Current Biology
Magazine

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Rapid tree carbon stock recovery in managed Amazonian forests

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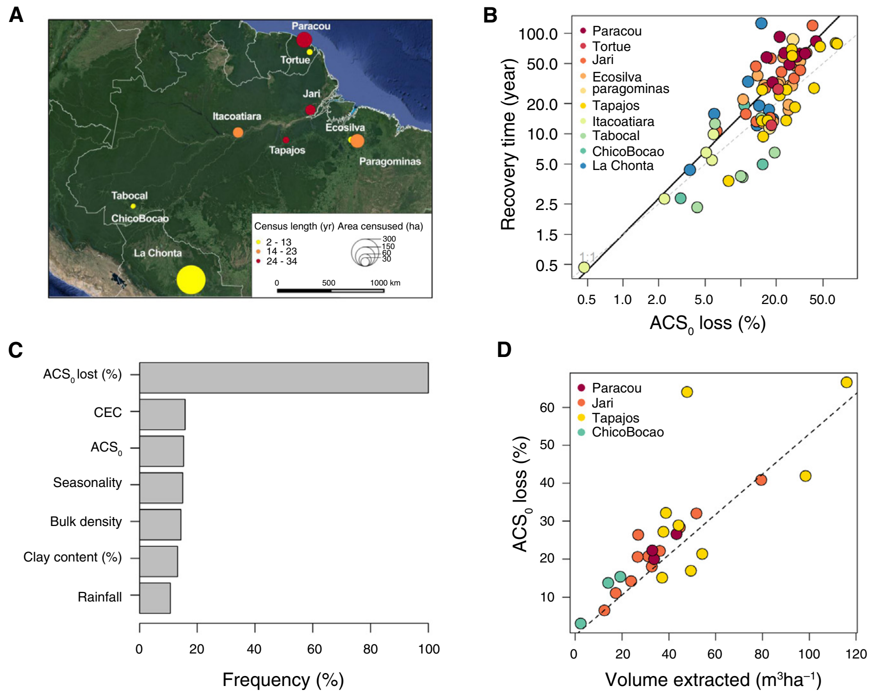

Figure 1. Assessing the main drivers of tree carbon recovery in managed forests in the Amazon Basin.
(A) Site locations, census length (color) and area censused (size). (B) Relationship between time of recovery and percentage of initial above ground carbon stocks lost (ACS_0 loss) due to selective timber harvests and damage-induced mortality at 10 sites across the Amazon Basin. OLS regression (solid) and 1:1 relationship (dashed) lines are shown. Sites are listed from northeast to southwest. (C) Frequency of selection of variables explaining t_{rec} (ACS_0 loss (%), initial ACS lost; bulk density, soil bulk density; ACS_0, initial ACS; CEC, cation exchange capacity; seasonality, coefficient of variation in monthly means of precipitation; clay content (%), percentage clay content in soil; rainfall, average annual rainfall). (D) Relationship between timber volume extracted (m^3/ha) and initial ACS lost (%) at four sites under RIL management ($y = 0.53*x$, $R^2 = 0.88$, $P < 10^{-6}$).

While around 20% of the Amazonian forest has been cleared for pastures and agriculture, one fourth of the remaining forest is dedicated to wood production [1]. Most of these production forests have been or will be selectively harvested for commercial timber, but recent studies show that even soon after logging, harvested stands retain much of their tree-biomass carbon and biodiversity [2,3]. Comparing species richness of various animal taxa among logged and unlogged forests across the tropics, Burivalova *et al.* [4] found that despite some variability among taxa, biodiversity loss was generally explained by logging intensity (the number of trees extracted). Here, we use a network of 79 permanent sample plots (376 ha total) located at 10 sites across the Amazon Basin [5] to assess the main drivers of time-to-recovery of post-logging tree carbon (Table S1). Recovery time is of direct relevance to policies governing management practices (i.e., allowable volumes cut and cutting cycle lengths), and indirectly to forest-based climate change mitigation interventions.

We found that the proportion of initial above-ground carbon stock lost (i.e., trees harvested and destroyed by logging operations) best predicted the time to recover initial carbon stocks. No other variables tested contributed substantially to the prediction of recovery time, despite the fact that the sampled plots span large geographic and environmental gradients across the entire Amazon Basin. These results reveal clear patterns that can clarify tradeoffs between short-term economics and long-term carbon storage/climate regulation for policy makers and forest managers.

While the REDD+ international agreement on climate change explicitly recognizes the contributions of sustainable management of forests and enhancement of forest carbon stocks in developing countries, less than 5% of tropical forest area is under some form of recognized sustainable management [1]. As a consequence, unplanned and destructive timber harvests are estimated to contribute 25% as much carbon loss as deforestation in the Amazon Basin [6]. Additionally, poorly managed forests are more susceptible to other threats, such as conversion to croplands or fire [2]. To understand the impact of logging on the global carbon cycle, a major gap in our knowledge must be filled, notably the rate at which this emitted carbon is recaptured by post-logging forest recovery across managerial, spatial, and environmental gradients. It is speculated that time to recover initial above-ground carbon stocks (ACS) varies with logging intensity and harvesting methods, along with initial forest structure and abiotic conditions [6]. In the present study, we use plot data to assess the effects of several biophysical variables, such as ACS lost due to logging (ACS_{loss}), rainfall, and soil properties, on time to recover initial ACS (ACS_0), hereafter recovery time (t_{rec} in year). These plots represent a breadth of logging intensities, soils, rainfall regimes, and forest structure and dynamics (Figure 1A) [5]. While reduced-impact logging (RIL) techniques were implemented at most sites, 7 plots (7.7%) were conventionally logged. Due to limited numbers of plots conventionally logged, and because our definition of logging accounts for most direct logging damages, we have decided not to include this term in our models, but a separate analysis is presented. We applied a standardized protocol to estimate ACS of live trees with stem diameters at breast height (DBH) ≥ 20 cm before (1–4 years) and after (1–33 years) selective logging. The main explanatory variables for t_{rec} and recovery rates (r_{rec} in Mg C/year) were selected using linear mixed models, treating sites as random effects to reduce pseudo-replication (Supplemental Experimental Procedures).

The percentage of initial ACS lost (ACS_{loss}/ACS_0; Figure 1B) is the best predictor of t_{rec} with a significant interaction (goodness of fit, $R^2 = 0.994$); no other variables tested contributed significantly to the predictions (Figure 1C and Table S2). More practically, $t_{rec} = (100 * ACS_{loss}/ACS_0)^{\theta}$, where $\theta = 1.106 \pm 0.022$. This result implies that losses of 10, 25 or 50% of pre-logging ACS would require 12, 43 or 75 years, respectively, to recover regardless of location in the Amazon region. In contrast, r_{rec} was more complex to predict, as it was positively correlated with initial ACS (i.e., forests with larger biomass stocks recover faster), but with a lower goodness of fit. Our r_{rec} estimates (0.04–2.96 Mg C ha^{-1} yr^{-1}, mean = 1.33 Mg C ha^{-1} yr^{-1}) sits at the lower bound of those reported in bookkeeping approaches (1.5–5.5 Mg C ha^{-1} yr^{-1} [7]). Although there is an apparent geographical uniformity of t_{rec} across the region, our results suggest that recovery rates correlate with the regional distribution of biomass stocks. We also expect that post-logging tree demography (growth, recruitment and mortality) will follow a similar pattern as that observed for structure and dynamics of unmanaged forests [8]. For instance, northeastern Amazonian forests with higher carbon stocks (initial ACS) are subjected to higher logging intensities, but tend to regenerate at faster rates than in the southwest.

Forest management regulations vary among Amazonian countries, but generally set minimum cutting cycles at 30–60 years, with harvests of 10–30 m^3 ha^{-1}. While these cutting cycles are generally insufficient to recover commercial timber stocks [9], such harvest intensities require 7 and 21 years, respectively, to recover their initial ACS, assuming ACS losses proportional to harvested timber volumes (Figure D) and linear biomass aggradation over time. Our results are likely to represent optimal recovery processes, given that plots that experienced negative r_{rec} over the study period were disregarded and most plots are located in well-managed areas. Accounting for further post-logging disturbances (e.g., fire or illegal logging), which many logged forests are experiencing [2,3], would undoubtedly extend the recovery times presented here. Nevertheless, these results reveal the overwhelming importance of logging intensity in the recovery capacity of Amazonian forests. If logging intensity is such a main driver of recovery rates in other tropical forests, such as Borneo, where high logging intensities can reach 150 m^3 ha^{-1}, often followed by other disturbances, there will likely be dramatic consequences for future carbon sequestration. Additionally, we propose our data-driven results to be used as cost-efficient estimates of post-logging carbon recovery instead of regional default values [7,10].

Globally, half of the remaining tropical forests (~400 million ha) is allocated for timber production [1] and there is growing evidence that these forests will play a crucial role in future timber supply and climate change mitigation [2,3,5]. However, forest managers and decision makers still lack the information and practical guidance to define sustainable harvest intensities or cutting rotations that at the same time ensure long-term timber harvest, maintenance of biodiversity and carbon stocks. Our results provide forest managers and policy makers with a new tool to make informed decisions, but also stress that forest management has to be effective on a regional scale where alternative management may coexist to maximize a compromise between timber production and preservation of essential environmental services.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures, Supplemental Discussion, Supplemental References and two tables and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2015.07.034.

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