



Reduced-impact logging practices reduce forest disturbance and carbon emissions in community managed forests on the Yucatán Peninsula, Mexico



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ABSTRACT

On the Yucatan Peninsula in Mexico, communities (*ejidos*) that selectively log their forests help reduce deforestation and are an important source of timber for national and international markets. If carried out without proper planning and reduced-impact logging (RIL) practices, forest disturbances and carbon emissions from these harvests can be substantial. To assess variation in logging-induced emissions and to estimate potential reductions in those emissions, we estimated carbon impacts from damage to trees > 5 cm DBH in the annual cutting areas of ten forest-managing ejidos. Baselines were developed for emissions from felling, skidding and transport of timber and then ejidos were compared with respect to whether they were Forest Stewardship Council (FSC) certified, size of annual cutting area, logging intensity, and implementation of RIL practices, particularly directional felling, skid trail planning, and the use of small modified agricultural tractors instead of large forestry skidders. The carbon impacts of enrichment planting in multiple-tree felling gaps (400–1800 m²) were also evaluated. Carbon emissions from selective logging averaged 1.52 Mg m⁻³ but ranged 1.19–2.55 Mg m⁻³ among the 10 ejidos. Most emissions were from the remnants of trees felled for their timber (73%), followed by skidding (11%), transport infrastructure (i.e. logging roads and landings; 8%), and collateral damage from felling (7%). Our analyses indicate that FSC certification was not associated with any difference in carbon emissions from selective logging but that employment of RIL practices resulted in fewer damaged trees and lower carbon emissions even in ejidos with high logging intensities. Use of modified agricultural tractors for log yarding (i.e., skidding) reduced C emissions by 0.15 Mg m⁻³ or 5 Mg km⁻¹ of skid trail. Greater collateral damage was found in multiple felling gaps but the increased emissions were offset by reductions in the remnants of harvest trees. Adoption of RIL-C practices by all community forestry ejidos in the region would contribute substantially to the Mexican forest sector's efforts to mitigate climate change.

1. Introduction

Carbon emissions from tropical forest degradation now exceed those resulting from deforestation (Baccini et al., 2017), and a major cause of this degradation is selective logging (Griscom et al., 2009; Simula and Mansur, 2011; Morales-Barquero et al., 2014). Emissions from selective logging of tropical forests (0.5 Gt year⁻¹ of C; Putz et al., 2008b) can be reduced, and post-logging rates of forest recovery can be increased

through implementation of reduced-impact logging (RIL) practices (Asner et al., 2010; Putz et al., 2008a). Selective logging should therefore not be considered degradation when harvesting and other silvicultural practices are applied by trained and supervised workers in ways that minimize biomass impacts, promote recovery, and sustain production of timber and other environmental services; well managed logged forests may even sequester more carbon than un-logged or un-managed forest (Bray et al., 2011; Putz and Romero, 2015; Griscom

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et al., 2014). The carbon benefits of timber stand management are further enhanced if the harvested wood is utilized in place of carbon costly materials such as aluminum, steel, and concrete (Putz and Romero, 2015).

Despite the global potential for sustainable forest management (SFM) to supply timber and mitigate climate change, in reality it is not widespread in the tropics where only an estimated 10% of permanent forest areas are managed sustainably (Poudyal et al., 2018). Accordingly, at least since the Paris Agreement, the United Nations' REDD + program (Reducing Emissions from Deforestation and Degradation) has endorsed SFM as an important instrument to enhance carbon stocks and to reduce emissions in tropical developing countries. Furthermore, given that close to a quarter of the world's forests are controlled by indigenous peoples or rural communities (White and Martin, 2002; Garnett et al., 2018), inclusion of community forest management (CFM) is critical to achievement of improved forest outcomes (Herold and Skutsch, 2011). Community forests provide important livelihood contributions to more than half a billion rural people world-wide, so integrating CFM into REDD + activities on the ground can be a low risk high success strategy to meet REDD + goals (Agrawal and Angelsen, 2009).

In Mexico, CFM helps maintain forest cover while it economically benefits rural forest communities (Bray et al., 2003; Bray et al., 2004; Antinori and Bray, 2005; Ellis and Porter-Bolland, 2008; Ellis et al., 2017). Over 60% of Mexican forests are owned by communities (Madrid et al., 2009) and CFM has contributed substantially to the country's forest sector for 40 years, providing an important source of timber as well as carbon reserves for climate change mitigation. Both nationally and internationally, CFM is promoted by government institutions and NGOs as a "climate smart" land use that also helps conserve biodiversity (Agrawal and Angelsen, 2009; CONAFOR, 2010; Bray et al., 2011). Recent carbon dynamics modeling indicates that Mexican forests under CFM, when combined with increased timber production and substitution of wood for carbon-intensive materials, are effective carbon sinks (Olguin et al., 2018). Moreover, recent field studies and household surveys strengthen the argument that conservation goals are better achieved when secure tenure, communal land management, and stronger community governance are in place (Rodríguez and Fleischman, 2018). It is in fact these qualities that have facilitated implementation of REDD+ in Mexico (Herold and Skutsch, 2011), bringing more attention to CFM as a promising strategy to combat climate change in Mexico and beyond.

On the Yucatan Peninsula, CFM takes place over an extensive area of tropical forests (about 7 million ha) and is conducted by *ejidos* (communities holding communal land tenure), mostly in the states of Campeche and Quintana Roo. Both states are important producers of tropical timber for national and international markets: annual volumes harvested range from 70,000 to 150,000 m³ with approximate market values of \$6–\$12 million (SEMARNAT, 2010; 2016). Forest ecosystems on the Yucatan Peninsula also have high conservation values, forming part of the Selva Maya, the largest contiguous tropical forest region in Central America and Mexico (Rodstrom et al., 1998), including large protected areas such as Sian Kaan and Calakmul Biosphere Reserves. These forests, particularly in Quintana Roo, have also played a major role in the development of sustainable CFM in the Mexican tropics; *ejidos* such as Noh Bec, Caobas, Petcacab and Tres Garantías were pioneers in the development of community-based forestry enterprises. These developments began with strong support and subsidies by the state and federal government in collaboration with the German government (GTZ), under the Plan Piloto Forestal (1984–1998; Ellis et al., 2014a).

Forestry on the Yucatan Peninsula involves the selective removal of the commercially valuable timber that is often present at low densities (1–10 trees ha⁻¹; Ellis et al., 2014b). *Ejidos* engaged in CFM are legally required to have an authorized forest management plan (FMP) for timber harvests that need to follow a polycyclic silvicultural system

with a 75-year rotation and 25-year cutting cycles (Ellis et al., 2014a). The 25-year cutting cycle takes into consideration a range of growth rates (0.4–0.8 cm year⁻¹) of the commercial species, although most FMPs focus on mahogany (*Swietenia macrophylla*), the most valuable timber species. Based on mandatory forest inventories, FMPs consider three size classes of timber: repopulation (10–25 cm DBH); reserve (25–35 cm DBH); and, harvestable (> 35 cm DBH). In the case of precious timber, mahogany and Spanish cedar (*Cedrela odorata*), and of chicle (*Manilkara zapota*), minimum cutting diameters (MCD) are larger (55 cm DBH) (Navarro-Martínez et al., 2018). Ultimately, how many and which trees are harvested varies with the volumes of different species demanded by buyers, and average only 30% of permitted volumes (Ellis et al., 2015; Rodríguez-Ward et al., 2016). Although the silvicultural system applied by CFM in the Mexican Selva Maya has sustained harvests for over 40 years, there are still concerns about regeneration and stocks of valuable timber species, particularly mahogany (Snook 2005a; Ellis et al., 2014a). Moreover, as noted above, there is recent interest in Mexico about the role of CFM in biodiversity conservation and climate change mitigation (AGECC, 2010; Cronkleton et al., 2011). Nevertheless, realizing the potential of CFM on the Yucatan Peninsula is impeded by silvicultural research gaps coupled with often perverse public policies and illegal logging (Ellis et al., 2014a; Ellis et al., 2015).

The potential of RIL to reduce carbon emissions from selective logging is well established (see Putz et al., 2008a; Asner et al., 2010; Griscom et al., 2014). RIL minimizes forest damage by applying practices such as preharvest inventories, planned logging road networks, directional felling, and winching (Bicknell et al., 2014). Across the tropics, RIL practices demonstrably reduce collateral damage and consequent carbon emissions: in Brazil, RIL showed a loss of 17% above-ground biomass compared to 26% with conventional logging (CL) (West et al., 2014); in Sabah, Malaysia, CL damaged 41% of residual trees < 60 cm DBH compared to 15% when implementing RIL practices (Pinard and Putz, 1996); and, in East Kalimantan, Indonesia, tree injury and death was lower with RIL (30%) compared to CL (48%) (Bertault and Sist, 1997). Research on carbon impacts from selective logging in the tropics that distinguished emissions from felled trees and from impacts on biomass due to felling, skidding and construction of logging infrastructure (i.e., log landings and logging roads) have also been conducted (Pearson et al., 2005; Pearson et al., 2006; Brown et al., 2011). Most recently, in six tropical countries Pearson et al. (2014) found large differences in gross carbon emissions from selective logging that ranged from 6.8 Mg ha⁻¹ in Brazil to 50.7 Mg ha⁻¹ in Indonesia. Given that carbon emissions per hectare predictably increase with logging intensity (i.e., volume of timber extracted per hectare), logging practices were best compared using the indicator of emissions per cubic meter harvested (i.e., Mg m⁻³ of C). Pearson et al. (2014) reported these carbon emissions as 0.66 Mg m⁻³ in Republic of Congo, 1.49 Mg m⁻³ in Indonesia, and 2.33 Mg m⁻³ in Guyana. Based on similar methods, Griscom et al. (2014) reported that carbon emissions from selective logging in Kalimantan, Indonesia averaged 51.1 Mg ha⁻¹ and 1.5 Mg m⁻³, with no overall differences between Forest Stewardship Council (FSC) certified and non-certified concessions other than lower skidding emissions from certified concessions. Despite the known contributions of selective logging to greenhouse gases and the recognized potential of RIL to reduce these emissions, there is still much to learn about improving practices that cause these emissions.

Tropical forest management can be improved in many different ways, such as through silvicultural treatments to increase the growth and regeneration of timber species, setting aside high-value conservation areas, implementing worker safety measures, and RIL, which is the focus of this study (Burivalova et al., 2017). Forest certification by the FSC, which is based on more than just timber harvesting practices, aims to promote SFM by meeting the high environmental and social standards associated with markets for certified timber. However RIL figures prominently in FSC principles and criteria (Gullison, 2003;

Rametsteiner and Simula, 2003; Ebeling and Yasué, 2009; but see Romero and Putz, 2018). In our research, we specifically focus on RIL practices that directly relate to carbon emissions from harvesting activities (felling, skidding, and transport of logs) and that can be measured in the field as described by Griscom et al. (2014) and Pearson et al. (2014). Known as RIL-C, these improved logging practices include directional felling, improved log extraction methods (i.e., skidding or yarding), skid trail and road planning, improved bucking, and long-line winching (Broadbent et al., 2006; Wit and Van Dam, 2010; Griscom et al., 2014). To allow comparisons among forests selectively logged at very different intensities, we express emissions both per hectare and per cubic meter of wood harvested. The only similar study in Mexico was conducted by Pearson et al. (2005) for logging in the temperate forests in the state of Chihuahua.

Estimating forest carbon emissions from selective logging and defining baselines are essential to the improvement of community-based forest management and emission reduction strategies on the Yucatan Peninsula. The outcomes of the research presented will aid in setting up results-based actions by the REDD + MRV component and strengthen the integration of community-based forestry as an important “natural climate solution”, defined by Griscom et al. (2017) as conservation, restoration and improved management practices in natural terrestrial biomes to mitigate climate change.

To that end we adopted the RIL-C protocol (Griscom et al., 2014; Pearson et al., 2014) to quantify carbon emissions from selective logging in ten CFM ejidos on the Yucatan Peninsula. Biomass impacts from harvested trees and collateral damage from felling and skidding logs, in addition to those from the construction of log landings and logging roads, were measured in the field to assess carbon emissions and to establish baselines for harvesting practices in the logging landscape sampled. Furthermore, we evaluated how tree damage and carbon emissions relate to forest management certification by the FSC and the implementation of specific RIL-C practices (directional felling, skid trail planning and the use of modified agricultural tractors for skidding). Ejidos are assessed in terms of their performance in committed emissions (as per the IPCC Tier 1 accounting approach; Davis et al., 2014), and potential reductions in carbon impacts from implementing RIL-C practices are estimated.

2. Methods

2.1. Logging landscape

We quantified carbon impacts from logging in the forested landscape of the Yucatan Peninsula. Located in southeast Mexico, the peninsula lies atop a karstic plateau that emerged from the ocean during the Tertiary and Quaternary (Lugo and García, 1999; Bautista-Zúñiga et al., 2005). We focused on the logging landscape in the southeastern quadrant of the Peninsula (Fig. 1) where the topography is mostly flat with elevations ranging 0–400 m above sea level, with some hilly terrain characteristic of the central and southern portions (Lugo and García, 1999; Orellana et al., 1999). The climate of the study region is warm and humid, with mean annual temperatures of 24–26 °C and annual precipitation of 800–1200 mm, with a pronounced November–April dry season with < 60 mm of rain per month (Gutiérrez-Granados et al., 2011; Koleff et al., 2012). In upland areas of the logging landscape, soils are mostly rendzinas (leptosols and phaeozems) that are shallow to moderately deep, rocky, poor in organic matter, and well drained. In depressions the dominant soils are gleysols and vertisols which are moderately deep to deep, rich in organic matter, and poorly drained (Vester and Martínez, 2007; Bautista-Zúñiga et al., 2011).

Vegetation of the logging landscape varies with geomorphology, soil, and climate (Miranda, 1978; Durán and Olmsted, 1999; Flores-Guido et al., 2010) as well as from natural and anthropogenic disturbances that resulted in a landscape mosaic of forest at different successional stages (Ellis and Porter-Bolland, 2008). Hurricanes and

fires are common, as are human impacts that date from the Maya civilizations thousands of years ago; the forests adapted to these frequent disturbances and are considered very resilient (Turner, 1981; Whigham et al., 1991; Snook, 1996; Snook and López, 2003; Navarro-Martínez et al., 2012). Forests are of low (10–15 m), medium (15 to 30 m), and high-stature (30–35 m) and vary from semi-evergreen (25–50% dry season leaf loss) to semi-deciduous (50–75% dry season leaf loss) (Miranda and Hernández-X., 1963; Flores and Espejel, 1994; Pérez-Salicrup, 2004). Above-ground forest biomass in the logging landscape reportedly averages 77 Mg ha⁻¹ of C (Morfin-Ríos et al., 2015; CONAFOR, 2017), but ranges 50–90 Mg ha⁻¹ (Douterlungne et al., 2013; Santos et al., 2015).

Logging in the study region is mostly in medium to high-stature forests that are semi-evergreen (Snook et al., 2005; Hernández-Stefanoni et al., 2006). These forests typically support around 100 tree species per hectare with common upland species including *Brosimum alicastrum*, *Manilkara zapota*, *Talisia olivaeformis*, *Bursera simaruba*, *Lonchocarpus longistylus*, *Nectandra salicifolia*, *Psidium sartorium*, *Guet-tarda combsii*, *Vitex gaumeri*, *Caesalpinia gaumeri* and *Lysiloma bahamense* (Hernández-Stefanoni et al., 2006; Gutiérrez-Granados et al., 2011). In flooded areas, *Hemotoxylon campechianum* and *Metopium brownei* are common, but many of the same species still occur (Flores and Espejel, 1994; Pérez-Salicrup, 2004). Over half of the tree species have commercial timber value (Vester and Martínez, 2007; Toledo-Aceves et al., 2009). As noted above, forests in the area typically recover quickly from disturbances (Whigham et al., 1991; Negreros-Castillo and Mize, 1993; Bonilla-Moheno, 2010; McGroddy et al., 2013.). Mahogany, a key timber species, occurs in higher densities on the Yucatan than in other regions in Latin America, and requires large canopy openings (at least 5000 m²) for successful regeneration (Snook, 2005b). The ecological resilience and abundance of high-value timber favored the historical importance of forest management on the Yucatan Peninsula (Snook, 1998).

Ejidos engaged in forest management must delimit their management areas and specify the extent of each annual cutting area (ACA) during their authorized logging period. Mandatory forest inventories are conducted to determine existing volumes and potential harvest volumes within ACAs. Harvests are limited to 15–20 trees ha⁻¹, with authorized volumes of 7–20 m³ ha⁻¹, depending on the ejido, but harvests are typically only 20–40% of what is authorized (Ellis et al., 2015). Timber harvests are based on a selection of mature, dead, and sick trees. Typically, trees to be felled are selected and marked in advance by forest technicians or logging crew chiefs, and are subsequently felled, bucked, and extracted, generally using a skidder (articulated forestry tractor; Fig. 2) that drags the timber to log landings of 400–1200 m² (Ellis et al., 2014b) locally called “bacadillas.” Subsequently, logs are trucked to local sawmills or to points of sale outside the forest. Even ejidos that own sawmills sell some roundwood to local or national buyers for processing elsewhere. Timber harvests are typically conducted during the January to May dry season.

Some forest communities recently opted to use modified agricultural tractors for skidding rather than the much larger skidders that remain operating in the region (Fig. 2). These 85–100 HP farm tractors are fitted with: (1) a caged cabin; (2) extra protection for radiators, tire valves, lights, motor and axles; (3) thicker tires; (4) a front-mounted blade; (5) a rear-mounted winch; and, (6) spark protector for the exhaust. The cost of these outfitted tractors ranges \$20,000–50,000 USD and are easily operated by community members. They are also cheaper to maintain by local mechanics than the forestry skidders, which are not readily available in Mexico and cost upwards of \$20,000 for a very used 1970s model. Most skidders on the Yucatan Peninsula are legacies of the Plan Piloto Forestal Project (PPF), which promoted community forestry in the 1980s and 1990s (Ellis et al., 2015). These skidders are harder to operate than farm tractors, they sometimes need to be rented, and often require contracted operators. Ejidos that own their own skidders suffer shortages of replacement parts and qualified mechanics,

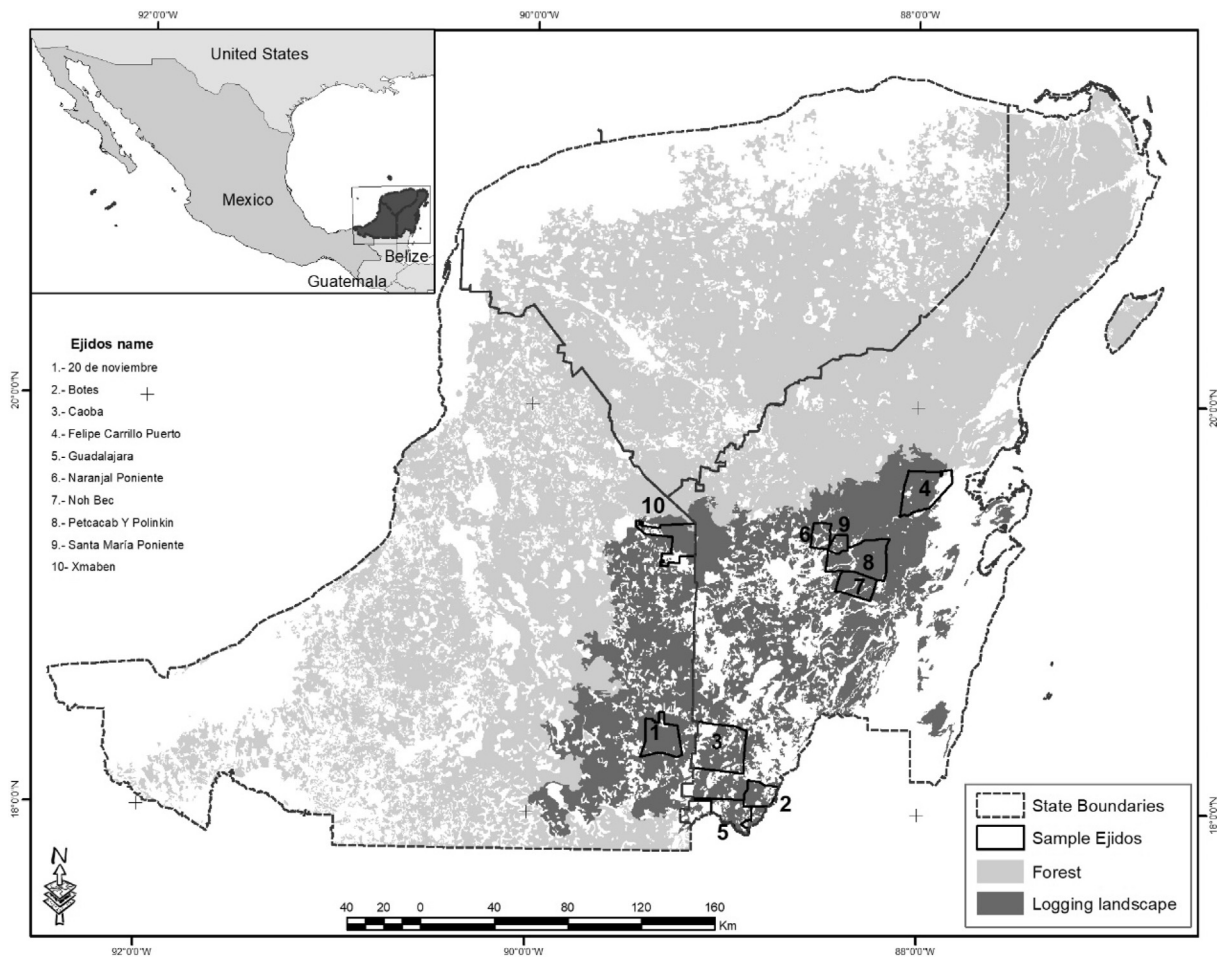


Fig. 1. The study logging landscape on the Yucatan Peninsula with the sampled ejidos indicated by number (see Table 1 for a key).

both of which are expensive. For these reasons, the opportunity to use modified agricultural tractors is especially beneficial for small ejidos that formerly relied on contracted skidders, which were costly and perceived to cause excessive disturbance.

2.2. Sampled CFM ejidos

We sampled ten CFM ejidos of which seven were selected at random. For the remaining three, we chose the only two ejidos in the region that were FSC certified at the time (Noh Bec and Caobas), and

one ejido (20 de Noviembre) that was previously selected for a pilot study by The Nature Conservancy (TNC; Fig. 1). The latter was sampled by its forest technician, Caobas was sampled by a doctoral student as part of her dissertation project (S. Armenta-Montero, in preparation), and the others were sampled by our team with assistance from local community forest technicians. Random selection of the seven ejidos was from a population of 33 ejidos with active management plans and ongoing logging that were stratified into those with large (> 500 ha) and small (< 500 ha) ACAs (Table 1). Given the high likelihood of positive selection bias in regard to the FSC certified communities, the results of



Fig. 2. A forestry skidder (left) and a modified agricultural tractor (right) used for log yarding on the Yucatan Peninsula.

Table 1

Characteristics of sampled ejidos. Forest biomass includes both above- and below-ground masses of trees > 7 cm DBH. DF = directional felling; STP = skid trail planning; MT = modified agricultural tractor.

Ejido	Forest biomass (Mg C ha ⁻¹)	Annual cutting area (ACA; ha)	Forest Mgmt. Area (ha)	Reported harvested volume from ACA (m ³)	Logging intensity (m ³ ha ⁻¹)	RIL-C practices	FSC
Caobas	76.6	Large (1059)	32,265	1605	Low (1.1)	DF, MT, STP	Yes
Noh Bec	64.2	Large (1008)	18,000	7000	High (6.9)	DF, STP	Yes
Petcacab [*]	76.8	Large (1180)	41,776	9000	High (7.6)	DF, STP	No [*]
Botes ^{**}	73.0	Small (400)	7358	500	Low (1.2)	MT,	No ^{**}
Guadalajara ^{**}	53.9	Small (240)	12,334	950	Medium (3.5)	MT	No ^{**}
Felipe Carrillo Puerto	95	Large (1843)	24,780	1600	Low (0.9)	None	No
Naranjal Poniente [*]	83	Small (300)	7500	1000	Medium (2.3)	None	No [*]
Santa María Poniente	78.6	Small (200)	4800	800	Medium (2.5)	None	No
X-Maben (Campeche)	88.7	Small (350)	2644	400	Low (1.1)	None	No
20 de Noviembre ^{**}	51.9	Large (1000)	22,725	700	Low (0.7)	None	No ^{**}

* Previously certified but lost FSC certification.

** Underwent certification auditing process but did not attain it.

our comparisons of FSC and non-FSC operations should be interpreted with caution.

Ejidos in this study vary in forest biomass as well as in overall extents, areas dedicated to forest management, and ACAs (Table 1). The ejidos also differ in other aspects of their forest environments as well as in characteristics of their management. For example, moisture regimes vary from the driest in X-maben towards the northwest limit of the study region to the wettest in Guadalajara and Botes at the southern extreme.

Ejido forests also vary in their history of use and disturbance, as reflected in their biomass, tree species composition, and stocking of timber species. Ejidos also vary culturally, socioeconomically and institutionally as well as in their experience with forest management, organization, and governance. For example, some ejidos harvest timber through working groups (internal groups of community members) allocated different portions of the ACA, while others communally manage their forest with assigned members for specific logging and transportation tasks. Some ejidos in the study hired non-community members to run the heavy equipment. Ejidos also differ in their experience with natural forest management. For example, Noh Bec, Petcacab, Caoba, and Guadalajara have participated in forest management since the PPF period (1983) and were associated with that prominent tropical forestry project. Guadalajara, Caobas and Botes are members of the *Sociedad de Productores Forestales de Quintana Roo S.C.* whereas Naranjal Poniente and Santa María Poniente belong to the *Organización Ejidal de Productores Forestales de la Zona Maya S.C.*, both very influential local forestry organizations in operation since the early 1980s (Snook 2005a). Noh Bec and Petcacab formerly belonged to these forestry associations but Noh Bec left when they created their own community forestry office and Petcacab switched to an independent forestry technician. Of all the ejidos studied, X-maben has the least experience in forest management and the least well-developed community forest organization and enterprise. As PPF was established in the state of Quintana Roo, the two ejidos from Campeche, 20 de Noviembre and X-maben, did not experience as much influence from PPF nor the above-mentioned technical organizations.

ACAs are sub-divided into smaller management sub-blocks that are typically 100 ha. RIL-C practices implemented by at least some ejidos were directional felling (DF) and skid trail planning (STP) in FSC-certified ejidos (Noh Bec and Caobas) as well as in Petcacab, which is in the process of re-obtaining certification. It should be noted that all three ejidos lost their FSC certification due to ecological damage and economic problems caused by Hurricane Dean in 2007. Noh Bec and Caobas recovered certification in 2012 and 2013, respectively. Modified agricultural tractors (MTs) for skidding, which we consider a RIL-C practice, were employed in Botes and Guadalajara, which are members of a prominent forestry association and had undergone FSC certification audits but never attained certification, and in most (80%) of the FSC-certified ejido, Caobas. The three RIL-C practices considered

for this study were also identified among the four most important improved management practices to reduce carbon impacts in our logging landscape, in addition to more efficient utilization of large branches and residues from felled trees (Villaseñor and Gonzalez, 2016). As noted above, Noh Bec, Caobas, and Petcacab were among the first established and most advanced community forestry enterprises, owning substantial sawmills that are also used by neighboring ejidos. In addition, Naranjal Poniente, Botes and 20 de Noviembre own small sawmills. Roundwood is also sold in all ejidos and processed in sawmills in nearby Felipe Carrillo Puerto, Chetumal, and Cancun.

2.3. Logging disturbance sampling

Forest disturbance from logging operations in the 2013 ACAs of Caobas and 20 de Noviembre were sampled January–April 2014; for the other eight ejidos we sampled the 2014 ACAs during March–November 2015. Two randomly selected 100 ha harvest blocks were sampled in ejidos with large ACAs, only one in ejidos with small ACAs. Delimited ACAs and sub-blocks were georeferenced from maps in forest management plans or from shapefiles provided by ejido forest technicians. Selected harvest blocks were then mapped in the field using Garmin GPS Map 60csx. In each sub-block all felled trees (stumps), skid trails, log landings, and logging roads were georeferenced. For field measurements of logging impacts on forest biomass, we adopted for Yucatan conditions the methodology provided by Griscom et al. (2014) and Pearson et al. (2014).

Felling biomass impacts (F) were calculated from samples of 5–15% of all trees felled for harvest in the harvest blocks (hereafter, harvest trees or HT). Stumps were selected by randomly choosing skid trails and then sampling every other stump or felling gap encountered. For each sampled gap, we recorded the location of each HT stump, determined its species, and measured the stump's diameter and height, removed log length (stump to canopy base), and diameter of the canopy base. The log harvested and removed from the forest is referred to as RW, and the stump, roots and canopy left in the forest make up the harvest tree remnants (HTR), which added to RW equals HT. In addition, collateral damage (CD) from felling was recorded for all trees > 5 cm DBH by species, DBH, and type of damage categorized as: TL (totally fallen), TS (trunk snapped), DC (> 50% damaged crown), BS (bark stripped), and LN (leaning ≥ 10°). Finally, damaged trees were categorized by species as commercial (COT), non-commercial (NCOT), or palm (P). When encountered, we skipped gaps caused by the felling of multiple trees (*bosquetes*) since in most cases they were already cleared for enrichment planting (Navarro-Martínez et al., 2017). *Bosquetes* were present in Noh Bec, Petcacab, Guadalajara and Caobas, and were established as part of a national reforestation program. To evaluate the carbon impacts of these larger multiple-tree felling gaps, we measured felling carbon impacts (HT and CD) in 10 *bosquetes* in Noh Bec, applying the

same methodology described for single-tree felling gaps.

Skidding impacts (S) were based on measures of damage to trees > 5 cm DBH in 15–20 skid trail plots in each sampled block that were 10 m long and the width of the trail. The plots were placed on randomly selected skid trails (see above) at random distances from the road or log landing. As in felling CD, species, DBH, and type of damage were recorded for damaged trees.

Estimates of emissions from logging roads (R) were based on measurements of their lengths and widths every 200 m within sampled harvest blocks. Similarly, estimates of forest disturbance from all log landings (L) in the blocks were based on measures of their areas. Emissions were estimated only for new roads; most roads in this logging landscape were initially constructed in the 1950s and were only rehabilitated for this round of logging (Ellis et al., 2015), which caused only minor emissions.

Reference levels of un-logged forest biomass in the sampled blocks were obtained by measuring basal area with a 2 BAF metric prism at 15–20 randomly selected points in unlogged stands past the ends of randomly selected skid trails. In Caobas and 20 de Noviembre, un-logged forest biomass estimates were obtained from forest inventories of the sampled sub-blocks conducted prior to logging. This inventory consisted of 500 m² circular plots in which the DBH and height of all trees > 10 cm DBH were measured prior to logging.

Sampling intensities varied among ejidos but was at least 100 ha in small ACA ejidos, and 200 ha in large ones (Table 2). Larger areas were included in the ejidos sampled first (2013; Caobas and 20 de Noviembre) with the goal of including entire ACAs (847 and 1000 ha, respectively). The number of harvested trees tallied and georeferenced in the sampled harvest blocks of each ACA (from 190 to 704) varied with logging intensities and the sampled area. The number of felled trees sampled for felling impacts in the ACAs also varied (from 19 to 348), but in all cases except for 20 de Noviembre, 5–17% of harvest tree gaps in the sub-blocks were sampled. The length of sampled skid trails per ejido ranged 6–21 km whereas logging road lengths ranged 0.4–2.9 km. The number of log landings sampled in harvest blocks ranged 1–10, and the total area they occupied was relatively small (from 0.1 to 0.9 ha). Basal area measurements in un-logged forest of sampled sub-blocks (16–25 m² ha⁻¹) mostly reflect the differences in forest conditions prior to logging (Table 2).

2.4. Calculation of carbon emissions

The total emissions from logging, E, is equal to F + S + R + L. For F and S; DBHs of felled and damaged trees were used to estimate their biomass and carbon using allometric equations. Chave et al. (2014) was used for above-ground biomass (AGB) using model 4 ($AGB = 0.0673(WD \cdot DBH^2 \cdot H) \cdot 0.976$), where WD = wood density and H = tree height. H was calculated with the equation ($H = \exp(0.893 - ENV + 0.760 \cdot \ln(DBH) - 0.0340 \cdot \ln(DBH)^2)$), where ENV is an indicator of environmental stress related to temperature, rainfall,

and geographical location (Chave et al., 2014). Wood density data for biomass calculations were obtained from the Global Wood Density Database (Chave et al., 2009). Below-ground biomass of felled and damaged trees was estimated using Mokany et al. (2006), which allows estimation for individual trees with a root: shoot ratio of 0.205 for moist tropical forest < 125 Mg AGB. A carbon factor of 0.47 was used to convert biomass to carbon (C). Carbon in the removed log (RW) was calculated using field measurements of log length, upper diameter, and lower diameter. The biomass of the tree crown and stump (HTR) was estimated by subtracting the biomass of RW from total harvest tree biomass. We considered emissions according to the type of damage to trees from felling or skidding, where TL and TS were 100%, and DC 20% emissions. Finally, as indicated above, R and L carbon impacts were estimated by calculating the biomass removed during infrastructure construction. Carbon impacts (Mg) from selective logging in CFM ejidos were extrapolated to Mg m⁻³ based on RW volumes and Mg ha⁻¹, based on the total area sampled in the ACA. Soil carbon emissions were not considered but seemed minimal.

2.5. Baselines and statistical assessments

Based on the carbon emissions from selective logging in the ten sampled ejidos, we calculated emission baselines for the different emission sources resulting from harvest operations. Specifically, baselines consist of the means of carbon impacts from felling, skidding, and logging infrastructure construction (CD, RW, HTR, S, L, R and E), calculated as Mg ha⁻¹ and Mg m⁻³. Linear regression was used to examine relationships between carbon impacts (Mg ha⁻¹ and Mg m⁻³) and roundwood volume harvested (m³) and logging intensity (m³ ha⁻¹) in sampled harvest blocks. Total emissions (E) and emissions from the different logging activities in the sampled ejidos are then compared with the derived regional baselines.

We use ANOVAs on our sample of ten ejidos (N = 10) to assess the correlations of carbon emissions (Mg m⁻³) from selective logging with FSC certification, implementation of RIL-C practices, and management characteristics, such as size of the ACA and LI (m³ ha⁻¹). Mixed models were used to test the effects of implementing specific RIL-C practices (DF, STP, and MT), FSC certification, and ejido forest management characteristics (ACA and LI) on emissions and on the number of damaged trees from felling (CD) and skidding (S). These complex models are based on the same principle as general linear models and make it possible to use repeated measures and include random factors. The explanatory variables can be quantitative or qualitative, and referred to as fixed and random factors (XLStat, 2017). For the case of felling CD, we evaluated RIL-C practice of DF, and for skidding carbon impacts (S), we evaluated the RIL-C practices of STP and MT. Other explanatory variables or fixed effects used in the mixed model included FSC, ACA, and LI. Since most ejidos were selected at random and considering the large variability among them, as described above (e.g. forest environments, socioeconomic and cultural), we used ejido as a random effect in

Table 2
Mapping and sampling effort in ACAs of CFM study ejidos.

Ejido	ACA sampled (ha)	# Mapped stumps	# Sampled stumps	Mapped skid trails (km)	# Skid trail plots	Mapped logging roads (km)	# Logging road meas.	# and Area of log landings (ha)	# Biomass sample sites & basal area (m ² ha ⁻¹)
Caobas	847	467	70	6.9	21	3.1	10	10 (0.40)	n/a
Noh-Bec	182	704	116	20.8	20	1.5	10	2 (0.75)	15 (18.7)
Petcacab	170	495	77	19.0	15	2.7	20	9 (0.87)	12 (21.8)
Botes	308	194	20	10.3	14	0.5	10	1 (0.12)	10 (20.9)
Guadalajara	270	370	19	16.9	18	1.0	10	2 (0.44)	10 (16.0)
F. Carrillo Puerto	240	255	38	16.4	15	2.9	20	4 (0.33)	15 (26.3)
Naranjal Poniente	116	190	69	9.1	17	1.2	8	3 (0.18)	15 (23.3)
Sta. Ma. Poniente	188	197	30	10.6	15	0.4	9	6 (0.56)	15 (22.3)
Xmaben	409	102	21	6.2	15	2.2	10	3 (0.29)	16 (24.7)
20 de Noviembre	1000	348	320	12.9	95	2.1	4	5 (0.34)	n/a

Table 3
Total carbon emissions and logging intensities from selective logging in sampled ejidos on the Yucatan Peninsula.

Ejido	Mg ha ⁻¹ of C	LI in sampled sub-blocks (m ³ ha ⁻¹)	Mg m ⁻³ of C
Caobas	1.5	1.3	1.2
Noh Bec	9.0	6.7	1.3
Petcacab	5.6	4.6	1.2
Botes	1.7	1.2	1.4
Guadalajara	4.5	3.6	1.3
Felipe Carrillo Puerto	2.2	1.2	1.9
Naranjal	3.5	2.5	1.4
Sta. Ma. Pte	3.0	2.4	1.2
Xmaben	0.74	0.3	2.5
20 de Noviembre	1.1	0.7	1.6
Mean	3.3	2.4	1.5

the mixed model. Skid trail plots and felling gaps (HTs) sampled in each ejido are then used as sample units and treated as replicates in the mixed model. In the case of 20 de Noviembre where all HT and skid trails were sampled, we randomly selected 30 skid trail plots and 35 HT to have a comparable random sample. Tukey (HSD) pairwise comparison tests were also applied to compare carbon emissions means from felling and skidding impacts between categories of FSC (yes or no), ACA (large or small), LI (low medium and high), DF (yes or no), STP (yes or no), and MT (yes or no).

3. Results

3.1. Overall carbon emissions from selective logging

Selective logging induced carbon emissions from the 10 ejidos sampled on the Yucatan Peninsula averaged 3.3 Mg ha⁻¹ but ranged from 0.8 to 9.0 Mg ha⁻¹ (Table 3). Emissions per hectare were closely correlated with LI (m³ ha⁻¹) in the sampled sub-blocks ($R^2 = 0.99$, $F(1,8) = 617.4$, $p < 0.0001$, Fig. 3). On the other hand, carbon emissions per cubic meter of timber harvested (Mg m⁻³) was weakly correlated with LI ($R^2 = 0.28$, $F(1,8) = 3.1$, $p < 0.11$, Fig. 3). Since C emissions per area (Mg ha⁻¹) were correlated with logging intensity, we did not use this indicator for further comparison of emissions performance by ejidos. Instead, we use the indicator Mg m⁻³, which was not correlated to LI, to present and compare carbon emissions performance.

The average total carbon emissions per volume of timber harvested for all 10 sampled ejidos was 1.5 Mg m⁻³ but varied from 1.2 to 2.5 Mg m⁻³. Relative to this baseline, Xmaben, Felipe Carrillo Puerto, and 20 de Noviembre, which implemented none of the tracked RIL-C practices, all had carbon impacts > 1.6 Mg m⁻³. Four of the five ejidos with the best performance (< 1.5 Mg m⁻³) implemented RIL-C practices and two were FSC certified. Caobas, in first place, is FSC-certified and implements all three RIL-C practices; Petcacab in second, implements DF and STP; Guadalajara in fourth implements MT; and Noh Bec in fifth, is FSC certified and implements DF and STP. Santa Maria Poniente and Naranjal Poniente, although they do not use any of the monitored RIL-C practices, performed well, ranking third and sixth place respectively. Finally, in seventh, also below our baseline, was Botes which implements MT.

3.2. Carbon emissions from selective logging disaggregated by operations

Carbon emissions per cubic meter of timber harvested (Mg m⁻³) from specific logging operations varied substantially among ejidos (Fig. 4 and Table 4). Harvest tree remnants (HTR) left in the forest after felling consistently constituted the major portion of carbon emissions, with a mean of 0.76 Mg m⁻³ (0.62–0.95 Mg m⁻³), which represents 28–61% of total ejido emissions. After HTR, the round-wood extracted

of felled trees (RW) represented average carbon emissions of 0.30 Mg m⁻³ (21%), quite consistently across ejidos (0.20–0.36 Mg m⁻³; 11–26% of total emissions). Skidding (S) was the third largest cause of carbon emissions with an average of 0.18 Mg m⁻³ (11% of total emissions) but varying widely (0.03–0.46 Mg m⁻³ or 2–18% of total emissions). Ejidos with the lowest skidding impacts, Botes and Guadalajara (0.03 and 0.06 Mg m⁻³ and 2 and 5% of total emissions, respectively), used MT exclusively. Noh Bec and Petcacab, which implemented STP, were also among the ejidos with low skidding carbon emissions (both 0.11 Mg m⁻³ and 8% of total emissions). Following skidding, collateral damage from felling (CD) caused carbon emissions that averaged 0.12 Mg m⁻³ or 7% of total emissions. CD varied widely (0.04–0.29 Mg m⁻³ and 3–11% of total emissions), and ejidos that implemented DF (Noh Bec, Caobas, and Petcacab) had the lowest emissions. As noted above for overall carbon impacts, Xmaben, Felipe Carrillo Puerto and 20 de Noviembre performed above the baselines for felling and skidding damage. Carbon emissions from logging infrastructure construction were very low relative to other disturbances, averaging only 0.07 Mg m⁻³ (5% total emissions) but varying 0.02–0.21 Mg m⁻³ (2–8% of total emissions). There were only road emissions (R) from the five ejidos with new logging roads; they averaged 0.08 Mg m⁻³ (4% of total emissions) for all 10 ejidos. Xmaben, where all the roads were new, was the only ejido with substantial carbon emissions from road development (0.61 Mg m⁻³), which constituted 24% of its total emissions.

For most baseline indicators of selective logging emissions by operation, Xmaben stands out as the worst performer, with the highest skidding impacts and a substantial portion of their carbon emissions from building new logging roads to access the ACA. Skidding impacts were also high in 20 Noviembre and Felipe Carrillo Puerto whereas felling collateral damage emissions were high in, Xmaben and 20 de Noviembre. The best overall performers (Noh Bec, Guadalajara, Botes and Caobas) had much lower carbon impacts from felling CD, S, L and R. These also include both FSC certified ejidos (Noh Bec and Caobas), plus all three ejidos that used MT for skidding (Botes, Caobas and Guadalajara).

The ANOVA model applied to assess the relationships between total carbon emissions and FSC certification, application of one or more RIL practices, and other management characteristics explained 76% of the variability in total carbon impacts (Mg m⁻³) from selective logging for the ten sampled ejidos ($N = 10$) and was significant at the 10%, but not 5% significance level [$F(4, 5) = 4.05$, $p = 0.079$]. Significant explanatory variables at the 10% level of significance included RIL ($p = 0.049$), LI ($p = 0.068$), and ACA ($p = 0.096$). Model parameters show ejidos not applying RIL-C practices had higher emissions ($p = 0.049$), but no difference was found between FSC and non FSC certified ejidos. Furthermore, model parameters indicated that ejidos with large ACAs had lower carbon emissions ($p = 0.096$) and ejidos with low logging intensities (LI) had high emissions ($p = 0.027$). However, as mentioned above, ejidos with small ACAs and low to medium harvest intensities also performed well, with the implementation of RIL (Botes and Guadalajara) or without any visible RIL practices in their 2014 ACA (Santa Maria and Naranjal Poniente). The worst performers (Felipe Carrillo Puerto, Xmaben and 20 de Noviembre) did not implement the monitored RIL-C practices, had low harvest intensities, and, except for X-Maben, also had large ACAs.

3.3. Felling emissions

Descriptive statistics for the number of damaged trees and carbon emissions from felling (CD) in the ten ejidos (Table 5) show that the three ejidos with the lowest number of damaged trees (Caobas, 3.0; Petcacab, 4.5 and Noh Bec, 5.1) all implemented DF and all had the lowest carbon emissions per felled tree (Noh Bec, 0.18; Petcacab, 0.12 and Caobas, 0.13 Mg). Interestingly, Caobas with lowest number of damaged trees per tree felled, was the only ejido sampled that was

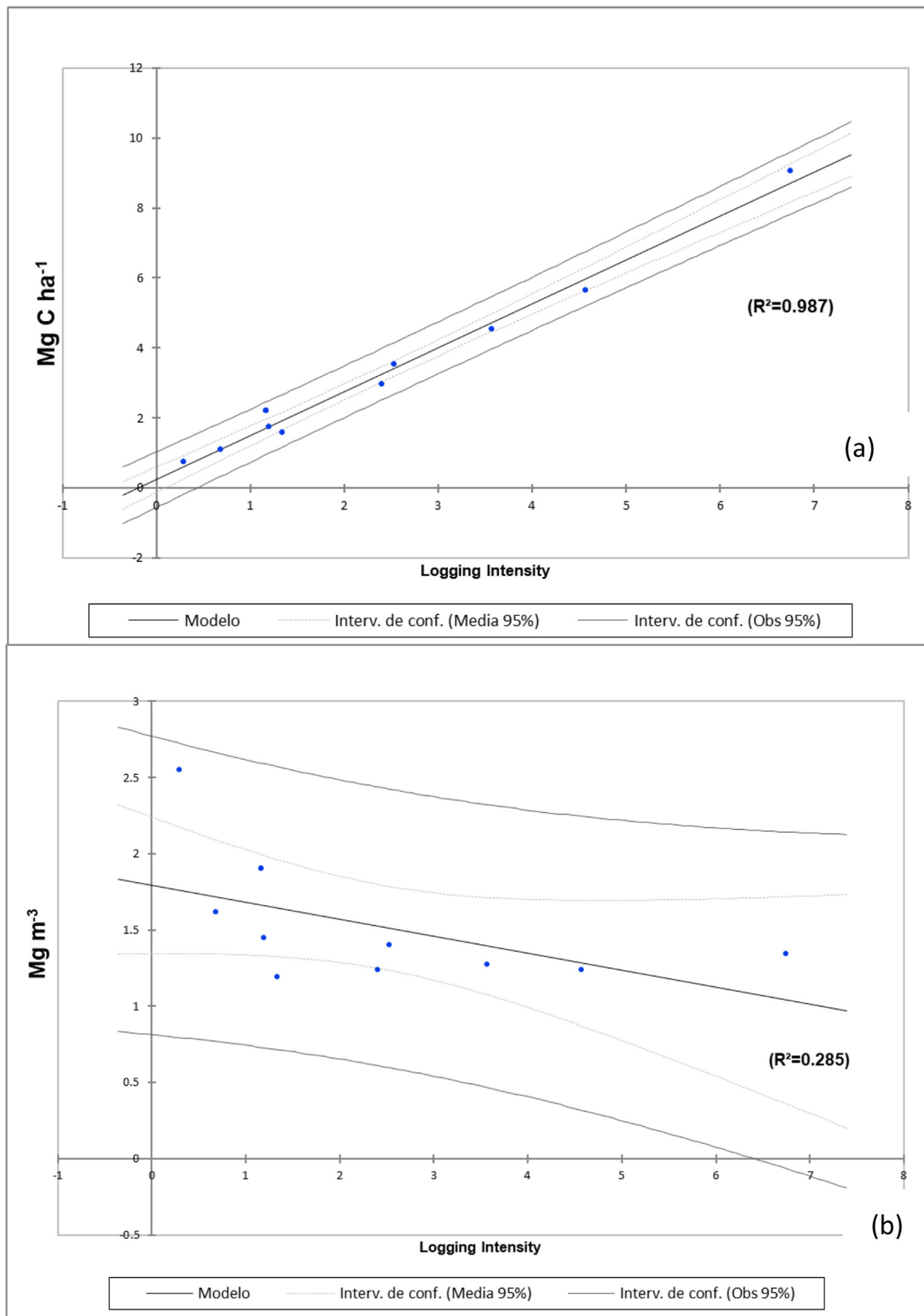


Fig. 3. Carbon emissions per area of ACA (Mg ha^{-1}) were strongly related to logging intensity (LI) expressed as cubic meters of timber harvested per hectare (a), but carbon emissions per volume of harvested timber (Mg m^3) were not strongly related to LI (b).

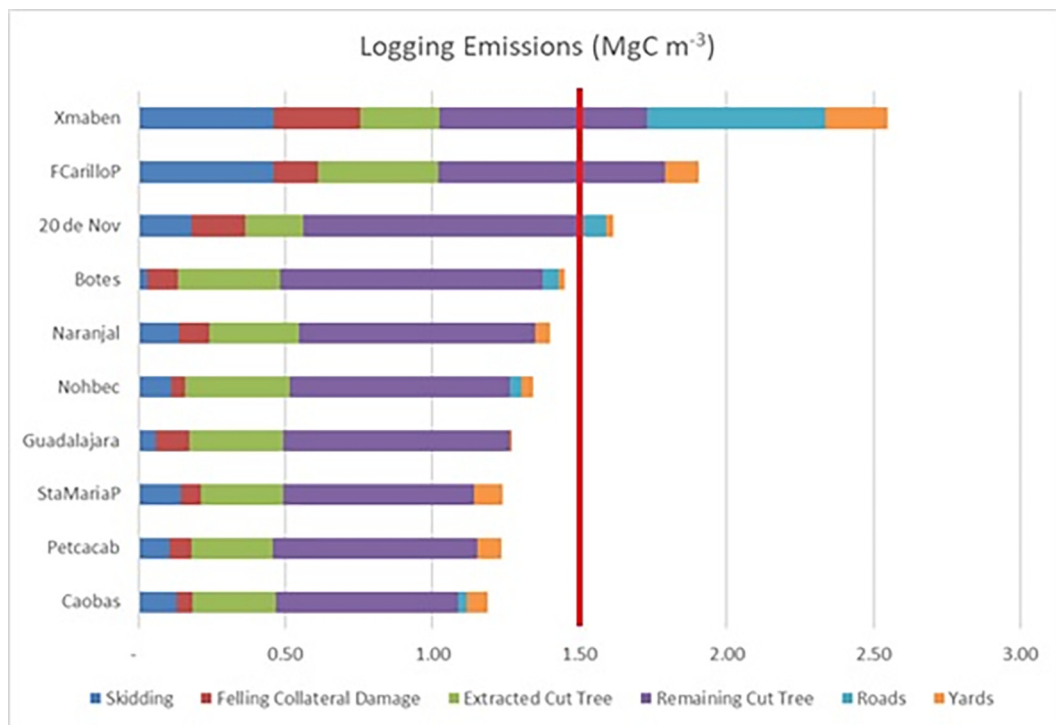


Fig. 4. Carbon emissions (Mg m^{-3}) from selective logging operations in community forestry ejidos on the Yucatan Peninsula. The red line indicates the total impact baseline calculated as the mean total emissions (Mg m^{-3}) of all ten ejidos.

cutting lianas prior to harvesting (at least 6 months). Again, as in the overall results, X-Maben and 20 de Noviembre had high carbon emissions per tree felled.

The mixed model type II results for the number of damaged trees per tree felled show that all fixed effects considered contributed to the model: FSC [$F(1, 4) = 31.18, p = 0.005$], DF [$F(1, 4) = 18.02, p = 0.013$], ACA [$F(1, 4) = 8.75, p = 0.042$] and LI [$F(2, 4) = 17.39, p = 0.011$]. In contrast, model parameters (Table 6) show that the most influential and significant variable was DF, indicating that ejidos that applied DF during felling damaged significantly fewer trees [$t = 7.78, p < 0.001$]. The model also shows that ejidos with high LI also damaged less trees per tree felled [$t = 5.78, p = 0.004$]. Tukey (HSD) comparisons show that there were no differences between ejidos with and without FSC certification ($p = 0.19$) or ejidos with large or small ACAs ($p = 0.14$). However, as reflected in the mixed model results, Tukey (HSD) comparisons show ejidos that implemented DF damaged fewer trees ($p = 0.001$), and ejidos with high intensities also damaged fewer trees than ejidos with medium ($p = 0.013$) and low ($p = 0.017$)

intensities. Ejidos applying DF on average damaged four fewer trees per tree felled, and ejidos with high LI damaged on average two more trees per tree felled. With respect to carbon emissions per tree felled the mixed model type II results indicated that the fixed effects did not contribute to the model: FSC [$F(1, 4) = 2.56, p = 0.185$], DF [$F(1, 4) = 1.94, p = 0.236$], ACA [$F(1, 4) = 0.79, p = 0.792$] and LI [$F(2, 4) = 0.56, p = 0.61$] and mixed model parameters also showed no significance of the explanatory variables (Table 7). Tukey (HSD) also failed to show significant differences among FSC, DF, ACA and LI categories.

3.4. Skidding emissions

The number of damaged trees per 10 m long skid trail plot in ejidos ranged from 1.3 to 4.1, and the three ejidos that used a modified agricultural tractor for log yarding (MT) damaged the lowest numbers (Table 8). These results indicate that use of modified agricultural tractors for skidding can reduce forest impacts by more than 100 trees

Table 4

Carbon emissions per unit volume of timber extracted (Mg m^{-3}) from felling, skidding and logging infrastructure (log landings and roads) in sampled ejidos ordered from lowest to highest. F-RW = felled roundwood harvested, F-HTR = felled tree remnants in forest, CD = collateral damage from felling, S = skidding, L = log landings, R = haul roads, E = RW + HTR + CD + S + L + R.

Ejido	F-RW (% E)	F-HTR (% E)	F-CD (% E)	S (% E)	L (% E)	R (% E)	E
Caobas	0.28 (23.7)	0.62 (52.1)	0.05 (4.6)	0.13 (11.0)	0.07 (6.1)	0.03 (2.5)	1.19
Petacab	0.27 (22.2)	0.70 (56.2)	0.07 (6.0)	0.11 (8.7)	0.09 (6.9)	0.00	1.24
Sta. Ma. Poniente	0.28 (22.5)	0.65 (52.5)	0.07 (5.4)	0.15 (11.8)	0.10 (7.9)	0.00	1.24
Guadalajara	0.32 (25.1)	0.77 (60.5)	0.12 (9.1)	0.06 (4.6)	0.01 (0.7)	0.00	1.27
Nohbec	0.36 (26.5)	0.75 (60.0)	0.04 (3.3)	0.11 (8.5)	0.04 (3.0)	0.04 (2.8)	1.34
Naranjal	0.30 (21.6)	0.80 (57.4)	0.11 (7.6)	0.14 (9.7)	0.05 (3.7)	0.00	1.40
Botes	0.35 (23.9)	0.89 (61.5)	0.10 (7.2)	0.03 (2.1)	0.02 (1.6)	0.05 (3.7)	1.45
20 de Noviembre	0.20 (12.3)	0.95 (58.6)	0.18 (11.3)	0.18 (11.1)	0.03 (1.6)	0.08 (5.1)	1.62
Felipe Carrillo Pto.	0.41 (21.5)	0.77 (40.6)	0.15 (7.9)	0.46 (24.1)	0.11 (5.9)	0.00	1.90
Xmaben	0.27 (10.6)	0.71 (27.7)	0.29 (11.5)	0.46 (18.1)	0.21 (8.4)	0.61 (23.7)	2.55
Baseline	0.30 (21.0)	0.76 (52.3)	0.12 (7.4)	0.18 (11.0)	0.07 (4.6)	0.08 (3.8)	1.52
Mean							

Table 5

Numbers of damaged trees and carbon emissions from felling collateral damage (CD) in community forestry ejidos ordered from lowest to highest emissions (Mg of C) and indicating forest management characteristics of ejidos. ACA = annual cutting area, LI = logging intensity, SD = standard deviation, HT = harvest tree.

Ejido	ACA	LI	RIL-C felling practice	Mean # damaged trees per tree felled (SD)	Total # damaged trees (# ha ⁻¹)	Mean DBH of damaged trees (SD)	Mean Mg of C from CD per tree felled (SD)
<i>Noh Bec</i>	Large	High	DF	5.1 (2.5)	3740 (21)	9.2 (4.5)	0.08 (0.09)
<i>Petacab</i>	Large	High	DF	4.5 (2.0)	2299 (8.5)	11.0 (6.1)	0.12 (0.18)
<i>Caobas</i>	Large	Low	DF	3.0 (1.8)	1404 (1.6)	15.2 (7.1)	0.13 (0.17)
<i>Santa María Poniente</i>	Small	Medium	None	5.2 (2.3)	962 (5.1)	12.1 (6.2)	0.16 (0.16)
<i>Felipe Carrillo Puerto</i>	Large	Low	None	6.1 (2.7)	2678 (11.1)	10.9 (5.1)	0.16 (0.14)
<i>Naranjal Poniente</i>	Small	Medium	None	5.6 (2.8)	2358 (20.3)	11.2 (6.3)	0.21 (0.05)
<i>Botes</i>	Small	Low	None	5.1 (2.0)	984 (3.2)	11.7 (6.9)	0.26 (0.02)
<i>Guadalajara</i>	Small	Medium	None	5.8 (3.6)	1908 (7.1)	14.0 (10.0)	0.32 (0.62)
<i>X-Maben (Campeche)</i>	Small	Low	None	6.4 (2.2)	922 (2.2)	12.2 (7.8)	0.34 (0.53)
<i>20 de Noviembre</i>	Large	Low	None	7.2 (2.1)	2436 (2.4)	16.3 (7.2)	0.34 (0.24)

Table 6

Mixed model parameters for number of damaged trees per felled tree with FSC, DF, ACA and LI as fixed factors. ACA = annual cutting area, LI = logging intensity, SD = standard deviation, HT = harvest tree.

Source	Coefficient	Standard error	GL	t	Pr > t
Intercept	5.756	0.374	480	15.397	< 0.0001
FSC-NO	0.000				
FSC-YES	0.558	0.352	4	1.585	0.188
DF-NO	0.000				
DF-YES	-4.181	0.537	4	-7.781	0.001
ACA-SMALL	0.000				
ACA-LARGE	0.867	0.472	4	1.837	0.140
LI-LOW	0.000				
LI-MED	-0.209	0.434	4	-0.481	0.655
LI-HIGH	2.129	0.362	4	5.877	0.004

Table 7

Mixed model parameters for carbon emissions per felled tree with FSC, DF, ACA and LI as fixed factors. ACA = annual cutting area, LI = logging intensity, SD = standard deviation, HT = harvest tree.

Source	Coefficient	Standard error	GL	t	Pr > t
Intercept	0.281	0.063	480	4.476	< 0.0001
FSC-NO	0.000				
FSC-YES	-0.035	0.108	4	-0.323	0.763
DF-NO	0.000				
DF-YES	-0.077	0.145	4	-0.531	0.624
ACA-SMALL	0.000				
ACA-LARGE	-0.035	0.086	4	-0.411	0.702
LI-LOW	0.000				
LI-MED	-0.074	0.079	4	-0.938	0.401
LI-HIGH	-0.053	0.109	4	-0.492	0.648

km⁻¹. Skid trail carbon emissions in measured plots ranged 0.01–0.09 Mg per 10 m. Four of the five lowest carbon impacts (< 5Mg C km⁻¹ of skid trail) were measured in ejidos with MT and/or STP.

Table 8

Damaged trees and carbon emissions (S) from 10 m long skid trails plot ordered from lowest to highest with relevant forest management characteristics of the ejidos.

Ejido	ACA	LI	RIL-C practices	Mean # damaged trees/plot (SD)	# Damaged trees km ⁻¹	Mean DBH (SD)	Mean Mg of C/plot (SD)	Mg C km ⁻¹
<i>Botes</i>	Small	Low	MT	1.3 (1.1)	129	7.8 (5.4)	0.01 (0.02)	1
<i>Guadalajara</i>	Small	Medium	MT	1.5 (1.1)	150	8.9 (4.5)	0.03 (0.04)	3
<i>Naranjal Poniente</i>	Small	Medium	None	2.4 (2.0)	240	7.7 (4.3)	0.04 (0.05)	4
<i>Petacab</i>	Large	High	STP	3.6 (1.5)	360	8.8 (3.5)	0.04 (0.03)	4
<i>Caobas</i>	Large	Low	MT STP	2.0 (1.4)	200	16.5 (12.3)	0.05 (0.04)	5
<i>Noh Bec</i>	Large	High	STP	3.8 (1.8)	380	9.3 (3.7)	0.07 (0.06)	7
<i>Felipe Carrillo Puerto</i>	Large	Low	None	3.3 (1.7)	330	9.1 (4.3)	0.08 (0.10)	8
<i>Santa María Poniente</i>	Small	Medium	None	4.1 (2.5)	410	8.8 (4.0)	0.08 (0.07)	8
<i>X-Maben (Campeche)</i>	Small	Low	None	3.5 (1.9)	350	10.2 (4.7)	(0.09) (0.07)	9
<i>20 de Noviembre</i>	Large	Low	None	5.5 (1.9)	550	8.9 (4.5)	0.09 (0.6)	9

Table 9

Mixed model parameters for number of damaged trees from skidding with FSC, DF, ACA and LI as fixed factors. ACA = annual cutting area, LI = logging intensity, SD = standard deviation, HT = harvest tree.

Source	Coefficient	Standard error	GL	t	Pr > t
Intercept	1.421	0.437	157	3.248	0.001
FSC-NO	0.000				
FSC-YES	0.200	0.713	4	0.281	0.793
MT-YES	0.000				
MT-NO	1.917	0.429	157	4.466	< 0.0001
STP-NO	0.000				
STP-YES	-0.897	0.988	4	-0.907	0.416
ACA-SMALL	0.000				
ACA-LARGE	0.910	0.559	4	1.629	0.179
LI-LOW	0.000				
LI-MED	-0.017	0.485	4	-0.035	0.974
LI-HIGH	0.248	0.756	4	0.328	0.759

Again, carbon emissions were lowest in Botes and Guadalajara where MTs were used exclusively.

Mixed model Type II results show that MT was the sole contributor to the model: FSC [$F_{(1, 3)} = 0.44$, $p = 0.555$], MT [$F_{(1, 3)} = 36.43$, $p = 0.009$], STP [$F_{(1, 3)} = 0.023$, $p = 0.888$], ACA [$F_{(1, 3)} = 4.2$, $p = 0.131$] and LI [$F_{(2, 3)} = 0.013$, $p = 0.987$] and model parameters (Table 9) also show that MT was the most significant variable ($p = 0.027$), showing that ejidos that did not use MT damaged more trees by skidding. All other variables (FSC, STP, ACA and LI) were not significant in the model. Tukey (HSD) tests also confirm that the only differences in skidding emissions were between ejidos that used MT and those that did not ($p = 0.027$), with no effects of the other fixed variables detected (FSC, STP, ACA and LI). Mixed model results for carbon impacts from skidding were similar. Type II test results showed that MT was the most influential fixed effect and all other were not significant: FSC [$F_{(1, 3)} = 0.004$, $p = 0.953$], MT [$F_{(1, 3)} = 6.37$, $p = 0.086$], STP [$F_{(1, 3)} = 1.178$, $p = 0.357$], ACA [$F_{(1, 3)} = 0.094$, $p = 0.78$] and LI

Table 10

Mixed model parameters for carbon emissions from skidding with FSC, DF, ACA and LI as fixed factors. ACA = annual cutting area, LI = logging intensity, SD = standard deviation, HT = harvest tree.

Source	Coefficient	Standard error	GL	t	Pr > t
Intercept	1.421	0.437	157	3.248	0.001
FSC-NO	0.000				
FSC-YES	0.200	0.713	4	0.281	0.793
MT-MT	0.000				
MT-NONE	1.917	0.429	157	4.466	< 0.0001
STP-NONE	0.000				
STP-STP	-0.897	0.988	4	-0.907	0.416
ACA-SMALL	0.000				
ACA-LARGE	0.910	0.559	4	1.629	0.179
LI-LOW	0.000				
LI-MED	-0.017	0.485	4	-0.035	0.974
LI-HIGH	0.248	0.756	4	0.328	0.759

[$F_{(2, 3)} = 0.319$, $p = 0.749$]. Mixed model parameters of carbon impacts from skidding (Table 10) also show that ejidos not using MT had somewhat higher emissions although not significant at the 5% level ($p = 0.092$). Tukey (HSD) tests failed to detect differences between all fixed effect categories.

3.5. Bosquete impacts

In the additional 10 multiple-tree felling sites sampled in Noh Bec (bosquetes) carbon emission from CD was higher (0.1 Mg m^{-3}) than in the single-tree gaps of the same ejido (0.04 Mg m^{-3}), but this was offset by lower HTR carbon emissions (0.67 Mg m^{-3}) compared to the single tree gaps (0.75 Mg m^{-3} of C). Skidding and hauling emissions were identical, since the same infrastructure was used to access bosquetes as single-tree gaps.

4. Discussion

4.1. Carbon emissions from selective logging on the Yucatan Peninsula

We evaluated forest disturbance and carbon emissions from selective logging in ten ejidos on the Yucatan Peninsula to establish baselines from which to assess potential emissions reductions from implementing RIL-C practices. Results from this study should facilitate monitoring and implementing carbon credit programs for community forestry enterprises in the region. The per hectare total carbon emission baseline we measured (3.3 Mg ha^{-1}) was much lower than the lowest values reported by Pearson et al. (2014) for Brazil (7 Mg ha^{-1}), and our highest carbon emissions (9.0 Mg ha^{-1}) was threefold lower than the highest values reported for Indonesia (51 Mg ha^{-1} ; Griscom et al., 2014; Pearson et al., 2014) and Guyana (30 Mg ha^{-1} ; Pearson et al., 2014). We found a very strong positive correlation ($R^2 = 0.98$) between emissions per hectare and logging intensity ($\text{m}^{-3} \text{ ha}^{-1}$), as also noted by Griscom et al. (2014) and Pearson et al. (2014) and reported previously for Indonesia (Bertault and Sist, 1997) and Guyana (Blanc et al., 2009). The low observed per hectare emissions from selective logging on the Yucatan Peninsula need to be interpreted in terms of the very low logging intensities; the overall mean intensity for the 10 ejidos was only $1.4 \text{ trees ha}^{-1}$ and $2.4 \text{ m}^3 \text{ ha}^{-1}$ with maxima of 4 trees ha^{-1} and $8 \text{ m}^3 \text{ ha}^{-1}$. These intensities are far lower than the recommended maxima suggested by researchers concerned about the effectiveness of RIL (8 tree ha^{-1} ; Sist et al., 2003; Roopsind et al., 2018) and maintenance of biodiversity ($10 \text{ m}^3 \text{ ha}^{-1}$; Burivalova et al., 2014).

On the Yucatan Peninsula, the mean carbon emissions per volume of harvested timber (1.5 Mg m^{-3}) was midway among the 0.99 to 2.33 Mg m^{-3} values reported by Pearson et al. (2014) for forests across the tropics that varied in biomass, standing stocks of timber, logging intensity, and the sizes and wood densities of harvested trees, all factors

that can influence carbon impacts from selective logging. However, as in the Griscom et al. (2014) study in Indonesia, we also observed large regional variation in total emissions from selective logging (1.2 – 2.5 Mg m^{-3}). In our logging landscape, ejidos varied in forest types, biomass and management characteristics such as logging intensity, size of ACA and application of improved practices. In this study, all the sampled ejidos were in their second 25-year logging cycle and may have been logged prior to the 1980s by the parastatal concession MIQRO (Ellis et al., 2014a). A long history of forest use and management, natural and anthropogenic disturbances, and environmental differences among the sampled ejidos explain the large variations in forest biomass, structure and composition, which also influence harvested species and volumes extracted (Ellis et al., 2015). This landscape-level diversity needs to be considered when assessing carbon emissions as well as when implementing landscape-scale conservation and development strategies.

4.2. Variation in carbon emissions and RIL-C practices among ejidos

Differences in forest environments and current and historical forest management interventions complicate the assessment of carbon emissions with respect to implementation of RIL-C practices. On the Yucatan Peninsula, ejidos often manage their forests for a diversity of products, not exclusively timber; some ejidos harvest primarily large diameter trees of high-value timber with medium to high wood densities, such as mahogany and chicozapote, while others harvest common species of smaller size classes and lower wood densities for charcoal and polewood (Sierra-Huelsz et al., 2017). Further complicating RIL-C performance assessments is the fact that RIL has never been researched and piloted in Mexico as it has in other tropical countries such as Malaysia, Guyana, Gabon and Brazil (e.g., Putz et al., 2008a; Blanc et al., 2009; Medjibe et al., 2013; Vidal et al., 2016). Although improved forest management, sustained yields, and biodiversity conservation are pursued in the region, RIL is still an acronym that is pretty much absent from the vocabulary of community foresters and forestry institutions in Mexico. And while dozens of forest management plans developed for ejidos in our logging landscape mention the application of improved practices such as DF and STP, the reality on the ground is that very few implement them. Surprisingly, even though the Yucatan Peninsula has been globally recognized since the 1980s for its cases of successful and sustainable community-based forest management, it still lacks genuine RIL extension efforts.

RIL-C practices, such as DF and STP, are implemented by some ejidos, but mostly because of their pursuit of FSC certification coupled with training programs, outside of a larger RIL extension endeavor. As mentioned above, the particular ejidos associated with FSC and involved with PPF (Noh Bec, Caobas, Petcacab) have also been central in the development of community forest management in the region. Key PPF impacts on forestry in the region pertain to the creation of permanent forest areas, devolved forest management authority to the ejidos, and the establishment of six community forestry enterprises including the purchase of sawmills and extraction machinery (Wilshusen, 2005). These three ejidos mentioned above, along with Tres Garantias, Chacchoben, and Nuevo Guadalajara, were the six main beneficiaries of the PPF project during the 1980s and 1990s. However, our results show that other ejidos with a history of involvement with major local silvicultural organizations (*Sociedad de Productores Forestales de Quintana Roo S.C.* and *Organizacion Ejidal de Productores Forestales de la Zona Maya S.C.*), also performed relatively well and were not FSC certified (e.g. Santa Maria Poniente), but may have been certified or pursued certification in the past (e.g. Naranja, Botes and Guadalajara). Improved forest management and RIL practices (although not labeled as such), which were initiated by the PPF and followed through by these forestry institutions a decade before the first FSC certified ejidos, may have been central in reducing forest impacts from selective logging in the region. With respect to the recent practice of using MT,

which this study shows substantially reduces skidding emissions, the ejidos that opted for this technology did so because it reduces costs and eliminates the need to out-source skidding operations or to sell standing timber directly to buyers who then organize all harvest operations. For ejidos with small ACAs, MTs are an appropriate skidding technology. Our results indicate that rather than FSC certification, it is RIL practices that reduce carbon emissions, benefits that may be maintained in most ejidos due to their experience and association with community forestry associations since the PPF project. Even though some of these ejidos have medium to high logging intensities, the implementation of RIL-C practices such as DF, STP and MT reduced their carbon emissions from timber harvest operations.

Despite variation among ejidos in logging-induced carbon emissions, this research demonstrated similar patterns in carbon impacts as in other tropical regions where selective logging is used. Our results also affirm that the majority of carbon emissions (73%) originate from the harvested trees (Griscom et al., 2014; Pearson et al., 2014), as the timber removed (21%) and the remnants of crowns and branches left in the forest (52%). Thus, to reduce carbon emissions from selective logging effectively and efficiently, attention is warranted to felling and bucking practices that result in greater timber recovery from trees felled for that purpose (e.g., lower stumps). These practices are hardly considered by most logging operations on the Yucatan Peninsula, although recently markets have developed for smaller and irregular bole parts and large branches for handicrafts.

Among the ten ejidos for which we measured selective logging-induced carbon emissions, three performed particularly badly (Felipe Carrillo Puerto, Xmaben and 20 de Noviembre). These poor performers did not implement any RIL-C practices and logged at the lowest intensities. In the worst-case ejido in terms of carbon emissions (2.5 Mg m^{-3}), we learned during field work that the ejido was going to suspend its forestry operations due to internal governance and management problems. Instead of carrying out the logging themselves, they had arranged for the buyer to enter the forest and harvest the agreed species and volumes, which consisted of a small volume of high-value species and was done in a visibly reckless manner. In contrast, the best performers had mostly adopted at least one of the three RIL-C practices we tracked, although in the case of Santa Maria Poniente, the ejido was not documented as implementing RIL-C during the 2014 harvest. Generally, most ejidos performed well and differences in harvest intensities were not associated with carbon impacts below the baselines. For example, Petcacab, which is in process of returning to FSC certification, had the second highest logging intensity but also the second lowest carbon emissions. On the other hand, Noh Bec with the highest logging intensity ($6.7 \text{ m}^3 \text{ ha}^{-1}$) and a large ACA ($> 500 \text{ ha}$), performed midway despite having the most experience with FSC certification, implementation of improved practices and well-organized and planned harvest operations, strategically establishing log landings, roads, and main skid trail networks in their ACAs. Caobas, the other FSC certified ejido, also has a large ACA but harvested at low intensity ($1.1 \text{ m}^3 \text{ ha}^{-1}$) and had the lowest carbon emissions per cubic meter of timber extracted. Loggers in Caobas very efficiently reduced harvest waste and minimized collateral damage by applying DF and STP RIL-C practices, but also by using a MT during harvest operations. Small CFM ejidos that belonged to a prominent forestry organization, such as Guadalajara (previously FSC certified) and Botes (which had undergone FSC certification audit but was never certified), were also good performers, and controlled their emissions from skidding through use of a modified agricultural tractor (MT), the only RIL-C practice they implemented. Several other ejidos with small ACAs ($< 500 \text{ ha}$) and medium logging intensities (from 2 to $4 \text{ m}^3 \text{ ha}^{-1}$) showed low emissions but without the obvious implementation of RIL-C practices, which argues for the importance of the tradition and experience of proper forest management by some forest communities and their technicians. Overall, it is important to keep in mind that given the lack of support for climate change mitigation, minimizing carbon emissions is not among the many

goals of forest managers in the region. When these emissions are minimized, it is for other reasons.

As mentioned above, not only are harvest intensities very low in our logging landscape compared to other tropical countries, harvest volumes are often less than half of what is permitted. Explanations for these conditions are complex and involve environmental, institutional, cultural and economic barriers to increased production. Understanding and overcoming these barriers could contribute substantially to the economic benefits from small-scale community forestry enterprises in the region while maintaining carbon stocks. Our results are assuring, in the sense that community forestry ejidos on the Yucatan have the potential to increase their timber volumes and logging intensities and at the same time reduce carbon emissions by applying RIL-C practices.

4.3. Potential reduction of carbon emissions with RIL-C practices

Given that impacts from felling and skidding still constitute substantial portions of carbon emissions from selective logging in our study region (7.4% and 11.0%, respectively), any improvements in these activities are important. Comparisons of felling and skidding impacts in sampled ejidos may answer the question of why emissions from some ejidos with medium-to-high logging intensities are lower per cubic meter of timber harvested than in the three ejidos that log at very low intensities. With regards to felling, all three ejidos that implemented DF (Noh Bec, Petcacab and Caobas) damaged the least number of trees (3–5) and had the lowest carbon impacts (0.08 – 0.13 Mg) per tree felled.

The greatest differences in damaged trees and emissions per felled tree were found between ejidos that implemented DF and those that did not. Caobas, the only ejido that cut lianas on trees to be felled prior to harvesting, had the least damage and emissions from felling, demonstrating the potential of including this practice in a package of RIL-C practices. Differences between large and small ACAs are small, but low logging intensity ejidos damaged more trees and showed higher carbon impacts from felling. These results suggest that the practice of DF rather than reduced logging intensity is responsible for reductions in collateral damage from felling. As noted above, other ejidos (e.g., Botes and Santa María Poniente) did not implement DF but nevertheless performed relatively well, which shows the difficulty in determining when and to what extents RIL-C practices (e.g., DF) are actually implemented.

The skidding emissions data demonstrate that all ejidos that used MT, implemented STP, or both, in the case of Caobas, performed well. Botes and Guadalajara, the only two ejidos that used MT exclusively, were the two best performers, with skid trail carbon emissions half or less than the average (1 and 3 Mg km^{-1} , respectively versus 6 Mg km^{-1}). The potential to reduce skidding carbon emissions by 5 Mg km^{-1} is worthy of attention. The carbon emission reduction potential of STP was less (3 Mg km^{-1}) but still large. Again, this indicates that on the Yucatan Peninsula it is not the intensity of logging that results in lower carbon emissions, but instead how the harvesting is done (Bicknell et al., 2014). The potential of RIL-C practices to reduce carbon emissions from selective logging by ejidos on the Yucatan Peninsula is well demonstrated by this research, but the other benefits of these practices deserve attention. Directional felling, for example, can reduce damage to future crop trees (Galante et al., 2012) and improved bucking techniques can increase the volume of wood obtained from felled trees and thereby increase economic gains. As mentioned earlier, the use of MT reduces costs of skidding and dependence on external contractors. Proper planning of skid trails, log landings and haul roads also reduce the costs of timber harvesting and any subsequent silvicultural treatments. There are also many biodiversity benefits of RIL that deserve attention (Burivalova et al., 2014; Bicknell et al., 2014).

Despite the rewards that adoption of RIL practices can bring ejidos, Mexico, and the world, there are still barriers that could explain why few ejidos on the Yucatan Peninsula do so. The presumed market benefits of FSC certification could motivate adoption of RIL practices insofar as those practices are required by FSC auditors. Despite the

major focus in the past five years by CONAFOR and international institutions (e.g. PNUD, Rainforest Alliance) on promotion of forest certification in the region, up to this date (late 2018), only Petcacab, which was enroute to certification when we sampled it in 2015 and one more ejido we did not sample, became certified, totaling four in our study area. The costs of certification are clearly an obstacle that only larger ejidos with larger management operations and harvest volumes can overcome. More generally, for the majority of smaller and less productive ejidos there is still insufficient institutional and financial support to promote RIL and other improved forest management practices. This condition is particularly unfortunate given that extension services and training for some practices such as DF and STP are inexpensive. Credit or subsidies to purchase smaller forestry or modified agricultural tractors (MT) could also be a cost-effective mechanism to promote RIL and to increase timber production and profits for smaller ejidos while reducing deleterious carbon and biodiversity impacts. CONAFOR and other institutions do provide subsidies for improved forest management, but they benefit mostly the larger and more productive ejidos.

Efforts to reduce stand damage caused by selective logging on the Yucatan Peninsula face a paradox that emerges because most of the high-value timber species are light demanding (Fredericksen and Putz, 2003). Of these species that require large canopy openings to regenerate, mahogany, is the best known (e.g., Snook, 2005a, 2005b) but there are others, including Spanish cedar and tzalam (*Lysiloma baha-mensis*). To promote regeneration of these species, large canopy gaps created by felling multiple trees (*bosquetes*) are considered ideal (Navarro-Martínez et al., 2017), but the creation of such openings releases substantial carbon. These *bosquetes* are further cleaned and reforested with high-value and light-demanding timber species such as mahogany and ciricote (*Cordia dodecandra*); if the planted trees grow quickly, the carbon debt is at least partially repaid, but only over several decades. Where RIL-C practices are not employed, the resulting hurricane-mimicking damaged areas, such as the wide skid trails, roads, and log landings, are also suitable sites for both natural regeneration and enrichment planting. Our research demonstrated that in *bosquetes*, the increased carbon impacts from collateral damage could be offset by the improved bucking of HT remnants. The integration of these multiple-tree felling gaps alongside conventional selective logging applying RIL-C practices can still result in substantial carbon emission reductions.

A new development in silvicultural practices is underway on the Yucatan that involves a severe tradeoff between timber production and carbon sequestration. Recently piloted in two ejidos with small trees and a scarcity of high-value timber, the silvicultural system calls for clearcutting patches of up to 3 ha and commercializing the cut trees as polewood, charcoal, and saw timber (Negreros-Castillo et al., 2018). The clearcuts are then to be planted with seedlings of commercial timber species, but the future yields, carbon dynamics, and biodiversity impacts of this new system are not known. A small clear-cut silvicultural system in the tropics is bound to bring some challenges for implementation of RIL. In contrast, this study demonstrates that use of RIL-C practices in more traditional selective logging for shade tolerant species combined with multiple-felling gaps to regenerate shade-intolerant species while maintaining logging intensities $< 10 \text{ m}^3 \text{ ha}^{-1}$ could reduce carbon emissions, increase production, and conserve biodiversity in large portion of the Yucatan Peninsula's forests.

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