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Opportunities for carbon emissions reduction from selective logging in Suriname

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1. Introduction

Improved forest management practices in tropical forests managed for timber can make a large contribution to climate change mitigation efforts (Houghton and Nassikas, 2018; Putz and Pinard, 1993). Well-managed tropical forests retain more carbon in vegetation and soils (e.g., Johns et al., 1996; Pinard & Putz, 1996) and more rapidly sequester carbon after logging (Roopsind et al., 2018; Vidal et al., 2016). Under the Paris Climate Accord, tropical countries can apply these reduced carbon emissions from improvements in forest management to meet their nationally determined commitments (NDCs; UNFCCC, 2013). Where selective logging is the principal forestry practice, these emission reductions could come from switching from conventional timber harvests to logging that includes a suite of reduced-impact logging (RIL) practices with trained forestry personnel (Sasaki et al., 2016). Emissions reductions achieved from improved forest management would be eligible for compensation under existing climate financing schemes, such as voluntary carbon markets (VCS, 2016) and the UN-REDD+ program (FCPF, 2018).

To claim emissions reductions payments from improved forest management, accurate and consistent methodologies are required to measure performance relative to an established forest reference emission level (FREL). A FREL sets the baseline against which emissions reduction targets are established and for subsequent monitoring under performance-based carbon payment programs (Angelsen, 2012; UNFCCC, 2013). In this study, we apply an emission assessment protocol (Ellis et al., in press) developed for selective logging to establish Suriname's FREL (Government of Suriname, 2018). This emission assessment protocol was piloted in Kalimantan Indonesia (Griscom et al., 2014) and subsequently approved for use by the Voluntary Carbon Standard (VCS, 2016). We complement the Griscom et al., (2014) protocol with elements from the FREL methodology developed by Winrock International for logging emissions in Guyana, Brazil, Belize, and Gabon (Brown et al., 2014; Pearson et al., 2014).

1.1. Forest management in Suriname

Suriname is a high forest cover low deforestation country, with the highest forest cover in the world at 93% (15.2 million hectares) and an annual deforestation rate assessed between 2000 and 2012 at 0.04% (5676 ha yr;$^{-1}$ SBB, 2017). Logging in Surname is a major economic activity and is characterized by the selective removal of high-value tree species. Logging results primarily in forest degradation and is the second largest source of carbon emissions after deforestation from gold mining in Suriname (Government of Suriname, 2018). In order to improve forest management and reduce forestry related emissions, Suriname has proposed RIL guidelines embedded in a draft national logging code of practice to be applied across all forest management enterprises (van der Hout, 2011).

These forest management enterprises, whether community forests or industrial concessions leased from the government, are divided into forest harvesting units (FHUs, or "kapvaks" in Dutch) which are approximately 100 ha from which timber can be harvested for 2 years. Average timber production is estimated at 8.80 m^3 ha^{-1} with a maximum allowable harvest of 25 m^3 ha^{-1} at logging rotations of 25 years (SBB, 2017; Werger, 2011). Harvesting practices in FHUs are categorized into three management systems: (1) conventional logging, where there is no forest management planning, including no pre-harvest forest inventory; (2) controlled logging, where forest management plans are prepared prior to timber harvests; and (3) controlled logging certified by the Forest Stewardship Council (FSC), hereafter referred to as FSC-logging that includes application of a broader suite of sustainable forest management practices (Table 1). Rules regarding protected species and minimum felling diameter are applicable to all three logging types, but other recommended RIL practices such as directional felling and winching are not mandated across all FHUs.

Conventional logging is usually permitted in areas where there is a possibility that overlapping land-use claims (e.g., sub-surface alluvial gold mining) could preclude sustainable forest management or, in the case of very small-scale community operations, where license holders lack the capacity and/or capital for intensive pre-harvest planning.

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Table 1
Forest management systems applied in Suriname (conventional logging, controlled logging, and FSC-logging) and their associated forest management guidelines and logging practices (NIMOS et al., 2017).

Management Type	Pre-harvest timber inventory	Skid trail and road planning	Forest management plans/annual harvest plans	Maximum allowable harvest (25 m^3/ha)	Minimum harvest cycle (25 years)	Third-party audits	Additional RIL practices (directional felling, winching, liana cutting)
Conventional logging (C)	No	No	No	√	√	No	No
Controlled logging (R)	√	√	√	√	√	No	Not strictly applied
FSC logging (FSC)	√	√	√	√	√	√	√

Controlled logging is done according to the national legal RIL requirements (e.g., pre-harvest inventory and preparation of harvest plans; (van der Hout, 2011) and the FSC certified concessions are required to apply a higher level of RIL practices that include trained forestry personnel. These three logging systems are coded as C, R and FSC for conventional, controlled and FSC-logging respectively (Table 1). In addition to variation among management systems applied at the FHU level, there is also variation in logging machinery (e.g., skidders, bulldozers, excavators) utilized, as well as in the technical skills of forestry workers.

In 2016 there was approximately 2 million ha of forests issued to forest management enterprises with annual active production areas of 32,328 ha (283 FHUs) classified under conventional logging and 18,134 ha (185 FHUs) under controlled timber harvests, and an estimated 6200 ha (62 FHUS) under FSC-logging (SBB, 2017). This study is an input to Suriname's determination of its FREL for development of its National REDD+ program. We hypothesized that logging systems that apply more RIL practices would have lower emissions per cubic meter of wood harvested, with emissions highest in FHUs under conventional logging, intermediate in FHUs under controlled logging, and lowest in the FSC-logged FHUs.

2. Methods

2.1. Study sites and sampling design

The study was conducted in the 50–200 km-wide lowland tropical forest belt of Suriname that stretches East-West just above the 4° N parallel (Fig. 1). In 2017 we assessed carbon emissions in 10 logged FHUs across the different forest management systems; conventional logging (N = 4), controlled logging (N = 4), and FSC-logging (N = 2). As there were only 2 FSC certified forest management enterprises at the time of the field surveys, we decided to sample both and spread the other 8 sampling locations over the other 2 management types in several different forest management enterprises. We randomly selected FHUs that met the following criteria: (1) the FHU was logged less than 6 months prior to emissions assessment (to ensure logging impacts were still visible); (2) all harvest operations were completed and legal access would not occur until the next harvest; and, (3) there was no evidence of other land uses, especially gold mining. The exclusion of mined areas prevented emissions inflation from disturbance not due to logging.

We sampled a randomly selected half (50 ha) of each sampled FHU, except the first FHU, which we sampled in its entirety (100 ha) during the development and testing of the sampling protocol. We categorized carbon emissions from logging into the following sources: (1) extracted log emissions (ELE) - carbon removed from the forest in the extracted section of the felled tree; (2) logging damage factor (LDF) - carbon from the unextracted sections of the felled trees (i.e., branches, roots) and trees damaged or killed during felling (i.e., collateral felling damage); and, (3) Logging infrastructure factor (LIF) – carbon lost from skid trails, log decks (i.e., areas where logs are temporarily stored before being trucked from the forest) and haul roads. The total emissions factor (TEF; Mg C m^{-3}) for each FHU is the combined emissions from ELE, LDF, and LIF.

2.2. Carbon accounting method

2.2.1. Unlogged forest biomass

Each logged FHU sampled for carbon emissions was paired with an adjacent unlogged FHU of similar forest type and terrain that was proposed to be logged by the forest management enterprise. We used a variable plot sampling method with a 40 BAF prism (40 ft^2 acre^{-1}; 9.18 m^2 ha^{-1}), with a total of 15 unlogged biomass plots that were paired with the logged FHUs that was sampled for carbon emissions. The unlogged biomass plots were established along transects at 100 m intervals. Once a tree was determined to be 'in' the biomass plot with

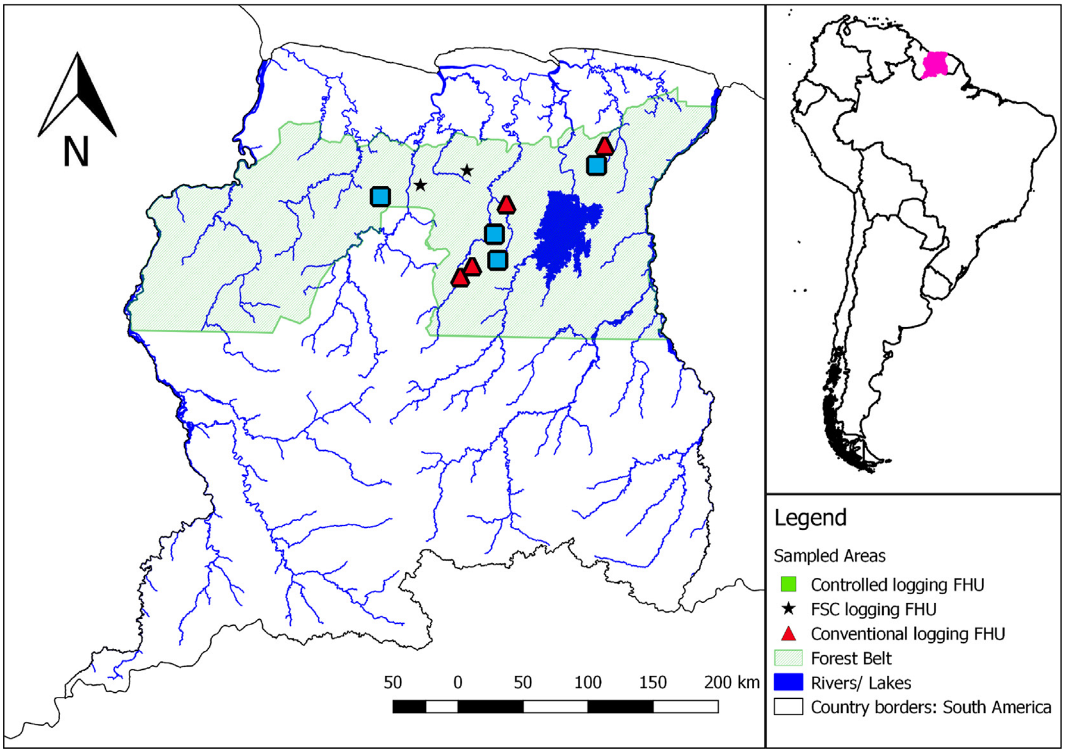

Fig. 1. Locations of forest harvest units (FHUs) sampled for carbon emissions by forest management classification (controlled logging, conventional logging, and FSC-logging) in Suriname. Inset map on the upper right is of South America with Suriname highlighted in pink.

the 40 BAF prism, its diameter at 1.3 m aboveground (DBH) was measured and its species recorded. We excluded areas such as creeks and swamps, as the primary goal of the unlogged biomass plots was to infer carbon lost from logging roads and log decks, which are generally constructed on ridges and in other areas with well-drained soils in the FHUs. We estimated the aboveground biomass of each tree with the ‘model II moist forest stands’ allometry proposed by Chave et al., (2005), and belowground biomass utilizing Eq. (1) from Mokany et al. (2006). We converted total tree biomass to carbon using the conversion factor of 0.47 (IPCC, 2006). We calculated carbon stocks per unit area as the basal area per unit area $*$ average BBAR; where BBAR is equivalent to $\frac{\text{tree carbon}}{\text{tree basal area}}$, also referred to as a mean-of-ratios-estimator (Bitterlich, 1984; Marshall et al., 2004).

2.2.2. *Extracted timber volumes*

Within the 50 ha sample area of each logged FHUs, all felled tree stumps were counted, and locations recorded with a Garmin GPS 62 s handheld unit. In a minimum of 25 felling gaps in each logged FHU, we recorded the height of stumps, length, and diameter of all log sections, and tree height. The status of each log section, whether present or absent (i.e., removed from the felling gap), was recorded. The length of the extracted section (if any) was determined as the distance from the stump or butt log to the top-cut below the tree crown or upper log section present. We assumed the absent log section is equivalent to the extracted timber and calculated its volume with the Smalian scaling formula (cm^3). The total extracted timber volume at the FHU level was then estimated based on the total number of tree stumps counted and the average volume extracted per stump based on the felled trees measured. As our volume estimate of the harvested tree was done at the stump, it does not account for subsequent bucking and rejection of logs or log sections within the forest that would reduce the overall timber volume recovered.

2.2.3. *Extracted log emissions (ELE)*

To simplify the carbon accounting process and to follow IPCC Tier 1 methods (IPCC, 2007) and the literature (Griscom et al., 2014; Pearson et al., 2014), we assumed that all carbon in the harvested portion of the tree (i.e., extracted timber) is emitted at the time of felling due to lack of data on wood processing recovery and decay rates of associated wood products. We converted the extracted timber volumes (cm^3) to extracted carbon as: ELE (Mg C m^{-3}) = vol (cm^3) $*\mathrm{WD_s} * 10^{-6} * 0.47$, where $\mathrm{WD_s}$ is species-specific wood density in g cm^{-3} (Chave et al., 2009; Zanne et al., 2009), 0.47 is the biomass-to-carbon ratio and 10^{-6} is the conversion factor to Mg. We also accounted for the missing mass in hollow portions of log sections in our biomass estimates of the felled trees based on the diameter and length of the decayed sections. If the hollow was only detected at one end of the log section, we assumed the hollow was half the length of the log, applying the bottom diameter of the hollow as the top diameter. The missing biomass estimated based on the dimensions of the hollow was then subtracted from the total tree biomass to account.

2.2.4. *Logging damage factor (LDF)*

The logging damage factor reflects the pool of dead carbon created in felling gaps where harvest volumes and ELE was measured. The LDF includes branches and roots of the harvested tree (unextracted biomass) and trees killed or severely damaged during harvesting (felling damage).

$$\mathrm{LDF\ (Mg\ C\ m^{-3})} = \frac{\sum_{\mathrm{gap_i}}^{n}\left(\frac{([(\text{biomass of tree}_i - \mathrm{ELE}_i) + \mathrm{CDgap}_i])}{\mathrm{Gap_i\ volume\ (m^3)}}\right)}{\text{Number of gaps}}$$

Here, biomass of tree$_i$ refers to the total biomass of each felled tree in felling gap$_i$, ELE$_i$ is the extracted biomass from tree$_i$ and is subtracted from the total tree biomass to estimate the unextracted biomass for tree$_i$, CDgap$_i$ is the carbon emissions from trees killed during felling in a specific gap and Gap$_i$ volume (m^3) is the timber extracted from the felling gap, as a single felling gap may contain several harvested trees. The diameter used to estimate the biomass of tree$_i$ applying the Chave et al. (2005) allometry when the log was extracted and there was no rejected log section, was the stump diameter as stem taper is minimal if there are no stem deformities. In instances where there was a rejected lower log section, due to buttresses or swollen stem, the top diameter of the rejected log section above any deformities was used to estimate the tree biomass. Only trees classified as snapped (stem broken at > 1.3 m) or grounded (stem broken at < 1.3 m or uprooted) were included in the LDF as felling damage, while trees with other damage types (e.g., bark damage and partial crown loss) were assumed to survive post-logging, as we lack data on the post-logging morality rates of the different damage classes (Fig. S1). Trees felled and not extracted were included as part of the LDF.

2.2.5. Skid trail emissions factor (SF)

All skid trails in the sampled FHUs were mapped with a Garmin 62 s GPS handheld unit to estimate the area covered by skid trails. At 200 m intervals along the skid trails in each sampled FHU, 10 m-long plots were established (N = 15 per FHU) to assess damage and death of trees ≥ 10 cm and to measure skid trail widths. The mapped length and average width of the skid trails were used to estimate the skid trail area (ha) in a FHU. Carbon emissions for the area occupied by skid trails was estimated based on the tree mortality recorded in the skid plots (Mg C ha^{-1} of skid trail) and the total area occupied by skid trails in a FHU. As the skid trail emissions was scaled up to the FHU level, the timber production estimated at the FHU could be used as the denominator to estimate the carbon emission factor (Mg C m^{-3}).

$$\text{SF (Mg C m}^{-3}\text{)} = \left(\frac{\text{Mg C ha}^{-1}\text{ of skid trail} * \text{skid trail area (ha) in FHU}}{\text{timber production (m}^{3}\text{) in FHU}}\right)$$

2.2.6. Haul road emissions factor (HF)

To estimate the carbon emissions from haul roads we utilized the baseline carbon stocks measured in unlogged biomass plots (Mg C ha^{-1}). We estimated the area deforested by haul roads in each FHU based on their respective length and width. Haul road widths were defined as the perpendicular distance between undamaged trees ≥ 10 cm DBH on either side of haul roads at the forest edge, with 10 measurements recorded for each FHU. We determined road intensity (length haul road per m^{3} extracted) as follows: (1) We combined GPS mapped haul roads in and near our focal FHU with remotely detected haul roads from Sentinel 2A satellite imagery (Copernicus, 2017) and Suriname forestry agency's national GIS database (SBB, 2016) on logging road infrastructure. (2) We treated haul roads similar to a catchment area of a river drainage system, as many haul roads are used to extract logs from several FHUs. We used our estimates of extracted harvest intensities (m^{3} ha^{-1}) from the sampled FHUs to scale up our timber production estimates across the entire catchment area served by the haul road in our focal FHU. (3) With the estimated timber production from the multiple FHUs served by the haul roads and the calculated area occupied by the haul roads, we estimate the carbon emitted from haul roads per cubic meter of wood harvested.

2.2.7. Log deck emissions factor (DF)

Similar to haul roads, we treated log decks as completely deforested areas. We measured the lengths and widths of 10 log decks in and around each sampled FHU and estimated their areas based on their respective shapes. We then counted the number of log decks within each sampled FHU in the field and calculated the total area occupied by log decks based on the average log deck size. Carbon emissions from log deck construction were then estimated based on the area deforested using the baseline carbon stocks for the FHU. We combined emissions from skid trails, haul roads, and log decks to estimate the logging infrastructure factor (LIF; Mg C m^{-3}). We acknowledge the reuse of logging infrastructure such as haul roads and log landings in subsequent harvest rotations would reduce the overall emissions estimated relative to the timber extracted. We, however, lack data on the re-use of logging infrastructure as the majority of logging concessions in Suriname have not begun a second rotation.

2.3. Statistical analysis

We fitted linear mixed effect models for carbon emissions from collateral felling damage estimated at the gap level (N = 239) and emissions from trees killed during the construction and use of skid trails from our skid trail plots (N = 152). We included the timber volume extracted (m^{3}) at the gap level (harvest intensity), management type, and slope (%) as predictor variables in the model on emissions from collateral felling damage. We did not have information on the intensity of use of skid trails based on the number of passes a machine would have made across the skid plots, and thus limits our ability to infer how the intensity of use influences skid trail emissions. We fitted the emissions model for collateral felling damage and skid trail emissions with FHUs as random effects to account for baseline differences among FHUs. For exploratory purposes, we fit a regression model with logging intensity (log transformed) as a predictor of the total emissions factor (TEF; Mg C m^{-3}) at the FHU level. We are cautious about our statistical inferences at the FHUs with respect to the relationship between TEF and logging intensity due to our small sample size of N = 10 FHUs (4 FHUs in conventional logging, 4 FHUs in controlled logging, and 2 FHUs in FSC-logging). The small sample size limits our confidence in making strong statistical inference, especially quantifying uncertainty and including additional predictor variables such as the logging system, terrain (slope) or baseline biophysical characteristics of the FHUs by means of random effects as we did for the models on collateral felling damage emissions and skid plot emissions (Greenland et al., 2000; Ogundimu et al., 2016). We built and implemented our models with the rstanarm package (Stan Development Team, 2017) that employs a Bayesian estimation routine for regression models in R (R Core Team, 2014). We incrementally added predictor variables, including interactions and the random effects, comparing each model with leave-one-out-cross-validation (LOO) and model averaging using the loo package to ensure model complexity did not reduce model performance, and report the best fit model in our results (Vehtari et al., 2018).

3. Results

Average harvest intensity was 11.73 m^{3} ha^{-1} (SE: ± 1.56), which resulted in carbon emissions of 2.44 Mg (SE: ± 0.36) for every cubic meter of timber extracted (Table 2). Unextracted biomass of harvested trees (0.70 Mg C m^{-3}; SE: ± 0.08; 29%) and collateral felling damage (0.57 Mg C m^{-3}; SE: ± 0.07; 23%) were the main sources of carbon emissions (Table 2 & Fig. 2).

Logging infrastructure associated with haul roads, skid trails, and log decks accounted for 21% (0.51 Mg C m^{-3}; SE: ± 0.16), 13% (0.31 Mg C m^{-3}; SE: ± 0.08) and 2% (0.06 Mg C m^{-3}; SE: ± 0.01) of logging related emissions, respectively (Table 2 & Fig. 2).

Carbon emissions were highest under conventional logging (3.23 Mg C m^{-3}; SE: ± 0.74), followed by controlled logging (1.96 Mg C m^{-3}; SE: ± 0.25), and FSC logging (1.82 Mg C m^{-3}; SE: ± 0.09; Table 2 & Fig. 3). Extracted timber volumes were lowest in conventionally logged FHUs (8.38 m^{3} ha^{-1}; SE: ± 1.87; 1.5 trees ha^{-1}) compared to controlled logging (13.41 m^{3} ha^{-1}; SE: ± 7.44; 2.9 trees ha^{-1}) and FSC logging (15.06 m^{3} ha^{-1}; SE: ± 3.80; 2.5 trees ha^{-1}). Logging intensity (m^{3} ha^{-1}; log transformed) explained 60% (R^2 95% CI: 0.3–0.8) of the variation in the total emissions factor (TEF – Mg C m^{-3}) across the 10 FHUs (Fig. 4).

3.1. Logging infrastructure

Skid trails averaged 5.73 m (SE: ± 0.30) wide and covered 703.06 (SE: ± 47.15) m^{2} ha^{-1} of logged forest across all FHUs. There was

Table 2
Timber volume extracted ($m^3 ha^{-1}$) and logging related carbon emissions ($Mg C m^{-3}$) by extracted and unextracted felled tree biomass, collateral felling damage, skid trails, haul roads and log decks across the 10 sampled forest harvest units (FHUs) classified by logging system (C = conventional logging; R = controlled logging; FSC = Forest Stewardship Council certified logging).

	Harvested Volume ($m^3 ha^{-1}$)	Extracted Wood Emissions ($Mg C m^{-3}$)	Unextracted Wood Emissions ($Mg C m^{-3}$)	Collateral Damage Emissions ($Mg C m^{-3}$)	Skid Trail Emissions ($Mg C m^{-3}$)	Haul Road Emissions ($Mg C m^{-3}$)	Log Decks Emissions ($Mg C m^{-3}$)	Total Emission Factor (TEF) ($Mg C m^{-3}$)
C1	11.74	0.29	0.43	0.32	0.14	0.36	0.04	1.57
C2	10.91	0.29	0.57	0.81	0.37	0.62	0.01	2.67
C3	7.33	0.33	0.80	0.90	0.78	0.80	0.03	3.65
C4	3.55	0.34	1.28	0.78	0.73	1.81	0.10	5.05
R1	16.20	0.26	0.50	0.24	0.11	0.12	0.05	1.29
R2	16.70	0.31	0.65	0.66	0.10	0.19	0.10	2.02
R3	8.60	0.31	0.83	0.40	0.46	0.35	0.10	2.46
R4	12.13	0.30	0.55	0.75	0.13	0.31	0.05	2.09
FSC1	9.80	0.30	0.75	0.44	0.09	0.25	0.08	1.90
FSC2	20.32	0.29	0.62	0.37	0.16	0.25	0.04	1.73
Mean (SE)	**11.73 (1.56)**	**0.30 (0.01)**	**0.70 (0.08)**	**0.57 (0.07)**	**0.31 (0.08)**	**0.51 (0.16)**	**0.06 (0.01)**	**2.44 (0.36)**
C - Mean (SE)	8.38 (1.87)	0.31 (0.01)	0.77 (0.19)	0.70 (0.13)	0.50 (0.15)	0.90 (0.32)	0.05 (0.02)	3.23 (0.74)
R - Mean (SE)	13.41 (7.44)	0.30 (0.01)	0.63 (0.07)	0.52 (0.12)	0.20 (0.09)	0.24 (0.05)	0.08 (0.02)	1.96 (0.25)
FSC - Mean (SE)	15.06 (3.80)	0.30 (0.01)	0.69 (0.06)	0.41 (0.03)	0.12 (0.03)	0.25 (0.00)	0.06 (0.02)	1.82 (0.09)

71.60 m^2 (SE: ± 11.84) of skid trail for every cubic meter of wood harvested (301 m^2 per tree felled; SE: ± 47.15), and 122 m of skid trail per hectare of forest across all the sampled FHUs (SE: ± 6.99; Fig. S2).

FSC-logged FHUs had the highest skid trail densities (mean = 759.92 $m^2 ha^{-1}$; SE: ± 226.56), with skid trail density per cubic meter of extracted timber lowest in FSC-logged FHUs (51.50 $m^2 m^{-3}$; SE: ± 2.95; Table 3).

Skid trail emissions per cubic meter of wood extracted in FSC-logged FHUs was 0.12 $Mg C m^{-3}$ (SE: ± 0.03), which was 40% and 76% lower compared to controlled (0.20 $Mg C m^{-3}$; SE: ± 0.09) and conventionally logged (0.50 $Mg C m^{-3}$; SE: ± 0.015) FHUs, respectively (Table 2). Excavators were found to be used for skidding in 70% of forest management enterprises, sometimes in combination with wheel skidders.

Carbon emissions from the skid trail plots (N = 156) indicated a reduction of 0.16 Mg C (95% CI, −0.34 to 0.004) and 0.19 Mg C (95% CI, −0.42 to 0.04) for every 10 m of skid trail constructed under controlled logging and FSC logging, respectively compared to conventionally logged FHUs (0.30 Mg C, 95% CI 0.15–0.46). Slope had a

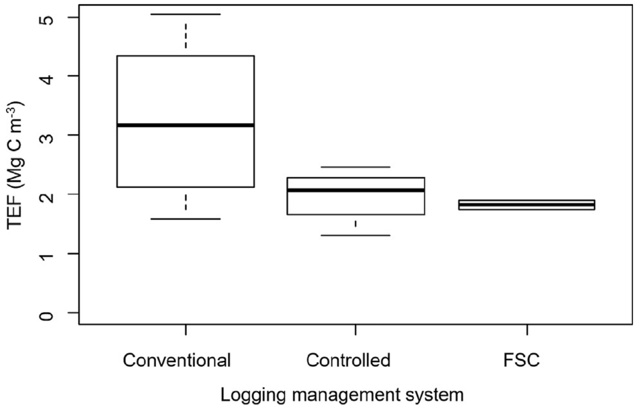

Fig. 3. Total logging-related carbon emissions from FHUs under conventional logging (N = 4), controlled logging (N = 4), and FSC logging (N = 2) expressed per cubic meter of wood removed from the felling gap.

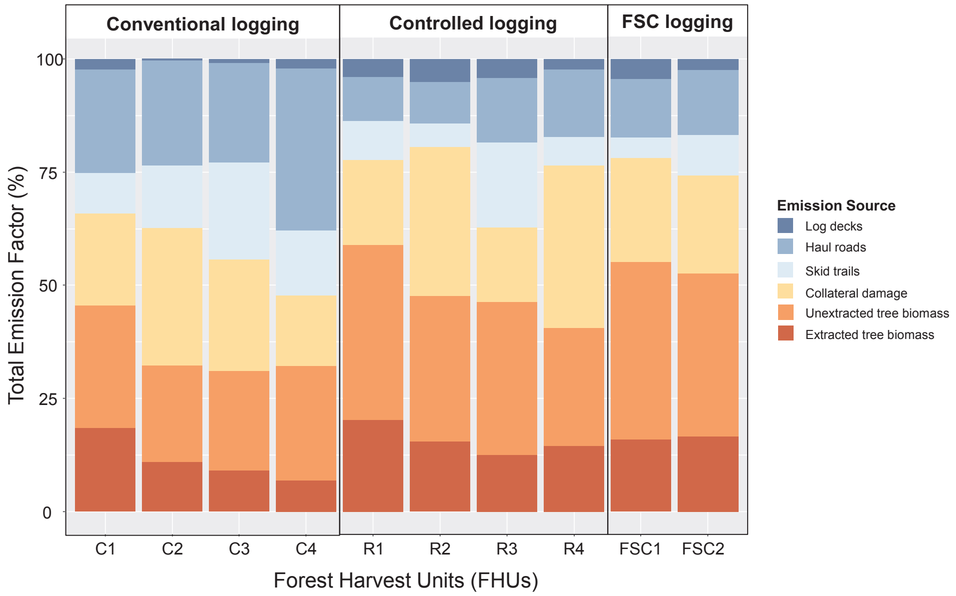

Fig. 2. Total emission factor (TEF) broken down by emission source (extracted tree biomass, unextracted felled tree biomass, collateral felling damage, skid trails, haul roads, and log decks) based on forest management type (conventional logging - C, controlled logging - R and FSC logging - FSC).

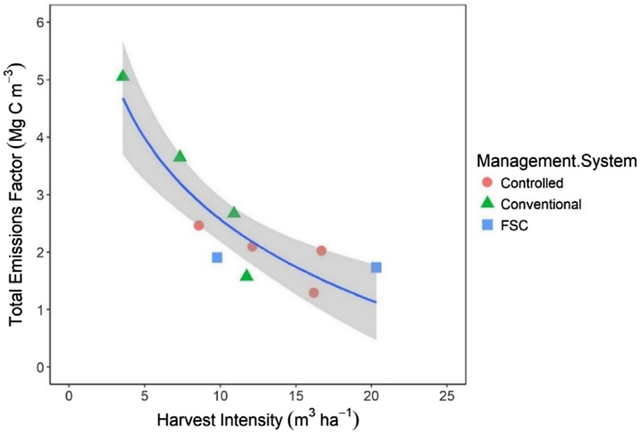

Fig. 4. Relationship between harvest intensity (m^3 ha^{-1}) and total carbon emissions. We fit a log curve (blue line) with the 95% CI captured by the grey band. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

small positive effect on overall skid trail emissions but was not significant (0.01 Mg C, 95% CI −0.01 to 0.02; Fig. 5).

Haul road emissions varied by a factor of 15 among FHUs, with haul road emissions from conventional logging 70% higher (0.90 Mg C m^{-3} SE: ± 0.32) than controlled logging (0.24 Mg C m^{-3}; SE: ± 0.05) and FSC logging (0.25 Mg C m^{-3}; SE: ± 0.00; Table 2). Haul road widths were also 40% wider in conventional logging (24.66 m; SE: ± 2.50) with density of haul roads per cubic meter of wood extracted three times (31.93 m^2 m^{-3}; SE: ± 8.18) that of controlled logging (9.17 m^2 m^{-3}; SE: ± 2.14) and FSC logging (10.89 m^2 m^{-3}; SE: ± 0.17; Table 3).

Log decks accounted for the smallest source of logging emissions, with

0.08 Mg C m^{-3} (SE: ± 0.02) in controlled logging, 0.05 Mg C m^{-3} (SE: ± 0.02) in conventional logging and 0.06 Mg C m^{-3} (SE: ± 0.02) in FSC logging (Table 2). The average size of log decks ranged from 0.07 ha (SE: ± 0.01) in conventional logging to 0.11 ha (SE: ± 0.01) in controlled logging (Table 3).

3.2. Felled tree emissions

Extracted C emissions were similar among the three logging systems (0.30 Mg C m^{-3}) with C emissions associated with the unextracted sections of felled trees highest in conventional logging (0.77 Mg C m^{-3}; SE: ± 0.19), followed by FSC logging (0.69 Mg C m^{-3}; SE: ± 0.06) and controlled logging (0.63 Mg C m^{-3}; SE: ± 0.07; Table 2 & Fig. S3). Felled trees that had no timber extracted constituted 10.26% (SE: ± 5.84) and 8.16% (SE: ± 9.45) of all stumps recorded in conventional logging and controlled logging respectively, and 3.64% (SE: ± 0.09) in FSC-logged FHUs (Table 4).

In our sample of 255 harvested trees in 239 felling gaps, 1277 other trees ≥10 cm DBH were uprooted or snapped (Figs. S1 and S4). An additional 470 trees lost > 50% of their crown, and 115 were leaning > 10 degrees (assumed to be from logging impact). The number of trees killed per felled tree was highest in conventional logging (6 trees killed per tree felled; Table 4).

Collateral felling damage emissions measured at the gap level, averaged 0.57 Mg C m^{-3} (SE: ± 0.07) across all FHUs, and was higher in conventional logging (0.70 Mg C m^{-3}; SE: ± 0.13) compared to controlled logging (0.52 Mg C m^{-3}; SE: ± 0.12) and FSC logging (0.41 Mg C m^{-3}; SE: ± 0.03; Table 2). Logging intensity had a significant effect on collateral felling damage emissions that resulted in an increase of 0.12 Mg C (95%; CI: 0.03–0.22) for every additional cubic meter of timber harvested (Figs. S5 and S6). Application of controlled logging and FSC logging reduced collateral felling damage emissions by 1.0 Mg C (95% CI, −3.15 to 1.15) and 1.3 Mg C (95% CI, −3.84 to 1.22), respectively, relative to conventional logging (3.3 Mg C, 95% CI, 1.6–5.0). Slope did not have a significant effect on felling damage emissions (−0.04, 95% CI, −0.14 to 0.06; Fig. 6).

4. Discussion

Overall carbon emissions from the forestry sector in Suriname (2.44 Mg C m^{-3}) were similar to those reported in Guyana (2.33 Mg C m^{-3}), a neighboring country that shares biophysical characteristics associated with Guiana Shield forests (Hammond, 2005; Pearson et al., 2014). Logging emissions measured in this study and the Pearson et al. (2014) study for Guyana, were dominated by the unextracted portions of the harvested trees and trees killed during felling (collateral felling damage), with logging intensity driving overall emissions compared to other countries (Ellis et al., in press). The high logging emissions related to the extracted and unextracted portions of the felled tree in Suriname and Guyana, is in part driven by the high wood densities across Guiana Shield forests (mean wood

Table 3
Logging machinery and infrastructure characteristics for log decks, skid trails, and haul roads in sampled FHUs by logging system (C = conventional logging; R = controlled logging; FSC = Forest Stewardship Council certified logging).

Forest Harvest Unit (FHU)	Machinery used	Average log deck area (ha)	Average skid trail width (m)	Skid trail density (m^2 ha^{-1})	Skid trail area per timber volume (m^2 m^{-3})	Skid trail length per tree harvested (m)	Average haul road width (m)	Haul road density (m^2 ha^{-1})	Haul road area per timber volume (m^2 m^{-3})
C1	Bulldozer	0.11	5.76	674.82	57.50	70	25.45	8.23	17.85
C2	Excavator	0.05	5.63	553.26	50.72	60	31.43	9.40	27.07
C3	Excavator	0.08	6.37	870.74	118.86	78	21.22	9.40	27.22
C4	Excavator	0.06	6.03	539.11	151.78	101	20.54	9.61	55.59
R1	Excavator & wheel skidder	0.09	5.02	690.53	42.62	38	14.73	5.96	5.42
R2	Excavator & wheel skidder	0.13	4.29	697.18	41.74	47	11.51	8.32	5.73
R3	Excavator	0.10	7.06	811.11	94.26	54	15.86	6.25	11.53
R4	Excavator	0.14	4.93	673.97	55.55	59	19.12	8.89	14.01
FSC1	Wheel skidder	0.07	5.02	533.37	54.45	53	14.35	7.55	11.05
FSC2	Wheel skidder	0.09	7.15	986.48	48.55	45	13.97	15.59	10.72
Mean (SE)		**0.09 (0.01)**	**5.73 (0.30)**	**703.06 (47.15)**	**71.60 (11.84)**	**60.54 (5.85)**	**18.82 (1.93)**	**8.92 (0.84)**	**18.62 (4.77)**
Mean C (SE)		0.07 (0.01)	5.95 (0.16)	659.48 (76.72)	94.72 (24.43)	77.21 (8.86)	24.66 (2.50)	9.16 (0.31)	31.93 (8.18)
Mean R (SE)		0.11 (0.01)	5.32 (0.60)	718.20 (31.35)	58.54 (12.32)	49.58 (4.56)	15.31 (1.57)	7.36 (0.73)	9.17 (2.14)
Mean FSC (SE)		0.08 (0.01)	6.08 (1.06)	759.92 (226.56)	51.50 (2.95)	49.11 (4.30)	14.16 (0.19)	11.57 (4.02)	10.89 (0.17)

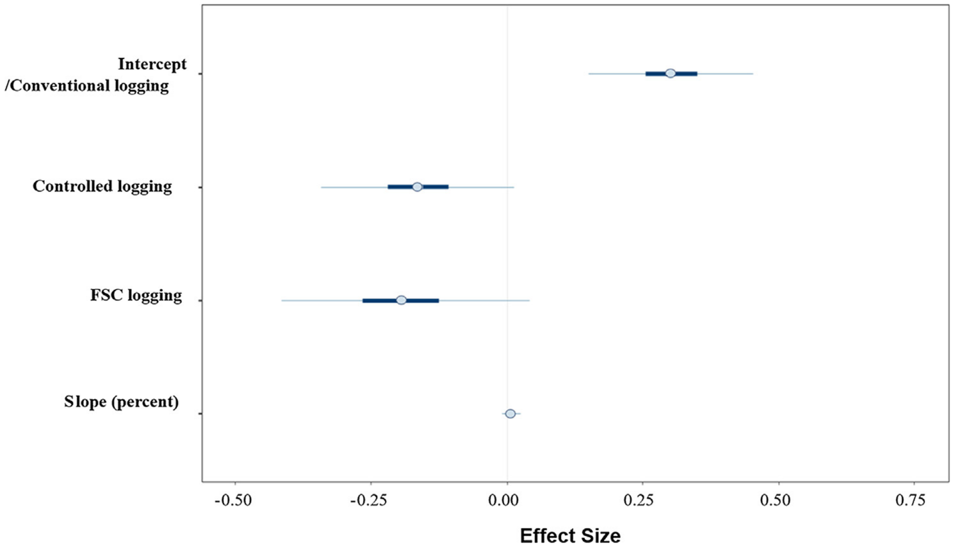

Fig. 5. Model coefficients for carbon emissions from 10 m long skid trail plots (N = 156). The intercept term on the y-axis is equivalent to C emissions from conventional logging. The coefficient parameters for controlled logging, FSC logging, and slope represent the effect of these parameters relative to conventional logging (Intercept). Circles represent mean effect size, thick horizontal lines are the 50% credible intervals, and thin horizontal lines are the 95% credible intervals ($R^2 = 0.11$).

Table 4
Average diameters and lengths of logs extracted from sampled FHUs (numbers of trees noted parenthetically) and percentage of felled trees that were cut from which no timber was extracted by logging system (C = conventional logging; R = controlled logging; FSC = Forest Stewardship Council certified logging).

Forest Harvest Unit (FHU)	Average extracted log length (m)	Average diameter of bottom section of extracted log (cm)	# Felling gaps sampled	Carbon stock in adjacent unlogged FHU (Mg C ha^{-1})	Felled trees not extracted (%)	# Trees felled per hectare	# trees killed per tree felled	Average mortally damaged collateral tree DBH
C1	18.00	73.37	26.00	200.25	11.54	1.31	4.65	24.26
C2	16.62	74.98	25.00	227.70	8.00	2.17	7.24	26.75
C3	13.72	64.68	26.00	295.61	3.85	3.19	5.08	26.08
C4	13.69	72.50	17.00	325.68	17.65	2.29	6.41	23.77
R1	15.85	65.50	26.00	230.52	0.00	2.29	3.62	19.96
R2	16.64	68.66	29.00	323.29	17.24	3.48	4.79	25.49
R3	13.41	72.07	26.00	305.38	15.38	2.55	4.58	22.31
R4	15.19	66.06	25.00	222.08	0.00	2.24	5.52	26.02
FSC1	14.21	71.57	28.00	224.04	3.57	1.96	4.36	23.66
FSC2	15.90	80.96	27.00	231.83	3.70	2.63	4.52	25.70
Mean (SE)	**15.32 (1.54)**	**71.04 (1.58)**	**25.50 (3.24)**	258.64 (15.14)	**8.09 (6.90)**	**2.41 (0.19)**	**5.08 (0.34)**	**24.40 (0.66)**
Mean C (SE)	15.51 (2.16)	71.38 (2.29)	23.50 (4.26)	262.31 (29.12)	10.26 (5.84)	2.24 (0.38)	5.85 (0.60)	25.21 (0.71)
Mean R (SE)	15.27 (1.38)	68.07 (1.50)	26.50 (1.73)	270.32 (25.73)	8.16 (9.45)	2.64 (0.29)	4.63 (0.39)	23.44 (1.42)
Mean FSC (SE)	15.06 (1.19)	76.27 (4.69)	27.50 (0.71)	227.93 (3.90)	3.64 (0.09)	2.29 (0.33)	4.44 (0.08)	24.68 (1.02)

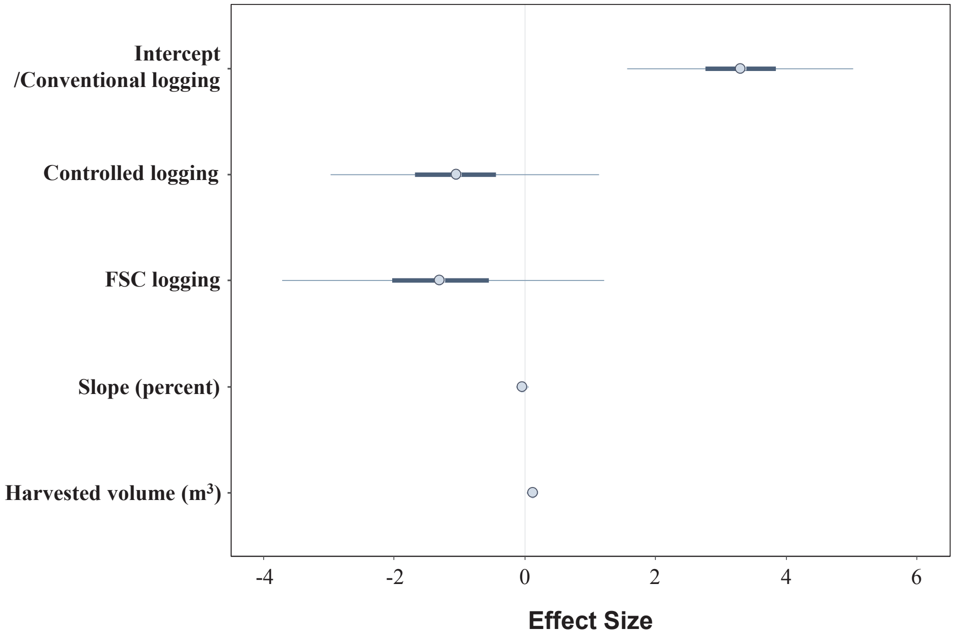

Fig. 6. Model coefficients for collateral felling emissions assessed at the gap-level (N = 239). The coefficient parameters for controlled logging, FSC logging, slope, and harvested volume assessed at the gap represent the effect of these parameters relative to conventional logging (intercept). Circles represent mean effect size, thick horizontal lines are the 50% credible intervals, and thin horizontal lines are the 95% credible intervals ($R^2 = 0.14$).

density = 0.63 g cm^{-3}; Johnson et al., 2016). For example, concessions C3 and C4, that applied conventional logging had the lowest harvest volumes, but the highest extracted log emissions as they favored species with high wood densities (0.73 and 0.75 g cm^{-3}, respectively).

Carbon emissions was about 40% lower under controlled logging (1.96 Mg C m^{-3}) and FSC logging (1.82 Mg C m^{-3}) compared to conventional logging (3.23 Mg C m^{-3}). The higher C emissions per cubic meter of timber extracted in conventionally logged FHUs is explained by low timber production in these FHUs, which was on average 50% less in conventionally logged FHUs compared to FHUs logged under controlled and FSC systems. We attribute the lower production volumes in conventionally logged FHUs to the lack of pre-harvest inventories, which can result in identification of 20% more harvestable stems (Marn and Jonkers, 1981; Putz et al., 2008) and can lead to an increase of 15% in timber volume harvested (Barreto et al., 1998). Additionally, as conventionally logged FHUs construct the same amount of infrastructure (Table 3) as the other management systems, but extract less timber, they have higher logging infrastructure emissions (Table 2). Though higher logging intensities reduce the total carbon emissions factor (Fig. 4), an appropriate balance needs to be struck, as higher logging intensities both deplete forest carbon stocks and lead to slower recovery time of forest carbon (Roopsind et al., 2018, 2017; Rutishauser et al., 2015). Additionally, higher logging intensities also negatively impact other ecosystem services such as biodiversity (Bicknell et al., 2014; Burivalova et al., 2014; Putz et al., 2012; Roopsind et al., 2017).

Carbon emissions from conventional logging also resulted in the highest collateral felling damage emissions (Table 2). The lower felling damage in the controlled and FSC logged FHUs compared to conventional logging (Table 4) could be a direct result of the application of directional felling practices with trained forestry workers. Observations in the field and communication with tree fellers though, gave the impression that the suite of practices intended to reduce felling damage and improve safety of forestry workers such as liana cutting, and directional felling are not fully applied or understood. A previous study conducted in Suriname has shown that the correct application of directional felling practices in under controlled logging reduces felling damage and protects future crop trees, in addition to aiding extraction (Hendrison, 1990). We cannot however definitively attribute the lower level of felling damage to the use of directional felling, as though FSC logged FHUs are required to apply directional felling and are audited on a regular basis for compliance, controlled FHUs that share the same level of collateral felling damage emissions in our study, are not mandated to apply directional felling.

In terms of logging infrastructure, haul roads, which result in clear patterns of forest loss and classified as deforestation, was 38% wider in conventionally logged forests than haul roads in controlled and FSC logged forests (Table 3). The average haul road width (24.7 m) observed in conventionally logged FHUs is however within Suriname's draft logging code that recommends a maximum width of 25 m (van der Hout, 2011). As we found the width of hauls in the control and FSC logged forests to be on average 10 m less than the recommended maximum width in the national logging code, we would recommend a downward revision of the maximum haul road width to reduce forest loss and associated carbon emissions. FSC and controlled FHUs also had shorter skid trails per extracted tree, an indication of effective skid trail planning. We were unable though to correlate our haul road emissions to use of specific machinery, and skill levels of machine operators, that explains forest road and other infrastructure quality (Hendrison, 1990; Majnounian et al., 2009; van der Hout, 1999).

The unextracted wood from felled trees was the largest source of emissions across all FHUs and logging systems. We suspect that the total carbon emissions from the unextracted portions of harvested trees are even higher than reported in our study due to repeated trimming and culling of logs before they are milled. To reduce these emissions, much of which can be considered wood waste (i.e., potential exists for utilization), there needs to be better access to appropriate timber milling machinery and training in crosscutting for improved wood utilization. Another source of carbon emission associated with the unextracted carbon pool that could be reduced with improved logging practices are trees felled and then rejected because of poor form, breakage, heart rots, or hollows or simply forgotten in the forest. We found the number of rejected trees were similar in the conventionally logged and controlled logged FHUs, but 50% less in FSC logged FHUs. This difference potentially reflects the benefits of training fellers to use practices such as plunge cuts, which FSC forestry workers indicated they were trained to apply.

In 2016, conventional, controlled, and FSC logged FHUs produced 309,569 m^3, 141,948 m^3, and 51,443 m^3 of timber, respectively in Suriname. Based on the carbon emission estimates per cubic meter of wood from our study, the forestry sector was responsible for approximately 1.37 million Mg C emissions, approximately 67% of the 2.06 million Mg C emissions from deforestation estimated for 2014–2015 (Government of Suriname, 2018).

Pre-harvest inventories, used to inform road and skid trail planning, represent a large opportunity for emissions reductions. For example, based on the 2016 timber production data and the emission factors per management type determined in this study, emissions could have been reduced by 393,263 Mg C if pre-harvest inventories and road planning were conducted in conventionally logged FHUs (effectively making them controlled logging FHUs). Additional emissions reductions across all management systems, albeit at a smaller scale relative to the phasing out of conventional logging, can be achieved by improved bucking practices, as the unextracted portions of harvested trees was the single largest source of carbon emissions. Improved bucking would also have the added benefit of higher timber volume production without felling additional trees or constructing additional roads and skid trails, as observed under the higher timber recovery in FSC-logged FHUs. Increase recovery of timber would, however, require investments in training and milling machinery that accepts shorter and less uniform logs.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2019.02.026.

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