ha research area (hereafter Kabo; 5°15′N, 55°43′W) in north-central Suriname (Fig. S1). Common canopy tree species in this lowland moist tropical forest are *Dicorynia guianensis* Amshoff (Fabaceae), *Qualea rosea* Aubl. (Vochysiaceae), and *Dendrobangia boliviana* Rusby (Cardiopteridaceae). The understory is composed mainly of palms, with *Astrocaryum sciophyllum* Pulle and *Astrocaryum paramaca* Mart. the most abundant (Jonkers, 1987). The soil is an ultic haplorthox, a low pH sandy loam that is characteristic of the highly weathered Precambrian Guiana Shield (Hammond, 2005; Poels, 1987; Quesada et al., 2010). Annual precipitation is 2385 mm with a mean of 98 mm in each of the driest months of September and October (Dekker and de Graaf, 2003).

2.2. Experimental design and logging treatments

Trees of commercial timber species (DBH ≥ 15 cm; Table S1) were marked, mapped, and measured across a 140-ha forest compartment in 1978. Experimental logging treatments designed to remove 1, 2, and 4 $m^2\ ha^{-1}$ of basal area were applied between 1979 and 1980 based on a randomized block design. Each logging treatment was applied to 4 ha with 3 replicates per logging treatment (Table 1; Fig. S1). The basal areas removed corresponded to average harvests of 15, 23, and 46 $m^3\ ha^{-1}$ of commercial log volumes (hereafter low, medium, and high-intensity timber harvests; Jonkers, 1987, 2011). Trees of commercial timber species ≥ 15 cm DBH were re-censused immediately after logging in 1980 in 1 ha permanent sample plots established within each of the 4 ha treatment blocks.

Growth, recruitment, and mortality of trees ≥15 cm DBH of all species, commercial and non-commercial, were subsequently monitored in these 1-ha plots (100 × 100 m) for each replicated treatment four times (1981, 1983, 2000 and 2012). Unlogged control plots of 1-ha were established within the study site in 1983 and remeasured in 2000 and 2012 (Fig. S1). Censuses adhered to protocols established by Jonkers (1983) based on standards set out in Synnott (1979). Tree species were identified by parabotanists (tree-spotters) based on common names and converted to their scientific names by a trained botanist. In instances where species were unknown, botanical collections were made for comparison with herbarium specimens. In cases of irregular stem form associated with buttresses and bole deformities, the point of measurement was moved to 1 m above the end of the deformity to continue growth monitoring.

When the forest was selectively logged by trained and closely supervised crews, the main skid trails were opened with a D6 bulldozer within 25-m wide strips between the 1-ha permanent sample plots. Trees were directionally felled to aid extraction with wheeled skidders. Tree location maps developed from a 100% pre-harvest inventory of harvestable trees, together with topographic maps, were used to inform the selection of trees to be harvested and to plan the most appropriate routes for extraction. There were a total of six skid trail entry points into the 1-ha permanent sample plots, three on the western side and three located on the east.

2.3. Stem densities and basal areas ($m^2\ ha^{-1}$)

We report changes over time in basal area, stem density, and diameter class distributions for the twelve 1-ha permanent sample plots. As pre-logging data were only available for commercial stems prior to logging, we track the changes in forest structure for the logged plots between the first census completed post-logging (1981) when all stems, commercial and non-commercial species, were recorded to the last census in 2012, except for timber stocks where we use the plot census data from 1980. We also report on the observed changes for the control plots between 1983 and 2012 as well as the basal area-weighted average wood density across censuses and diameter classes for all plots. We acknowledge that forest structure can vary greatly across small spatial scales, and the use of only three 1-ha control plots as baseline reference values is not ideal. We address this limitation in our statistical models for ACS recovery through the estimation of plot-level ACS prior to logging based on an emissions factor associated with logging intensity (Appendix 2).

2.4. Aboveground carbon stocks (ACS; $Mg\ C\ ha^{-1}$)

To estimate aboveground biomass for each tree across censuses we applied the pan-tropical allometric model of Chave et al. (2014;