



Carbon emissions from selective logging in the southern Yucatan Peninsula, Mexico

Emisiones de carbono del aprovechamiento forestal selectivo en el sur de la Península de Yucatán, México

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ABSTRACT

Tropical forests contain approximately 40% of the carbon accumulated in terrestrial biomass. However, the loss and degradation of forests worldwide liberates this carbon and contributes 11% of total global emissions. Forest degradation is an increasing source of carbon emissions, contributing 25% in tropical forest environments; and selective logging is among the principal causes. The central objective of this study was to evaluate biomass impacts and committed carbon emissions from selective logging in two forestry communities (ejidos with common forest use and rights) in the southern Yucatan Peninsula, Mexico. We compared emissions performance from logging operations in both ejidos, one of them certified as sustainably managed by the Forest Stewardship Council (FSC). The species of roundwood extracted as well as the number of impacted trees from harvesting were recorded and the type of collateral damage from felling, skidding, and transport of timber was quantified. Biomass of harvested timber and impacted vegetation was estimated to calculate carbon emissions using allometric equations. Results indicated that selective logging generated 1.2 Mg m⁻³ and 1.5 Mg m⁻³ of total carbon emissions in the Caobas and 20 de Noviembre ejidos, with 5% and 12% corresponding to collateral damage during felling, respectively. Overall lower committed emissions and collateral damage from felling and skidding were present in Caobas, the FSC certified ejido. We discuss how forest certification, through implementation of reduced impact logging (RIL) practices can significantly reduce carbon emissions from selective logging in the region.

KEYWORDS: carbon emissions, collateral damage, forest certification, reduced impact logging, selective logging.

RESUMEN

Los bosques tropicales contienen aproximadamente 40% del carbono acumulado en la biomasa terrestre. Sin embargo, la pérdida y degradación de los bosques libera este carbono y contribuye con 11% de las emisiones globales totales. La degradación forestal es una fuente creciente de emisiones de carbono, que contribuye con 25% en ambientes tropicales; y la tala selectiva es una de las principales causas. El objetivo central de este estudio fue evaluar los impactos a la biomasa y las emisiones de carbono generadas por la tala selectiva en dos comunidades forestales (ejidos con uso y derecho forestal común) en el sur de la Península de Yucatán, México. Se comparó el rendimiento de emisiones de las operaciones de tala en ambos ejidos, uno de ellos certificado con manejo sostenible por el Consejo de Administración Forestal (FSC). Se registraron las especies de madera en rollo extraídas, así como el número de árboles afectados por la cosecha, y se cuantificó el tipo de daño colateral causado por la tala, el arrastre y el transporte de madera. La biomasa de la madera cosechada y la vegetación impactada fue estimada para calcular las emisiones de carbono utilizando ecuaciones alométricas. Los resultados indicaron que la tala selectiva generó 1.2 Mg m⁻³ y 1.5 Mg m⁻³ de emisiones de carbono totales en los ejidos de Caobas y 20 de Noviembre, con 5% y 12% correspondientes a daños colaterales por derribo, respectivamente. En general, hubo menores emisiones generadas y daño colateral por derribo y arrastre en Caobas, el ejido certificado por FSC. Se discutió cómo la certificación forestal, a través de prácticas de tala de impacto reducido (RIL) pueden reducir significativamente las emisiones de carbono de la tala selectiva en la región.

PALABRAS CLAVE: certificación forestal; daños colaterales; emisiones de carbono; tala de impacto reducido; tala selectiva.

INTRODUCTION

Climate change caused partly by anthropogenic emissions of CO₂, increases global risks associated with increasing temperature (Intergovernmental Panel on Climate Change [IPCC], 2014). Terrestrial ecosystems are an important sink of CO₂ (1 Gt of carbon per year) (Fahey *et al.*, 2009), and tropical forests contain approximately 40% of the carbon accumulated in terrestrial biomass (Denman *et al.*, 2007), 60% of which corresponds to the organic carbon in the soil (Scharlemann, Tanner, Hiederer & Kapos, 2014). In the case of Mexico, estimates suggest that the amount of carbon stored in both tropical and temperate forests is between 4361 Mt and 5924 Mt (Maser, Ordoñez & Dirzo, 1997), resulting in a significant global carbon sink.

Loss and degradation of forests are one of the most important sources of CO₂ emissions (Maser *et al.*, 1997). Global rates of forest loss are estimated to be 13 million hectares per year (ha yr⁻¹) (Kindermann *et al.*, 2008), and from 1970 to 2010 they accounted for 11% of CO₂ emissions, considered one of the principal causes of climate change (IPCC, 2014). Net forest loss from 2001 to 2010 has resulted in emissions of 4.0 Gt yr⁻¹ of CO₂, decreasing to 2.9 Gt yr⁻¹ from 2011 to 2015, however, emissions of CO₂ from degradation have increased from 0.4 Gt yr⁻¹ in 1990, to 1.0 Gt yr⁻¹ from 2011 to 2015 (Federici, Tubiello, Salvatore, Jacobs & Schmidhuber, 2015). In tropical forest regions, degradation contributes 20% to 25% of the total forest emissions (Griscom *et al.*, 2009; Pearson, Brown, Murray & Sidman, 2017), 2.1 billion tons of CO₂ per year (Pearson *et al.*, 2017). During the 1990s, carbon emissions associated with land use change and forestry made up the second largest source of carbon emissions (30%) after fossil fuel emissions (67%) in Mexico (Instituto Nacional de Ecología y Cambio Climático [INECC], 2012). However, by 2010, forest related carbon emissions decreased from 101 257 Mt to 45 670 Mt and moved to fourth place (6.3%) in national emissions after fossil fuels, agriculture, and industrial processes (INECC, 2012), mainly due to a decrease in deforestation in Mexico (Food and Agriculture Organization [FAO], 2015).

While deforestation implies the removal of forest cover, forests degradation involves reductions in the capacity of forests to provide goods and environmental services through changes that affect their biomass, structure, and composition (Simula & Mansur, 2011). The main causes of degradation are unsustainable or illegal logging, shifting agriculture, invasive species, fire, firewood collection, and grazing of livestock (Griscom *et al.*, 2009; Halperin & Turner, 2013; Thompson *et al.*, 2013). Thus, degradation typically results in the maintenance of forest cover, but with subtle losses in the forests capacity to provide environmental services, such as carbon sequestration and storage (Sasaki & Putz, 2009). Therefore, detecting and monitoring forest degradation is more difficult and costlier than deforestation since it can occur at different levels of impact or successional phases (Putz & Redford, 2010). To facilitate quantifying and monitoring degradation, carbon-based degradation is often applied as a working definition, which is the direct, human-induced, reduction in forest carbon reserves from natural forest ecosystems that persists for a period of time, and is not classified as deforestation (Murdiyarso *et al.*, 2008; Griscom *et al.*, 2009).

It has been documented that selective logging contributes to carbon emissions and stock reductions (Bryan, Shearman, Ash & Kirkpatrick, 2010; Martin, Newton, Pfeifer, Khoo & Bullock, 2015). Selective logging is the removal of commercially valuable trees from a forest (Martin *et al.*, 2015), usually at very low densities, depending on the scale of the operation. Selective logging in tropical forests is carried out on a large scale in countries such as Brazil, Borneo, Guyana, Indonesia, Malaysia, Papua New Guinea, Central African Republic and other tropical countries (Putz *et al.*, 2012). Globally there are around 400 million hectares of tropical forest with timber exploitation by selective logging (Asner, Rudel, Aide, Defries & Emerson, 2009) which contribute to many local and regional economies (Martin *et al.*, 2015). Due to the diversity of tropical trees and limited timber markets, typically up to 20 trees per hectare are harvested, and for each tree felled, between 10 and 20 additional trees are



estimated to be damaged (Putz *et al.*, 2008b). Furthermore, there are direct impacts from skidding logs (the removal of logs from the forest) and construction of logging infrastructure (e.g. logging roads and log landings) (Martin *et al.*, 2015; Putz *et al.*, 2012). However, when undertaken with proper management plans and ensuring sustainable yields, selective logging shows potential in reducing deforestation and maintaining carbon stocks (Putz *et al.*, 2012).

Given the importance of degradation as a source of carbon emissions, the United Nations Framework Convention on Climate Change (UNFCCC), during the Montreal and Copenhagen conferences in 2005 and 2009 respectively, establishes the importance of a mechanism for Reduction in Emissions from Deforestation and Degradation (REDD) (Angelsen *et al.*, 2009), which would subsequently also focus on the conservation, sustainable management of forests and increased carbon stocks (REDD +) (Morales-Barquero *et al.*, 2014). Research to evaluate and reduce carbon emissions caused by degradation through selective logging is urgently needed to facilitate the implementation of REDD+ (Morales-Barquero *et al.*, 2014; Foundation for International Environmental Law and Development [FIELD], 2013). REDD+ activities in Mexico are relatively advanced due to favorable conditions such as secure forest tenure, community forest management, existing payment for environmental services programs, and free and open access to national forest inventory data (Borrego & Skutsch, 2014). However, in Mexico, efforts to quantitatively assess carbon emissions and reduction potentials from selective logging, in addition to determining the potential in carbon sequestration from managed forests, have been minimal.

On the Yucatan Peninsula, approximately 60% of forested land is communally owned (Instituto Nacional de Estadística y Geografía [Inegi], 2016) by 1389 ejidos. Of these, 220 or 16% ejidos are engaged in forestry activities, mainly through selective logging, with 50% located in the state of Quintana Roo (Inegi, 2016). Community forest management in ejidos is recognized as the management of forest resources and services by communities within or near

forest areas that have self-governance under shared norms, collective rights or community institutions (Cronkleton, Bray & Medina, 2011; Ellis *et al.*, 2015). Various studies have documented that community forest management for timber production and subsistence purposes can have positive impacts in reducing deforestation and conserving forests (Cronkleton *et al.*, 2011; Porter-Bolland *et al.*, 2012), although its impacts on forest degradation are mostly unknown on the Yucatan Peninsula.

A recent REDD+ strategy that targets selective logging in tropical forests is the implementation of Reduced Impact Logging (RIL) practices in order to reduce the negative impacts of timber harvesting through improved forestry practices such as directional felling, skid trail and road planning, and pre-logging liana cutting (Putz, Sist, Fredericksen & Dykstra, 2008a). According to various studies, the impact of collateral damage to trees can be reduced by up to 50% when implementing RIL practices (Mazzei *et al.*, 2010; West, Vidal & Putz, 2014). Nevertheless, in Mexico, carbon emissions from selective logging have not been estimated, nor have there been evaluations of the impact of RIL practices on emissions reductions. Also lacking are evaluations of improvements achieved through forest certification. Field studies are thus urgently needed to obtain data on carbon emissions from selective logging in the country.

OBJECTIVES

In this study, we measure carbon emissions from selective logging in two forestry ejidos on the Yucatan Peninsula, Caobas and 20 de Noviembre. Moreover, in the former case, we evaluate the impact of implementing RIL practices achieved through the Forest Stewardship Council (FSC) certification.

MATERIALS AND METHODS

Study Area

This study was conducted in a region known as the Selva Maya, specifically in the southern portion of the Yucatan Peninsula. The Caobas ejido is located in the municipality

of Othón P. Blanco in the state of Quintana Roo and the 20 de Noviembre ejido is located in the municipality of Calakmul in Campeche state (Fig. 1). These ejidos were chosen because they are among the largest and most representative forest communities of the region. Moreover, they share similar forest management and cutting areas, forest type (sub perennial medium tropical forest) and history of community forest management since 1983. However, as noted above, they show significant differences in management practices. Both ejidos are located at an altitude of around 190 meters above sea level (m a.s.l.) and have a predominant warm subhumid climate with abundant rains during the summer, an average annual rainfall of 1200 mm, and average annual temperature of 26 °C. The dominant soils are gray to reddish Redzinas and Gleysols, which have low permeability or drainage, a thin layer of organic matter and limestone texture (González, Schmook & Calmé, 2007; Sociedad de Productores Forestales Ejidales de Quintana Roo S. C. [SPFEQRSC], 2012). The main economic activities for both ejidos are forest related with timber harvesting occurring from January to July and tapping chicle or gum (*Manilkara zapota* (L.) P. Royen) from the forest from August to January.

Both ejidos apply a polycyclic silvicultural system with a 75-year rotation and a 25-year cutting cycle based on the growth and yield of mahogany (*Swietenia macrophylla* King), the guiding timber species for silviculture in the region (Ellis *et al.*, 2015; Navarro-Martínez *et al.*, 2017). Timber harvesting must be done according to an authorized Forest

Management Plan, for a period of 10 years to 20 years depending on the size of the management area and number of annual cutting areas (ACA). Selective logging is conducted within the delimited ACAs where potential volumes are assessed based on previous forest inventories, and harvested trees are marked in the forest prior to felling. Minimum cutting diameter for precious or high value timber, such as mahogany, chicle, and Spanish cedar (*Cedrela odorata* L.) is 55 cm diameter at breast height (dbh), and 35 cm dbh for other common tropical species. The trees that are ultimately harvested from the ACA are a function of the particular volume demand for different timber species by buyers in the region (Ellis *et al.*, 2019). Differences in forest management practices of both ejidos are presented in table 1. For example, skidding of logs to log landings is done for the most part using a modified agricultural tractor in Caobas, while a larger and wider conventional articulated forestry tractor (skidder) is used in 20 de Noviembre. The Caobas ejido has a forest area of 32 500 ha, including a wildlife conservation area of 8797 ha, and is certified by the FSC of Rainforest Alliance, implementing RIL practices such as directional felling, skid trail planning and other conservation measures. The 20 de Noviembre ejido has a forest area of 22 725 ha with a community conservation zone of 1913 ha and has been developing plans to implement RIL practices to improve forest management, but currently employing conventional logging methods.

TABLE 1. RIL practices conducted in the ejidos Caobas and 20 de Noviembre of the Yucatán peninsula, Mexico.

<i>RIL Practice</i>	<i>Ejido Caobas</i>	<i>Ejido 20 de Noviembre</i>
Planning of logging roads and skid trails	YES	NO
Mapping and marking of harvested trees	YES	YES
Pre-cutting of lianas and vines	YES	NO
Directional felling	YES	NO
Cutting stumps close to ground level	NO	NO
Type of machinery	Agricultural tractor	Tree farmer

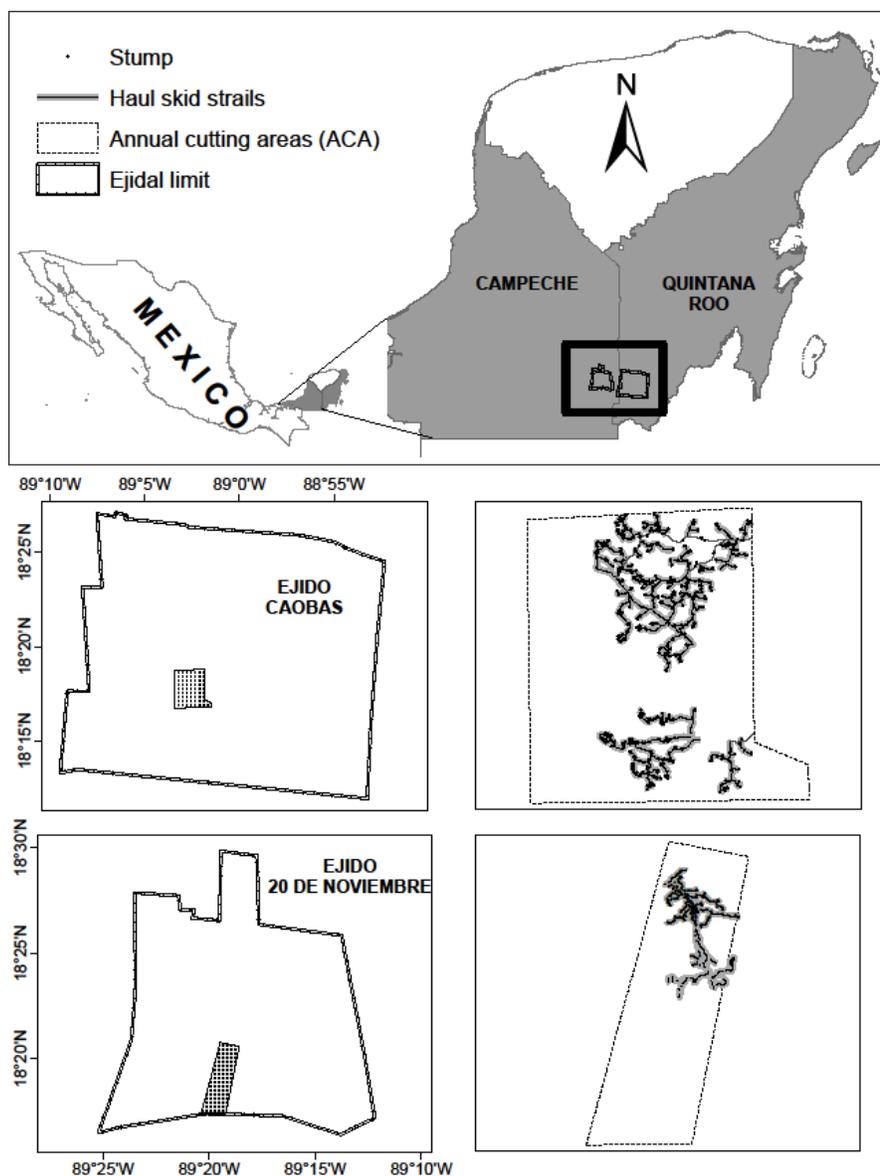


FIGURE 1. Geographic location of the ejidos Caobas and 20 de Noviembre in the southern Yucatán, Peninsula, Mexico.

Field sampling

Field measurements of harvested trees and the impacts on tree biomass from selective logging were conducted in both ejidos applying a methodology adapted from Griscom, Ellis and Putz (2014). The entire 2013 ACA (1000 ha) of the 20 de Noviembre ejido was sampled during January and April 2014. The data was collected for The Nature Conservancy by the ejido forest technician and provided by P. Ellis. Similarly, in the ejido Caobas, 85% of the 2014 ACA (1059 ha) was sampled at the time of harvest. Sampling involved

measuring harvested trees and collateral damage from felling, skidding logs, and transporting timber (which includes construction of log landings and logging roads) in selectively logged forests. Biomass impacts were assessed for each activity type involved in harvesting timber (felling, skidding and transport) as described in Walker *et al.*, (2012) and Griscom *et al.*, (2014):

- Felling. All felling gaps in the ACA were located and georeferenced, and in all the felling gaps in the 20 de Noviembre ejido and 15% of the felling gaps in the

Caobas ejido, the species and dimensions of the felled tree (stump diameter, remnant crown diameter and length of removed trunk) were recorded. Also, the species, type of damage and stem diameter of damaged trees and palms caused by felling were recorded.

- Skidding. The skid trails formed by skidding logs were also measured and georeferenced in the ACA. Plots (10 m × the width of the trail) were established every 100 m along the length of skid trails, recording species, type of collateral damage and stem diameter of impacted trees and palms, while also noting the machinery used for skidding, i.e., a modified agricultural tractor (Tr) or a Tree Farmer (Tf), and whether the skid trail was new or old.
- Transport. Access roads and log landings (locally known as “bacadillas”) were georeferenced and measured. The latter correspond to zones where all of the vegetation has been cleared in an area of approximately 500 m² to 800 m² in order to temporarily collect all of the harvested trunks before transport. The dimensions (width and length) and shape of approximately eight log landings were measured in each ejido to calculate biomass removal. Construction of access roads also involves clearing of all vegetation, and the entire length and width of the roads at 10 different sections within the ACA were measured to calculate biomass removal.

Collateral damage to above ground biomass during felling and skidding activities was recorded for all trees greater than 5 cm dbh (diameter at breast height) within sampled felling gaps and skid trail plots, and damage to trees was categorized as: G (totally fallen), S (snapped or broken), C (crown damage), B (bark stripped) and L (leaning ≥ 10°). In addition, the type of impacted tree was categorized as commercial (COI), non-commercial (NCOI), or palm (P).

The reference biomass and carbon stocks (C) present in the sampled ACA prior to logging were calculated based on inventories conducted in 2005–2008 in a collaboration between ejidos and the National Forestry Commission (Conafor). This inventory consisted of a network of successive circular plots of 500 m², located along the length of imaginary parallel lines within the permanent forest

management area. These sampling lines had a lateral equidistance of 250 m. Identification of trees, dbh, and height were measured in each plot. In order to calculate the biomass and carbon reserves present before logging, we considered the plots established within the ACA of both ejidos prior to felling.

We use forest biomass calculations to evaluate impacts from clearing for access road and log landing construction during the transport of timber. The aim of the field sampling methodology was to compare the impacts on biomass and carbon emissions from the different forestry activities (felling, skidding and transport) by the use of allometric equations, and to identify those that contribute the greatest quantity of carbon during selective logging harvesting operations.

Although there are effects on carbon in organic soil (Pinard, Putz & Tay, 2000; Abdullahi, Siwar, Shaharudin & Anizan, 2018), we do not include this part because it is considered that selective logging has a low impact on the short-term carbon stock (Vanguelova, Pitman, Luro & Helmisaari, 2010; Zhang *et al.*, 2018).

Data analysis

Data collected during field sampling was used to estimate the impacted aboveground biomass and calculate carbon emissions from selectively logged areas. To estimate biomass, we considered five allometric equations used for calculating above ground biomass (AGB) of tropical dry forests (Table 2); three generated for the Yucatán Peninsula (Cairns, Olmsted, Granados & Arguez, 2003; Urquiza-Haas, Dolman & Peres, 2007; Guyot & Proust, unpublished data) and two global equations (Chave *et al.*, 2005; Chave *et al.*, 2014). Since these allometric equations integrate tree height data, the required total height data was estimated using the formula of Chave *et al.* (2014): $H = \exp(0.893 - 0.385741 + 0.760 \cdot \ln(D) - 0.0340 \cdot \ln(D)^2)$. For wood density per species, the records of Gil-González and Prada-Garzón (2008) and the International Tropical Timber Organization (ITTO, 2012) were used, as well as the project page of Reinforcing REDD+ and South-South Cooperation (Conafor, 2015).



TABLE 2. Allometric equations used to obtain biomass in tropical dry forests.

Author	R ²	Allometric equation
Cairns <i>et al.</i> , 2003	0.956	AGB = exp[-2.173 + 0.868*ln(D ² H) + 0.0939/2]
Chave <i>et al.</i> , 2014	0.932	AGB = 0.0673(pD ² H) ^{0.976}
Chave <i>et al.</i> , 2005 (Model I)	0.923	AGB = exp[-2.187 + 0.916*ln(pD ² H)]
Urquiza-Haas <i>et al.</i> , 2007	0.902	AGB = exp {2.12605 + 0.868 ln(D ² H)}
Guyot and Proust, unpublished data	0.843	ln(AGB) = 1.3636*ln(D) + 1.6150*ln(H) - 2.9267

AGB is the total dry weight (kg), D is the diameter at breast height (cm), H is the height (m) and p is the specific weight of the timber (g cm⁻³).

To obtain total tree biomass we also consider the formula of Mokany and collaborators (2006) for root biomass: RB = 0.489 (AGB)^{0.89}. The total biomass value (AGB + RB) in kilograms was subsequently extrapolated to tons per hectare (Mg ha⁻¹) and multiplied by 0.47 (carbon factor) in order to obtain the quantity of carbon per hectare (Mg ha⁻¹) of the ACA and per cubic meter of timber harvested (Mg m⁻³), to assess impacts per volume of roundwood extracted, (i.e., by area and by efficiency, respectively).

A regression analysis was conducted to evaluate the allometric equations (Table 2). While the closest relationship (0.95) to the forestry inventory data was found with Cairns *et al.* (2003) (Table 2), we opted for Chave and collaborators (2014) with the second-best fit (R² = 0.93) to facilitate global comparisons, since it includes a bioclimatic variable (E) which is a function of climate water deficit, temperature seasonality and precipitation seasonality.

RESULTS

A total of 815 stumps were georeferenced in the ACAs of both ejidos, of which 418 were sampled to measure extracted timber and collateral damage. In addition, 41.3 km of skid trails and 5.2 km of haul roads were measured and sampled (Table 3) within the two ACAs. The most commonly felled species were tzalam (*Lysiloma latisiliquum* (L.) Benth.: 31% of the total) and caoba (*S. macrophylla*: 28%) in the Caobas ejido, and machiche (*Lonchocarpus castilloi* Standl.: 32%), pucté (*Bucida buceras* L.: 25%) and zapote (*M. zapota*: 20%) in the 20 de Noviembre ejido. A total of 46% of the felled trees presented dbh values of between 46 cm and 63 cm and the rest (54%) were smaller diameter timber

(35 cm to 45 cm dbh). The main types of collateral damage during felling were S and G in both ejidos, and from skidding, G trees in the 20 de Noviembre ejido, and S and G in the Caobas ejido (Fig. 2).

Carbon emissions

Using the allometric equation of Chave and collaborators (2014), it was estimated that the impact on forest vegetation generated by selective logging in the studied ejidos produces an average of 1.32 Mg ha⁻¹ year⁻¹ of carbon emissions. This value was 1.61 Mg ha⁻¹ in the Caobas ejido and 1.05 Mg ha⁻¹ in the 20 de Noviembre ejido (Table 4), despite much higher harvest yields in the former (see Table 3). However, use of a unit of measurement per hectare can be problematic due to the fact that this shows the quantity of carbon extracted per unit area of the ACA, rather than by the volume harvested in the ACA. For this purpose, we used the measurement of carbon emissions per cubic meters of timber extracted (m³) in order to analyze and compare the efficiency of harvest activities in minimizing carbon emissions. These results were 1.2 Mg m⁻³ in the Caobas ejido and 1.5 Mg m⁻³ in the 20 de Noviembre ejido, considering that the first extracted twice the volume of wood. Of the total emissions, 65% come from felled tree remainders and the extracted tree, although of this proportion, less than 7% of carbon impacts come from roundwood extracted from the site. The second greatest source of emissions come from skidding operations (around 11%) and carbon impacts from timber transport activities (i.e. construction of log landings and haul roads)

TABLE 3. Summary of the sampling conducted in two ejidos in the southern Yucatán peninsula, Mexico.

Activity		Ejido Caobas	Ejido 20 de Nov
Felling area (ha)		847.2	1000
Volume extrated (m ³)		1605	685.7
Biomass (Mg ha ⁻¹)		76.6	51.9
Felling (No.)	Trees felled and quantified	467	348
	Trees felled and measured	70	320
	Average number of trees damaged per individual felling event	3.2	6.5
Skidding	Average skid trail width (m)	3.0	3.2
	Total skid trail length (km)	6.9	12.9
	Skid trail plots (No.)	21	95
Transport	Average road width (m)	4.3	5.5
	Total road length (km)	3.1	2.1
	Number and area of the log landings (m ²)	9 (10 745)	7 (3362)

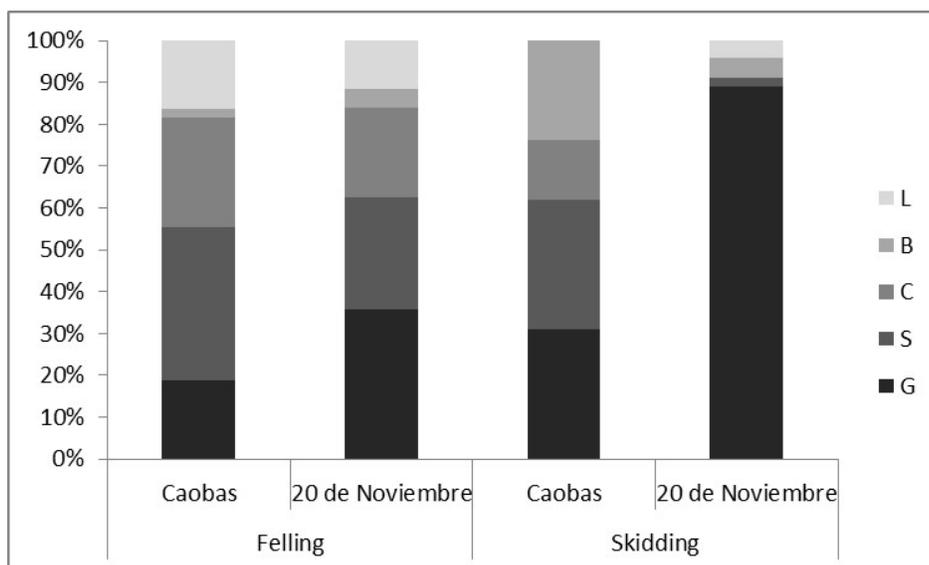


FIGURE. 2. Types of collateral damage through felling and the opening of skid trails in the ejidos Caobas and 20 de Noviembre of the Yucatán Peninsula, Mexico. G, totally fallen; S, broken; C, decrowned; B, bark stripped; L, leaning $\geq 10^\circ$



TABLE 4. Estimation of carbon emissions from selective logging in the ejidos Caobas and 20 de Noviembre, in the southern Yucatán Peninsula, Mexico.

	<i>Ejido Caobas</i>			<i>Ejido 20 de Noviembre</i>		
	Mg ha ⁻¹	Mg m ⁻³	%	Mg ha ⁻¹	Mg m ⁻³	%
Haul road (T)	0.04	0.03	2	0.06	0.08	5
Log landings (T)	0.10	0.07	6	0.02	0.03	2
Skid trails (S)	0.18	0.13	11	0.12	0.18	12
Felled tree remainder (F)	1.07	0.80	67	0.67	0.98	64
Felling damage (F)	0.07	0.05	5	0.13	0.18	12
Harvest timber (F)	0.15	0.11	9	0.05	0.08	5
Total	1.61	1.19	100	1.05	1.53	100

were the lowest source (< 8%). There are important differences between the two studied ejidos in terms of collateral damage caused during felling, which accounts for 5% and 12% of the total emissions in Caobas and 20 de Noviembre ejidos, respectively. This is in addition to the opening of haul roads (Table 4).

DISCUSSION

Carbon emissions as a result of forestry activity

This study quantified committed carbon emissions from selective logging in the southern Yucatan Peninsula. Carbon impacts per intervened area are 1.61 Mg ha⁻¹ and 1.05 Mg ha⁻¹ for the Caobas and 20 de Noviembre ejidos, respectively. These values are far below results obtained for Indonesia in Dipterocarpaceae forest using the same methodology by Griscom *et al.* (2014), which was 51.1 Mg ha⁻¹ of carbon. Moreover, the average number of damaged trees per felling event in the southern Yucatan Peninsula (5) is considerably less than the 10–20 trees damaged per felled tree reported for logging in other countries of the tropics (Putz *et al.*, 2008b).

Results of the committed carbon emissions per cubic meter (Mg m⁻³) of harvested timber show clear differences between the two ejidos. Even though three times more trees were harvested in the Caobas ejido than in the 20 de Noviembre ejido, the collateral damage per volume

extracted caused by felling and opening of skid trails is greater in the latter (Table 3). Collateral damage per harvested volume from felling operations was much lower in Caobas, thanks in part to directional felling, an activity classified as a RIL practice (Putz *et al.*, 2008a), showing only 0.05 Mg m⁻³ of resulting emissions of carbon compared to 0.18 Mg m⁻³ due to the felling in the 20 de Noviembre ejido. Furthermore, in Caobas, the lianas and vines are cut just before felling, which prevents the entanglements that can cause the loss of neighboring trees. This is another RIL practice (Putz *et al.*, 2008a) and is also recommended for the safety of the ejido brigades that conduct selective logging.

In the case of the skid trails, we found a value of 0.13 Mg m⁻³ of carbon in the Caobas ejido compared to 0.18 Mg m⁻³ in the 20 de Noviembre ejido. These differences could be due in part to the type of machinery used and the way the skid trails are opened. In Caobas, logs are mainly skidded with a modified agricultural tractor (Table 1), necessitating the manual cutting of only smaller trees to cut a path that allow the tractor to skid logs. Smaller width and weight of the modified tractor notably causes less forest biomass impacts than a conventional skidder (locally known as Tree Farmer) which was used by 20 de Noviembre for all skidding operations. Skidding with a Tree Farmer allows straight-line advances through the forest, crushing all of the trees in the skid trail. This type of

vehicle also explains why the most common type of damage observed in the 20 de Noviembre ejido is totally fallen (G).

With respect to opening of haul roads, the Caobas ejido uses old roads that were opened more than thirty years ago while forestry operations in the 20 de Noviembre ejido regularly opens new roads, increasing the quantity and size of damaged trees and thus the amount of carbon impacts. Regarding this activity, it is important to mention that both ejidos plan roads and skid trails prior to harvesting. This is one of the main RIL practices recommended in order to minimize forest impacts from selective logging. However, the use of alternative skidding or hauling technology, such as a modified agricultural tractor also shows more promise as an additional method to substantially reduce carbon emissions from skidding timber. Ellis *et al.* (2019) found that the use of modified agricultural tractors for skidding reduced carbon emissions by 0.15 Mg m⁻³ or 5 Mg km⁻¹ of skidtrail in forestry ejidos of the region.

Comparing our data with those of other countries, we found that ejido Caobas presents one of the lowest carbon emission rates per cubic meter of timber extracted, 1.19 Mg m⁻³ (Table 5). According to Pearson, Brown and Casarim (2014) and Griscom *et al.* (2014), all the studies conducted so far correspond to timber

company concessions who are in charge of logging and harvest much larger timber volumes. This contrasts with our study, in which both ejidos conduct selective logging through community forestry management. It is also important to note that the other countries studied typically employ heavy machinery (bulldozers) and, on most occasions, take no measures to protect trees of less than 50 cm of dbh (Pearson *et al.*, 2014).

Forestry certification

Forestry certification aims to maintain the integrity of forestry ecosystems (Kalonga, Midtgaard & Klanderud, 2016) through recognition and certification of responsible practices in forest management (Romero *et al.*, 2015). At present, there is some controversy regarding the effectiveness of forestry certification in terms of fulfilling its main objective (Romero *et al.*, 2015; Burivalova *et al.*, 2016; Kalonga *et al.*, 2016). Since 2013, the Caobas ejido has had the certification seal of the FSC, assigned by Rainforest Alliance. This certification requires the annual analysis of all relevant documents, permits, and forestry reports of the ejido, combined with field surveys. Certification is only reauthorized when the ten principles of the FSC are found to have been met (FSC, 2010).

TABLE 5. Carbon emissions per cubic meter (Mg m⁻³) in different countries that practice selective logging.

Country	Region	Mg m ⁻³	Mg ha ⁻¹	Publication
Guyana	Upper Demerara/Berbice	2.3	30.3	Pearson <i>et al.</i> (2014)
Mexico	Campeche (20 de Noviembre)	1.53	1.05	Present study
Indonesia	East Kalimantan	1.4	51.1	Griscom <i>et al.</i> (2013)
Mexico	Quintana Roo (Caobas)	1.19	1.61	Present study
Republic of Congo	Sangha	1.0	8.9	Pearson <i>et al.</i> (2014)



For the last two years, ejido Caobas has marked the extracted trees, cut lianas and vines prior to felling, practiced directional felling and, starting in 2016, has also georeferenced trees for extraction and the planning of skid trails. In 20 de Noviembre, directional felling has been tried in some years, but this activity is still not a consolidated practice within the ejido. However, directional felling can help explain the large differences in collateral damage from felling observed between these ejidos, (5% of emissions in the Caobas ejido compared to 12% in the 20 de Noviembre ejido).

From this study, it is apparent that certification and RIL practices by community forest management in the southeastern Yucatán Peninsula appear to help reduce the impact of timber harvesting on carbon emissions. Another notable ejido in the same region is Nohbec, which is certified by the FSC and also incorporates RIL practices, including skid trail planning and directional felling (Rainforest Alliance, 2004). Forestry certification has also been reported to be associated with social and environmental benefits (Burivalova *et al.*, 2016). Our findings support previous studies showing that RIL practices are associated with reduced forest disturbance from harvesting (Ellis *et al.*, 2019).

CONCLUSIONS

The impact of selective logging on estimated carbon emission rates in the southern Yucatán Peninsula is low compared to other regions of the world. The lowest rates were observed for the Caobas ejido, with a long history of community forestry management, implementation of forestry practices that are classified as reduced impact logging (RIL), and FSC certification. Forestry certification appears to fulfill its main objective in Caobas, which is to maintain the integrated and sustainable management of their forests. The 20 de Noviembre ejido provides an example of the efforts that are being made in the region to improve and attain greater efficiency in forestry management, although in reality RIL practices are implemented in relatively few ejidos of the region and forest certification is very difficult to attain for most

forestry ejidos (Ellis *et al.* 2019). The implementation of RIL practices, such as the use of agricultural tractors, directional felling, planning of skid trails, and the geopositioning of felled trees can all contribute to the certification, however there are also economic and environmental benefits to implementing RIL by community forest management in the region.

RIL practices and community forest management in selectively logged areas on the Yucatan Peninsula can contribute to maintaining carbon stocks and also minimizing carbon emissions in this important forest and biodiverse region. These actions should therefore be considered and integrated into guidelines for the implementation of carbon markets on the part of REDD+ and Conafor in Mexico. Only recently, have organizations such as TNC have begun to promote and finance support for the implementation of RIL-C practices by forestry ejidos on the Yucatan Peninsula; the “C” implying logging practices that have a clear impact on reducing carbon emissions (Ellis *et al.* 2019).

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