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# Selective logging emissions and potential emission reductions from reduced-impact logging in the Congo Basin

Peter M. Umunay[a,*], Timothy G. Gregoire[a], Trisha Gopalakrishna[b], Peter W. Ellis[b], Francis E. Putz[c]

[a] The School of Forestry and Environmental Studies, 360 Prospect St, Yale University New Haven CT 06511, USA
[b] The Nature Conservancy, 4245 N Fairfax Drive, Arlington, VA 22203, USA
[c] Department of Biology, University of Florida, PO 118526, Gainesville, FL 32611-8526, USA

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ABSTRACT

To estimate carbon emissions from selective logging in Central Africa, we employed the reduced-impact logging for carbon emissions reductions (RIL-C) protocol to quantify baseline carbon emissions from legal timber harvests by source (i.e., hauling, skidding, and felling). We modeled the relationships between emissions and biophysical conditions, logging practices, and forest policies and then used these models to estimate potential emission reductions from full implementation of RIL-C practices. We applied the method in 8 forest management enterprises (FMEs; i.e., concessions) in the Democratic Republic of Congo (DRC), 9 in Gabon, and 6 in the Republic of Congo (RoC). Committed logging emissions expressed per cubic meter of timber harvested (to control for differences in logging intensities) ranged from 0.63 Mg C m$^{-3}$ in a FME in RoC to 4.8 Mg C m$^{-3}$ in a FME in Gabon, with an overall average of 2.1 Mg C m$^{-3}$. Logging emissions were dominated by damage caused by road and log landing construction (i.e., hauling; 50%) and felling (43%; includes carbon in extracted logs). Total emissions represented only about 9% of unlogged forest biomass carbon stocks. Average emissions were highest in Gabon (2.65 Mg C m$^{-3}$) followed by DRC (1.84 Mg C m$^{-3}$) and RoC (1.54 Mg C m$^{-3}$). Emissions from concessions certified by the Forest Stewardship Council (FSC, N = 6) and those that were not certified (N = 17) did not differ. Nearly half (51%) of logging emissions could be avoided without reducing timber yields if all best examples of RIL-C logging practices observed were applied in the same FME. At the country level, if all FMEs were to utilize these practices, emissions reductions would be 34% in RoC, 45% in DRC, and 62% in Gabon. When combined with country-level logging statistics, emissions from selective logging as currently practiced in the six countries of the Congo Basin are equivalent to 40% of the region's total emissions from deforestation.

## 1. Introduction

Avoidance of tropical deforestation and forest degradation is recognized as a key climate change mitigation strategy that was formally recognized in the Paris Agreement (Bustamante et al., 2016; Carodenuto et al., 2015). Compared to forest degradation, carbon emissions from deforestation are relatively easy to measure with remote sensing (e.g., Avitabile et al., 2012; Zarin et al., 2016). In contrast, quantifying emissions from degradation (i.e., loss of carbon from forests that remain forests) requires detailed site-specific information that is hard to derive from passive remote sensing imagery (Herold et al., 2011; Ryan et al., 2014; Zhuravleva et al., 2013). Given that field measurements require suitable sampling protocols and financial support, it is no surprise that global emissions from forest degradation are poorly quantified (Agyeman et al., 1999; Baccini et al., 2017; Hosonuma et al., 2012; Morales-Barquero et al., 2015, 2014; Thompson et al., 2013).

Several studies have demonstrated the important contribution of forest degradation to global carbon emissions (Ernst et al., 2013; Hosonuma et al., 2012; Ryan et al., 2012; Zhuravleva et al., 2013). Globally, an estimated 850 million hectares of tropical forest were degraded between 1990 and 2010, emitting 10–40% of total net emissions globally (Houghton et al., 2012). A more recent study suggests that forest degradation is responsible for the majority (69%) of carbon emissions from tropical ecosystems (Baccini et al., 2017). Similarly, regional-scale analyses estimate that 22–57% of total forest emissions are from degradation (Asner et al., 2012; Hosonuma et al., 2012). In tropical Africa, a recent study reported that degradation

* Corresponding author.
*E-mail address:* peter.umunay@yale.edu (P.M. Umunay).

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accounted for 81% of emissions (Baccini et al., 2017) of which ∼32% was from timber harvests (Hosonuma et al., 2012; Thompson et al., 2013). These studies provide motivation to focus on forest degradation from selective logging but, given that they were based on remote sensing with few field measurements, they do not allow detailed insights into the forest management practices and biophysical factors (e.g., topography, climate, and soils) that influence emissions.

Selective logging occurs in at least 20% of the world's tropical forests (Blaser et al., 2011; Pearson et al., 2017). While most studies on this topic focused largely on the extent of damage to residual stands and carbon emissions (e.g., Medjibe et al., 2011), emissions sources (e.g., from haul roads, skid trails, and collateral damage from felling) are less well quantified (but see Griscom et al., 2014; Pearson et al., 2014), especially in Africa. This data scarcity causes uncertainty in estimates of greenhouse gas emissions from logging. It is known that excessive emissions result from uncontrolled selective logging by untrained crews operating in the absence of detailed harvest plans and without incentives to minimize avoidable stand and soil damage (e.g., Pinard and Putz, 1996; Asner et al., 2005; Pearson et al., 2017). There is a clear need for fine-scale direct measurements of emission-causing activities that allow decoupling of overall emissions estimates into causative activities. This information can be used to design effective ways to reduce these emissions through improved practices.

To minimize the deleterious environmental impacts of selective logging, foresters have pushed for improved harvesting practices for nearly a century (e.g., Bryant, 1923; Dykstra et al., 1996; Ewel et al., 1980; Hendrison and Wageningen., 1990). In 1993 these well-established practices became known as "reduced-impact logging" (RIL) (Putz and Pinard, 1993) with a focus on carbon emission reductions. Overall, RIL practices are intended to minimize the disruption of tropical forest carbon and water cycles via pre-harvest tree selection, cutting lianas before logging, directional felling, and planning of skid trails (e.g., Pinard et al., 1997; Miller et al., 2011). Positive effects of the adoption of RIL techniques on rates of post-logging biomass and timber volume recoveries are substantial and well- recognized in the literature (e.g., Miller et al., 2011; Vidal et al., 2016). Knowing this, efforts should now focus on developing consistent guidelines and practices, standardizing worker training, reducing worker turnover and injuries, and developing suitable methods to measure and monitor carbon emissions (Griscom et al., 2014; Pearson et al., 2014). Such an approach should allow disaggregation of the recommended RIL practices so as to measure the emissions reductions associated with each.

Tested in Indonesia, the RIL-C protocol focuses on carbon emission reductions (Ellis et al., 2016; Griscom et al., 2014) to reflect increased concerns about climate change as well as increased opportunities to benefit financially from those reductions (e.g., REDD+, voluntary carbon markets, Nationally Determined Contributions to the UN Paris Agreement, and corporate commitments) (VCS, 2016). The carbon emission reduction benefits of RIL derive from increased efficiency and from respect for rules related to riparian buffer zones, slope restrictions, and sometimes by protecting big trees. Although following RIL guidelines does not assure long-term timber yield sustainability (e.g., Ruslandi et al., 2017), their adoption can reduce adverse environmental impacts (e.g., soil compaction and erosion, and collateral stand damage) and enhance worker safety. The RIL-C monitoring protocol allows disaggregation and measurement of the emissions-causing practices (felling, yarding, and hauling) and allows estimation of potential emission reductions from their improvement. Nonetheless, there remains a need to set performance levels by which the implementation of RIL practices can be assessed and compared with the baseline emissions to estimate RIL additionality and effectiveness in emissions reductions.

Here we apply the RIL-C monitoring protocol developed for Indonesia (Griscom et al. 2014) to Congo Basin forests to quantify logging emissions and potential emission reductions. The objectives of this study are: (1) to quantify emissions from hauling, skidding, and felling in 23 concessions that span three Congo Basin countries; (2) to analyze the relationships between total emissions and a range of explanatory variables including biophysical and spatial variables, logging practices, and policies; and, (3) to estimate potential emissions reductions with full RIL implementation. We place our modeled estimates of potential RIL reductions in emissions into a broader context by estimating the magnitude of potential reductions across three sampled countries (Democratic Republic of Congo, Gabon, and Republic of Congo) as a contribution to each countries' pledge, as signatories of the Paris Climate Agreement, to 20–50% emissions reductions, as specified in their Nationally Determined Commitments (NDC).

## 2. Methods

### 2.1. Reduced-impact logging for carbon emission reductions (RIL-C) methodology

The RIL-C protocol was developed to measure emissions from selective logging in Indonesia by its main source (either felling, skidding, or hauling), and to estimate the possible emissions reductions from adoption of improved logging practices (Ellis et al., 2016; Griscom et al., 2014). This protocol was approved for use in East and North Kalimantan by Verified Carbon Standard (VCS). It includes predetermined additionality benchmarks and crediting baselines that serve to reduce operational costs while mitigating emissions through simplified monitoring, reporting, and verification. The method divides logging-induced carbon emissions into those from felling, skidding (i.e., timber yarding), and hauling (i.e., haul roads and log yards); committed emissions (Mg C) are expressed per cubic meter of timber harvested and per hectare. We estimated changes in biomass pools and related emissions directly by measuring losses in live biomass and incidental damage to other trees. In this sense, the method follows the gain-loss approach as opposed to estimating the difference in carbon emissions and removals from pre- and post-logged forest (Plugge and Köhl, 2012).

### 2.2. Site descriptions

Democratic Republic of Congo (DRC): The DRC's 155 million hectares of forest constitutes one third of all forests in the Congo Basin; annual deforestation rates reached 4% between 2000 and 2014 in forest with > 50% tree crown cover (Abernethy et al., 2016). In 2016, 81 concessions were operational of which 57 operated with timber licenses in an area of ~ 10.7 million ha, while 21 concessions were timber licenses to communities (∼4 million ha), and three timber licenses (394,359 ha) on hold by the government (WRI–Domaine Forestier de la RDC 2016). Of all these industrial logging concessions, at the time of this study (2017) only seven had validated management plans and none were Forest Stewardship Council (FSC) or PEFC certified (Blaser et al., 2011; de Wasseige et al., 2015). Large-scale industrial timber harvesting is not fully developed in DRC due to lack of infrastructure and political instability. Most of the logs are exported towards Europe and Asia, with little pre-export processing. It should be noted that artisanal and illegal logging greatly increased during the 1996–2002 conflict and was often followed by deforestation (DRC – RPP 2010). DRC is the only country in the region that allocates logging concessions to communities, but their operations are rudimentary and yield little timber.

Republic of Congo (RoC): The RoC's 24 million ha forest covers 71% of the country with an annual deforestation rate of 1.6% between 2000 and 2014 (Abernethy et al., 2016). To promote sustainability, in 2000 the government of RoC required logging concessions to operate according to government-approved forest management plans. In mid-2009, there were 52 large-scale concessions covering nearly 12 million hectares, 8 million in the northern region and about 4 million in the south and central regions of the country. Following governmental policies, these concessions were often divided into management units of about 50,000 ha (Blaser et al., 2011). In 2016, 51 logging concessions covered 12.6 million ha of which about 4.6 million ha were under government-approved management plans and a total of 3 million ha (or 12 FME) were FSC certified (de Wasseige et al., 2015; Karsenty and Ferron, 2017). Almost all logging concessions are owned by foreign companies, with little development of community-owned concessions.

Gabon: The timber industry plays an important role in the economy of Gabon in terms of its contributions to GDP, foreign exchange, and employment. With 24 million ha of forest, Gabon is the most forested country in the region (88%) and, in 2014, suffered the lowest deforestation rate of 1.1% (Abernethy et al., 2016). In 2015, 150 companies operated with timber licenses that covered 14.3 million ha (Karsenty and Ferron, 2017) or > 50% of total forested area (de Wasseige et al., 2015). Gabon's timber sector, which is dominated by foreign companies, exported about 4 million cubic meters of industrial logs in 2000 out of which 70% was in the form of raw round logs. In 2009, prior to its 2010 log export ban, Gabon produced an estimated 3.4 million $m^3$ of industrial logs, out of which 1.87 million $m^3$ of logs and 157,000 $m^3$ (roundwood equivalent) of sawnwood were exported, which made Gabon the world's second largest exporter of tropical hardwoods in that year (Blaser et al., 2011; Rana and Sills, 2017). As of 2015, 2.4 million ha of forest in 25 FMEs were FSC certified (17%), 50% of forest was included in management plans registered with the government, and the remainder was being harvested under temporary logging permits (de Wasseige et al., 2015). Efforts to promote sustainable forest management, certification, and log export bans are endorsed by the government as ways to promote economic development and reduce deforestation.

### 2.3. Field sampling

Data were collected in 23 commercial forest concessions in the Congo Basin (nine concessions in Gabon, eight in DRC, and six in RoC) that were selected to cover a wide range of management categories, logging practices, and pre-logging biomass carbon stocks (Table 1). Sample blocks were selected with a stratified random procedure to ensure a representative sample of FMEs based on factors such as their size, soil type, elevation, carbon density, certification status, and worker training in RIL practices. If a randomly selected sample block was inactive or in accessible, it was replaced by a new randomly selected sample block from the same stratum. Concessions were categorized as FSC-certified (FSC), with registered management plans (MP), or with only temporary logging permits (TP). For consistency, we combined MP and TP as non-certified concessions to compare with FSC-certified concessions throughout. In annual cutting blocks in each FME we measured the widths of active roads and road corridors at 20 locations. In addition, and where possible we measured the areas of 10 log yards in each cutting block. Skidding and felling were measured in a randomly selected 50 ha sub-block in each concession. For each sampled sub-block, we measured skid trail lengths, mapped skid trail networks, and measured trees ≥ 10 cm DBH that were damaged by skidding in 15 skid trail plots. To account for felling damage, we first selected 30% (309 of the 1039) of the felled trees for measurement of dendrometric variables (stump, tree and log diameter, height, and diameter of any hollows or heartrots), then measured any trees ≥ 10 cm DBH that were killed (e.g. uprooted or snapped) or that suffered bark or crown damage during felling. Finally, the biomass carbon stocks of unlogged forest were estimated with data from 15 prism plots (345 in total) measured in an adjacent, unlogged block within each sampled concession. Detailed information on field measurements can be found in Griscom et al. (2014) and conversion of field measurements into estimates needed for application of the carbon accounting equations are presented in the supplemental material (S1 – Logging Equations in Ellis et al. 2019, in this issue).

### 2.4. Carbon emissions accounting

Total emissions from timber harvests were estimated as the sum of three sources: (1) hauling (H), which includes log landings, haul roads, and road corridors; (2) skidding (S), calculated as emissions from skid trail plots times the length of the skid trail network; and (3) felling (F) that combines emissions from harvested trees (H) and those that suffered collateral damage. Committed emissions from above- and below-ground biomass are expressed both as $Mg\,C\,m^{-3}$ and as total Mg of carbon emitted per Mg of timber harvested (referred to as the Carbon Impact factor or CIF), to account for differences in wood densities and logging intensities (Feldpausch et al., 2005). To estimate logging emissions per hectare ($Mg\,C\,ha^{-1}$), total emissions (E) were divided by the areas of sampled blocks. We used equation (12) from Fayolle et al. (2018) and wood density data from the Global Wood Density database to calculate aboveground biomass, while we estimated below-ground biomass from shoot biomass using equation (1) from Mokany et al. (2006). We converted biomass into carbon using a standardized carbon fraction of 0.47 (Brown and Lugo, 1992; Chave et al., 2014; Fayolle et al. 2018). Details about the methods used to estimate committed emissions from field measurements are provided in the supplementary information (S1).

**Hauling emissions** *(H)*. Hauling emissions included emissions from destruction of trees ≥ 10 cm for creation of logging roads (R) and log landings (L). To calculate the area of forest cleared for haul roads, we measured the width of haul road surfaces and adjacent strips of felled and bulldozed trees (hereafter 'haul road corridors') at 100 m intervals. While in the field we distinguished between new haul roads (clearing of forest) and old haul roads (re-clearing of previously cleared road corridors). Emissions from new haul roads ($R_N$ in Mg C) were estimated as:

$$R_N = \frac{\bar{w_R} * l_{NR}}{10000} * BD$$

where $\bar{w_R}$ is the mean haul road corridor width (m), $l_{NR}$ is the length of newly constructed haul roads allocated to a sample block (m), and BD is the biomass carbon density of adjacent unlogged forest ($Mg\,C\,ha^{-1}$). Emissions from re-clearing old roads ($R_O$ in Mg C) were estimated as:

$$R_O = \frac{(\bar{w_R} - \bar{w_{AR}}) * l_{OR}}{10000} * LR * SS$$

where $\bar{w_{AR}}$ is the mean measured haul road corridor width (m), $l_{OR}$ is the

**Table 1**
Key characteristics of the 50 ha areas sampled in 23 selected concessions grouped by country and management status: FSC = certified by FSC; MP = concession with a management plan validated by the government; and, TP = concession operating with a temporary permit but working toward completion of a management plan.

| Country | Status | N | Mean slope (%) | Mean elevation (m) | Trees harvested (# $ha^{-1}$) | Volume harvested ($m^3$ $ha^{-1}$) | Mean unlogged carbon density ($Mg\,C\,ha^{-1}$) |
|---|---|---|---|---|---|---|---|
| DRC | MP | 3 | 18 | 483 | 1.2 | 21 | 129 |
| | TP | 5 | 16 | 467 | 2.4 | 51 | 207 |
| Gabon | FSC | 3 | 9 | 353 | 3.2 | 46 | 225 |
| | MP | 3 | 8 | 360 | 1.4 | 56 | 126 |
| | TP | 3 | 7 | 377 | 1.1 | 22 | 250 |
| RoC | FSC | 3 | 25 | 425 | 3.3 | 40 | 157 |
| | MP | 2 | 24 | 408 | 3.1 | 18 | 161 |
| | TP | 1 | 26 | 420 | 2.4 | 38 | 179 |

**Table 2**
Mean estimates ( ± SE) of field variables measured to estimate emissions from hauling, skidding, and felling in 23 logging concessions (DRC = 8, Gabon = 9, and RoC = 6) of which 6 were FSC certified. The waste index estimates the percentage of wood left in forest due to poor utilization of merchantable portions of logs. Treatments with the same superscripts did not differ (ANOVA Tukey's HSD, P > 0.05).

| Country | Mean road width (m) | Mean corridor width (m) | Skid trail width (m) | Mean DBH (cm) | Mean extracted log length (m) | Waste (%) |
|---|---|---|---|---|---|---|
| DR Congo, | 5.5(0.4)[a] | 23.3(2.03)[a] | 3.8(0.1)[a] | 118(6.2) | 18(1.4)[a] | 8.1(0.4)[a] |
| Gabon | 5.9(0.4)[b] | 24.0 (2.1)[b] | 5.8(0.3)[a,b] | 107(4.7) | 21(1.1)[a] | 30.1(0.8)[b] |
| R of Congo | 8.5(0.2)[a,b] | 34.8(3.3)[a,b] | 3.7(0.3)[b] | 117(11) | 19(1.3)[a] | 3.5(0.2)[a] |
| **Status** | | | | | | |
| FSC | 7.5(0.6)[a] | 28.5(4.7)[a] | 4.5(0.5)[a] | 106(3.9) | 20(1.5)[a] | 17(1.1)[a] |
| Non-FSC | 6.1(0.4)[a] | 26.0(1.6)[a] | 4.5(0.3) [a] | 116(5.2) | 19(0.9)[a] | 15(0.4)[a] |
| Mean (N = 23) | 6.4(0.3) | 27(1.7) | 4.5(0.3) | 113(4.1) | 19.5(0.7) | 16(0.4) |

length of re-cleared old haul road, LR is the average logging rotation with 30 years as the default value, and SS is the secondary forest carbon sequestration rate ($Mg\,C\,ha^{-1}\,yr^{-1}$) with a default value of 2.726 (Bonner et al., 2013). Finally, emissions from log landings (L, Mg C) were estimated from the average log landing area in each concession (ha), the number of log yards per length of haul road surveyed ($m^{-1}$), and length of haul roads allocated to a sample block (m).

**Skidding (S)**. Skidding emissions were computed as the product of the emissions from the average skidding collateral damage ($CD_S$) per area ($Mg\,C\,ha^{-1}$) and the area of skid trails ($A_S$). GPS tracks of skid trail centerlines were used to calculate meters of skid trail per ha, adjusted to cutting block area based on the areas of gaps and overlaps for adjacent skid trail access areas. Skidding emissions were therefore calculated as:

$$S = C\bar{D}_S * A_S$$

where the average skidding collateral damage per area of skidding in sample block ($C\bar{D}_S$, $Mg\,C\,ha^{-1}$) was derived from the skidding collateral damage for all skidding damaged trees measured (Mg C) divided by area of all skid plots measured (ha).

**Felling (F)**. Felling emissions represent those that occurred when a tree or several trees were felled and created a canopy gap. The resulting emissions are from the above-ground and below-ground biomass of stumps and portions of felled trees left as dead wood in the forest, and adjacent trees ≥ 10 cm killed or severely damaged. Felling emissions were calculated as:

$$F = CD_F + HT$$

where $CD_F$ is the collateral damage emissions from felling in the sampled block (Mg C), calculated from the mean collateral damage emissions per measured tree ($Mg\ C\ tree^{-1}$) multiplied by the number of felled trees (stumps) measured. HT is the emissions from harvested trees (Mg C), derived from the average harvest tree emissions ($\hat{HT}$) per measured tree in the sampled block ($Mg\ C\ tree^{-1}$) multiplied by the number of felled trees (stump count). Additional details about calculation of gross committed emissions are summarized in S1 (logging equations file).

### 2.5. Statistical analyses

We fitted linear models on untransformed data to predict felling emissions due to collateral damage, and extracted and unextracted log emissions at the felling gap level (N = 309). We also fitted regression models for total emissions in $Mg\,C\,m^{-3}$ at the concession level (N = 23). We considered log diameter, mean log length, volume of wood extracted, tree density, logging intensity, and slope as potential predictor variables. We specified country or certification status as qualitative variables in the model because of the varied harvest treatments in use over time which combined to affect C stocks. We fitted our models using the gls () function in R version 3.3.1 (R Core Team, 2016). Our final model for total emissions as a function of logging intensity is:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \epsilon$$

where

$Y$ = In(TotalEm3)

$X_1$ = In(Logging Intensity)

$X_2$ = indicator variable for DRC ($X_2 = 1$ if country ≡ DRC, 0 otherwise)

$X_3$ = indicator variable for Gabon ($X_3 = 1$ if country ≡ Gabon, 0 otherwise)

According to this model, three parallel lines on the logarithmic scale are produced because when

- country ≡ DRC, $Y = \beta_0 + \beta_1 X_1 + \beta_2 + \epsilon$
- country ≡ Gabon, $Y = \beta_0 + \beta_1 X_1 + \beta_3 + \epsilon$
- country ≡ RoC, $Y = \beta_0 + \beta_1 X_1 + \epsilon$

Parallel lines are produced bacause $\beta_2$ and $\beta_3$ are just offsets to the RoC intercepet term, $\beta_0$ on the logarithemic scale.

### 2.6. Emissions reduction scenarios with RIL-C implementation

We considered the following two scenarios about RIL-C implementation based on our field data: (1) a reference scenario that shows the expected emissions if current relationships and trends continue; (2) a 'RIL-C Level 1 scenario' that models the impacts on emissions if the FMEs achieved the best observed performance levels for each of the four RIL-C practices.

## 3. Results

### 3.1. Field measurements

The sampled concessions vary substantially in physical features and timber extraction methods (Table 2). Across all sites, logging road corridor width averaged 27 ± 1.7 m (mean ± 1 SE throughout), with a mean active surface width of 6.4 ± 0.3 m. Road were widest in RoC (34.8 ± 3.3 m and 8.5 ± 0.2 m, respectively; Table 2). Skid trails were substantially wider in the nine concessions in Gabon (5.8 ± 0.3 m), than in the eight concessions in DRC (3.8 ± 0.1 m), or the six concessions in RoC (3.7 ± 0.3 m). Maximum slopes measured 15 m up and down-hill from each stump were 10% in Gabon, 28% in RoC, and 30% in DRC, with corresponding means of 8%, 25%, and 17% respectively.

Of the 309 felled trees measured across the 23 concessions, the largest were around 200 cm DBH (mean = 113 ± 4.1) and the longest logs extracted were 35 m (mean = 19.5 m ± 0.7 l; Table 2). The proportions of trees felled from which no logs were extracted ranged from 3.5% in RoC to 30.1% in Gabon (Table 2). The 6 FSC concessions felled and abandoned trees without extracting any wood just as often as the 17 non-certified concessions (17% and 15% of felled trees, respectively; P = 0.12).

**Table 3**
Committed emission from hauling, skidding, and felling by country and averaged by concession status (mean ± SE). The carbon impact factor (CIF; see SI) is expressed in units of Mg C emitted per Mg C in the harvested wood. Treatments with the same superscripts did not differ (ANOVA Tukey's HSD, P > 0.05 and 95% CI).

| Country | Hauling Emissions Mg C $m^{-3}$ | Skidding Emissions Mg C $m^{-3}$ | Felling Emissions Mg C $m^{-3}$ | Total Emissions Mg C $m^{-3}$ | Carbon Impact Factor Mg C Mg $C^{-1}$ |
|---|---|---|---|---|---|
| DR Congo (N = 8) | 0.52 ± 0.1[a] | 0.2 ± 0.05[a] | 1.1 ± 0.15[a] | 1.84 ± 0.3[a] | 5.8 ± 0.97[a] |
| Gabon (N = 9) | 1.60 ± 0.4[b] | 0.11 ± 0.04[a] | 0.97 ± 0.22[a] | 2.65 ± 0.5[a] | 10.7 ± 1.9[a] |
| R of Congo (N = 6) | 0.93 ± 0.3[a, b] | 0.07 ± 0.04[a] | 0.54 ± 0.06[a] | 1.54 ± 0.3[a] | 6.8 ± 2.5[a] |
| **Status** | | | | | |
| FSC (N = 6) | 1.20 ± 0.3[a] | 0.10 ± 0.04[a] | 0.84 ± 0.3[a] | 2.14 ± 0.6[a] | 9.7 ± 3.1[a] |
| Non-FSC (N = 17) | 0.98 ± 0.2[a] | 0.14 ± 0.03[a] | 0.94 ± 0.11[a] | 2.05 ± 0.3[a] | 7.3 ± 1.1[a] |
| Mean (N = 23) | 1.04 ± 0.2 | 0.13 ± 0.03 | 0.91 ± 0.11 | 2.1 ± 0.25 | 8.0 ± 1.1 |

### 3.2. Committed emissions from selective logging

Selective logging in the 23 concessions generated a mean of 2.1 ± 0.25 Mg C $m^{-3}$ (18.4 Mg C $ha^{-1}$) of committed emissions, which represents a transfer of 9% of live above- and below-ground tree carbon biomass into necromass based on a mean pre-harvest forest biomass of 202 Mg C $ha^{-1}$ (Table 3). Emissions per cubic meter of timber extracted in Gabon were 30% higher than in DRC (2.65 ± 0.5 Mg C $m^{-3}$ in Gabon vs 1.84 ± 0.3 Mg C $m^{-3}$ in DRC) and 42% higher than in RoC (1.54 ± 0.3; Table 3). Carbon emissions per cubic meter of timber harvested did not differ between FSC-certified and non-certified concessions (Table 3).

Felling emissions, the sum of emissions from unextracted logs and portions thereof, collateral damage, and extracted wood, contributed 43% of the total emissions (Table 3). Of the felling emissions, the felled tree remainder, or portion of felled trees left on-site, represented 22%, collateral damage caused by felling of trees selected for harvest represented 13%, and 9% of emissions were from the extracted wood. Hauling emissions that combine emissions from roads and log yards accounted for 50% of emissions, of which 45% of were from logging roads (only 5% from log yards), while skidding damage contributed only 6%.

Committed emissions from hauling (1.04 ± 0.2 Mg C $m^{-3}$; Table 3) varied almost three-fold between the lowest value in DRC (0.52 Mg C $m^{-3}$) to the highest in Gabon (1.6 Mg C $m^{-3}$). In all cases, log landings contributed relatively little to hauling emissions (11% in Gabon, 10% in DRC, and 5% in RoC). Road emissions represented as much as 60% of total emissions in Gabon and RoC compared to < 28% of total emissions in DRC (Table S1). FSC concessions showed somewhat lower hauling emissions than non-certified concessions, but the difference was not significant (Table 3). Committed emissions from skid trails also differed by country from 4% and 5% of total emissions in Gabon and RoC, respectively, to 11% in DRC.

Committed emissions from logging gaps varied by less than a factor of two between the lowest felling damage in RoC and to the highest in DRC (Table 4). Emissions from tree remainders (i.e., the stumps, tops, and logs left in the forest) accounted for 50% (DRC) and 52% (Gabon and RoC) of the total emissions per tree harvested. Collateral damage emissions varied from 34% (Gabon) and 30% (DRC) to just 20% (RoC), while emissions from extracted wood contributed 15% in Gabon, 23% in DRC, and 26% in RoC. FSC concessions showed 9% lower emissions from felling than non-certified concessions. Volumes extracted per tree ranged from 10.5 $m^3$ (Gabon) to 13.3 $m^3$ (RoC) with extracted masses of 6.7, 8.6 and 9.6 Mg C for RoC, Gabon, and DRC, respectively.

We observed large differences among concessions in carbon emissions per unit volume of timber extracted, which ranged from 4.8 Mg C $m^{-3}$ in concession GAB9 to 0.63 Mg C $m^{-3}$ in RoC6 (Fig. 1). Emissions from roads and the remainders of cut trees represented the major sources of emissions, followed by collateral damage and extracted timber, while log yards and skidding emissions remained the lowest. For some concessions in Gabon (GAB9 and GAB6), road emissions were three to four-times higher than from the concessions with the lowest emissions from this source.

The proportion of above and below ground biomass carbon of unlogged forest emitted from all logging sources averaged 9% across all concessions with 10% for the highest intensity logging (RoC and Gabon), and as little as 7% in DRC (Table 5).

### 3.3. Landscape characteristics and logging emissions

We explored for the factors responsible for differences in committed emissions by concession, management status, and country. In the 23 concessions, committed emissions per $m^3$ of timber extracted decreased with timber volumes harvested per ha ($P = 0.04$; Fig. 2a). In contrast, committed emissions per ha were not related to harvested volumes ($P = 0.84$; Fig. 2b). Emissions did not vary with certification status ($P = 0.62$). However, when fitting separate models, committed emissions per $m^3$ harvested decreased when volume of wood extracted increased, representing 81% the variation among the 6 FSC concessions ($P = 0.02$) and only 7% of the variation among the 17 non-certified concessions ($P = 0.29$). The decrease in committed emissions per ha did not differ as a function of certification status ($P = 0.35$). For FSC concessions, volumes extracted explained 30% of the variation in committed emissions per ha ($P = 0.26$), while it explained only 2% of the variation in non-certified concessions ($P = 0.60$).

Emissions did not increase strongly with size of felled trees

**Table 4**
Timber volumes extracted and emissions (mean ± 1 SE) per felled tree and the resulting emissions from collateral damage aggregated by country and certification status.

| Country | Volume extracted per tree ($m^3$) | Carbon extracted tree (Mg C) | Collateral damage emissions (Mg C $m^{-3}$) | Extracted wood emissions (Mg C $m^{-3}$) | Tree remainder emissions (Mg C $m^{-3)}$ | Felling emissions (Mg C $m^{-3}$) |
|---|---|---|---|---|---|---|
| DR Congo | 11.1 (1.3) | 9.6 | 0.33 (0.07) | 0.25 (0.02) | 0.55 (0.09) | 1.1 (0.15) |
| Gabon | 10.5 (2.1) | 6.7 | 0.33 (0.09) | 0.15 (0.01) | 0.5 0.13) | 0.97 (0.22) |
| RO Congo | 13.3 (3.4) | 8.6 | 0.11 (0.03) | 0.15(0.02) | 0.28 (0.04) | 0.54 (0.06) |
| **Status** | | | | | | |
| FSC | 10.1 (2.3) | 7.5 | 0.23 (0.11) | 0.16 (0.02) | 0.45 (0.18) | 0.84 (0.3) |
| N-FSC | 11.8 1.5) | 8.5 | 0.28 (0.05) | 0.19 (0.02) | 0.46 (0.06) | 0.94 (0.11) |
| Mean (N = 23) | 11.4 (1.3) | 8.2 | 0.27 (0.05) | 0.18 (0.01) | 0.46 (0.06) | 0.91 (0.11) |

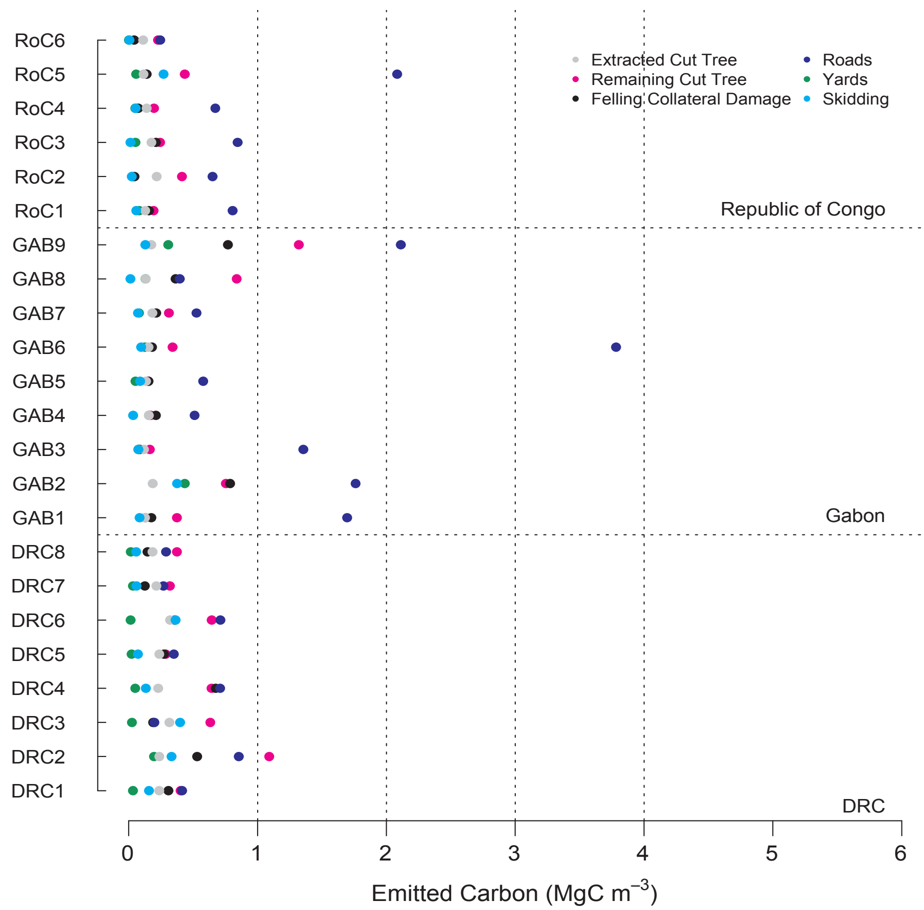


**Fig. 1.** Committed emissions (biomass carbon transformed into necromass) by six categories of logging impacts in the twenty-three concessions sampled in the three Congo Basin countries.

(P = 0.11); the linear relationship only explained 12% of the variation. Likewise, there is only a weak relationship between collateral damage and the number of felled trees in felling gaps (*P* = 0.36). Emissions varied with neither certification status nor country.

Fifty-two percent of the variability among concessions in felling emissions was explained by the densities of trees felled for harvest ($R^2 = 0.54$, $P < 0.001$; Fig. 3). When concession status (i.e., certified or not) and country were added as variables, the model did not improve.

Although felling accounted for almost half of the overall emissions from logging, there was no relationships between felling emissions and either diameter of trees harvested or slope (8–30%) near the trees (Fig. 4). However, collateral damage emissions at the tree level increased with slope in DRC concessions ($R^2 = 0.44$; $P < 0.001$), but not in Gabon ($R^2 = 0.02$; $P = 0.14$) or RoC ($R^2 = 0.08$; $P < 0.001$). Felling emissions per m$^3$ extracted increased with slope at the concession level ($R^2 = 0.24$; $P = 0.02$). Harvested trees in Gabon and DRC concessions were typically larger than those in the RoC (Fig. 4), but when country was included as a variable in the model, no differences in tree size were detected.

### *3.4. Potential for emissions reductions with RIL-C*

No single concession had the lowest emissions for each RIL-C activity, but based on the best-performing concessions for each RIL-C activity (e.g., the concession with the lowest felling emissions), the overall Level 1 emissions reduction would be 51% (Table 6). Most of those reductions would be from not felling trees from which no timber is extracted and from reduction of road corridor widths to 22 m. Additional emissions reductions could be achieved through better planned and shorter skid trails, especially in DRC where skidding contributed 11% of total emissions.

**Table 5**
Committed emissions per ha from selective logging expressed relative to the pre-harvest carbon density of 202 Mg C ha$^{-1}$. Treatments with the same superscripts did not differ (ANOVA Tukey's HSD, P > 0.05 and 95% CI).

| Country | Emissions (Mg C m$^{-3}$) | Emissions (Mg C ha$^{-1}$) | Carbon Impact Factor, Mg C emitted per Mg C extracted | Biomass carbon stocks (Mg C ha$^{-1}$) | Proportion of biomass carbon transferred to necromass |
|---|---|---|---|---|---|
| DR Congo | 1.84(0.3) | 13.6(1.9) [a] | 5.8(0.97) | 202 | 0.07 |
| Gabon | 2.65(0.5) | 20.8(1.9) [b] | 10.7(1.9) | 202 | 0.10 |
| R of Congo | 1.54(0.3) | 21(1.8) [b] | 6.8(2.5) | 202 | 0.10 |
| Status | | | | | |
| FSC | 2.14(0.6) | 19.7(2.1) [a] | 9.7(3.1) | 202 | 0.10 |
| Non-FSC | 2.05(0.3) | 17.9(1.6) [a] | 7.3(1.1) | 202 | 0.09 |
| Mean (N = 23) | 2.1(0.25) | 18.4(1.3) | 8(1.1) | 202 | 0.09 |

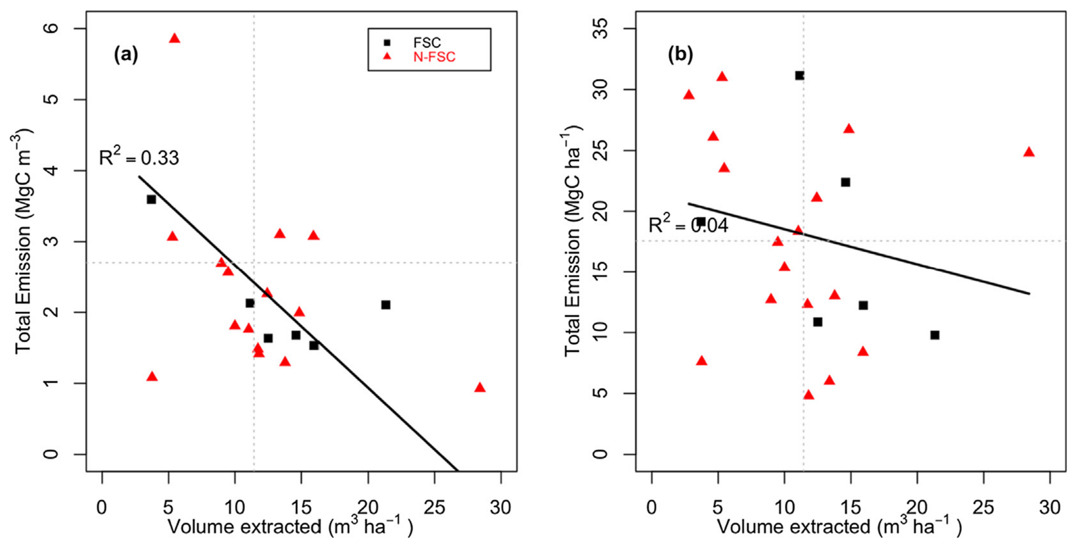


**Fig. 2.** Total emission per cubic meter of timber extracted (a) and per hectare (b) as a function of harvest intensity expressed as volume per hectare in FSC certified (squares) and un-certified concessions (triangles). With increases in logging intensity, emissions decreased per cubic meter ($P < 0.01$, $R^2 = 0.33$) but did not decrease per hectare ($P = 0.35$, $R^2 = 0.04$). Expressed in either way, there was no apparent relationship with certification status ($P > 0.89$).

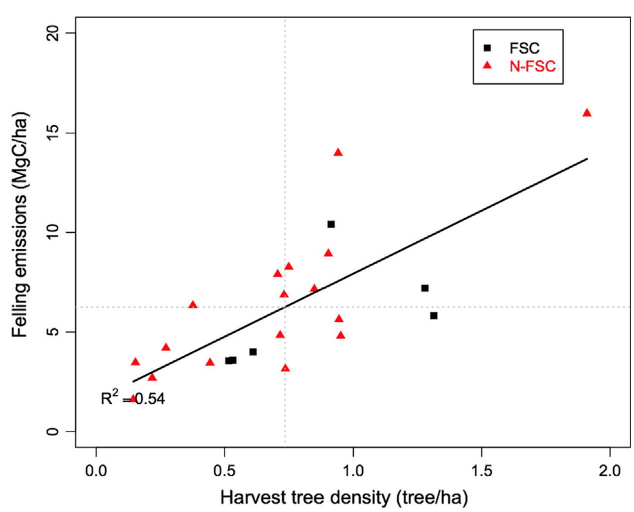


**Fig. 3.** Simple linear regression model between felling emissions and the number of harvested trees per ha in sampled block for FSC-certified and un-certified (N-FSC) concessions. Harvest tree density explained 54% of the variability among concessions in per ha felling emissions ($P < 0.001$).

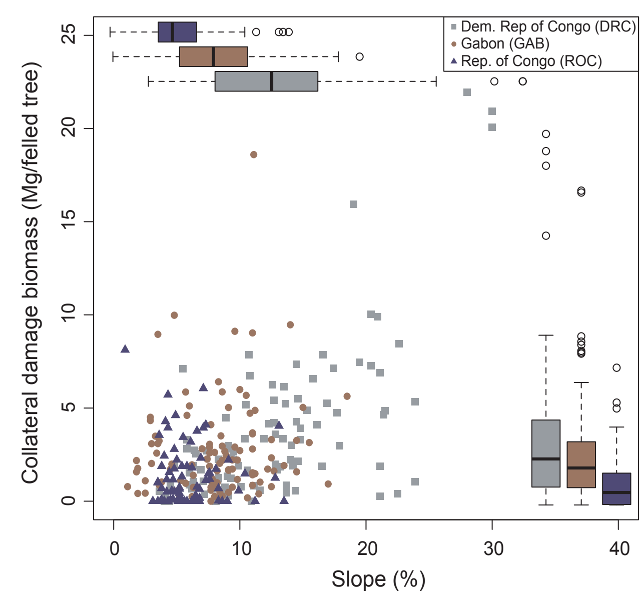


**Fig. 4.** Slope explains only 27% of the variation across the three countries in collateral damage emissions per felled tree ($R^2 = 0.27$; $P < 0.001$), but both collateral damage and slope differed among countries (Tables 1 and 4). There is no correlation between collateral damage emissions and slope in Gabon and RoC ($R^2 < 0.01$; $P \geq 0.2$), where slopes were fairly gentle, but a positive correlation in DRC ($R^2 = 0.44$; $P < 0.001$) where slopes were often steep. Grey squares = concessions in DRC (n = 102 trees), orange circles = Gabon (n = 135 trees), and purple triangles = RoC (n = 75 trees). Boxplots show variation in slope and collateral damage emissions per country; outliers represented by open circles.

Emission reductions potentials were highest in Gabon (62% with Level 1 implementation), 45% in DRC, and 34% in RoC (Fig. 5). With 53% and 58% of total emissions from roads in Gabon and RoC, respectively, concessions in those countries could reduce their road-related emissions by more than half if their roads were the width of the four best concessions in DRC, one certified concession in Gabon, and one uncertified concession in RoC. All three countries have the potential to reduce emissions from collateral damage emissions by 52%, 43% by not felling trees that yield no timber, and 29% by better bucking to maximize wood extraction.

## 4. Discussion

### 4.1. Selective logging intensity and stand damage

We estimate that committed emissions from selective logging in the Congo Basin average 18.4 Mg C ha$^{-1}$, 2.1 Mg C m$^{-3}$, or 8 Mg C Mg C$^{-1}$ (destroyed biomass per m$^3$ of timber harvested). This impact represents a transfer of 9% of above- and below-ground tree biomass to necromass. These estimates are similar to those reported by Pearson et al. (2014) for RoC (8.9 Mg C ha$^{-1}$ and 0.99 Mg C m$^{-3}$), Indonesia (1.49 Mg C m$^{-3}$), and Guyana (2.33 Mg C m$^{-3}$). In terms of per hectare reductions in biomass due to selective logging in Gabon, Medjibe et al. (2013) reported a loss of 2.9% in an FSC-certified concession and 6.3% in a nearby uncertified concession for an average of 4.1% average loss of pre-logging biomass (i.e., 17.2 Mg C ha$^{-1}$ or ~ 10 Mg C ha$^{-1}$ based on our methods). Our estimated average committed emission is about 51% higher than the results from these two previous studies but about 64% to 80% lower than those reported by Griscom et al. (2014) for East

**Table 6**
Emissions reductions from demonstrated (Level 1) target implementation levels for four RIL-C practices. We selected the mean of the best recorded concessions with the lowest values for each operation.

| Logging Activity Category | Emissions Category | Mean Emissions Baseline (Mg C m$^{-3}$) | RIL-C Level 1 Emissions Reductions (Mg C m$^{-3}$) | Level 1 Implementation description |
|---|---|---|---|---|
| Felling and log recovery: Includes pre-harvest inventory, felling, bucking and extraction practices | Emissions resulting from collateral damage | 0.27 | 0.14 | Best recorded used directional felling, liana cutting (RoC concessions), and worker training |
| | Emissions from trees felled and abandoned | 0.46 | 0.23 | Avoided felling hollow trees |
| | Emissions from trees felled with some volume extracted | 0.18 | 0.13 | Maximize extraction of wood so that only 5–10% of merchantable wood is left in forest) |
| Hauling: well-planned road network, narrower haul roads and smaller log landings. | Emissions from clearing road corridors and log landings. Includes emissions from poorly planned road networks and road edge tree deaths | 1.04 | 0.44 | Mean road corridor width < 22 m and find the optimal ratio between lengths of roads and skid trails to shorten the former (data not shown) |
| Skidding: well-planned skid trail networks | Emissions from skidding damage | 0.13 | 0.106 | Grand mean of best recorded (concessions in Gabon and RoC) |

Kalimantan, Indonesia (51.1 Mg C ha$^{-1}$), Mazzei et al., 2010 for Brazil (94.5 Mg ha$^{-1}$), and Pinard and Putz (1996) for Malaysia (104 Mg ha$^{-1}$).

In the Pearson et al. (2014) study, felling emissions, which include logging damage and extracted log emissions expressed per cubic meter of timber harvested dominated the total emissions in Indonesia (55%), Guyana (58%) and RoC (76%). Griscom et al. (2014) estimated that 59% of committed emissions from selective logging in Indonesia were from felling (38% was from the remainder of felled trees and 21% from collateral damage), 24% from skidding, and 16% from hauling. We estimated 43% of emissions in the three Congo Basin countries we studied were from felling, 50% from hauling, and only 6% from skidding, although these factors varied by country. Elsewhere in Gabon, Medjibe et al. (2013) reported 13.1–24.2 Mg ha$^{-1}$ from felling, 28.8–54.0 Mg ha$^{-1}$ from the extracted logs, and 5.9 – 12.1 Mg ha$^{-1}$ from skidding (road emissions were not reported). These three factors from Medjibe et al. (2013) are similar to those we obtained for Gabon, despite the high and variable extraction rates among the sampled concessions.

Unlike the finding of Medjibe et al. (2013) in Gabon, we found that average emissions in FSC-certified and non-certified concessions did not differ, but FSC concessions showed somewhat higher roads emission and lower emissions from felling and skidding. One FSC concession in Gabon (GAB9) showed the highest emissions of all 23 concessions studied. To assure that RIL practices are employed and to track emissions reductions, we recommend that FSC auditors employ a version of the RIL-C sampling protocol.

Emissions from felling varied substantially among the 23 concessions distributed across the three countries (Fig. 1). This variation was observed despite similar densities of harvested trees (Fig. 3), and the lack of a relationship between felled tree sizes or the number of felled trees per gap and logging emissions. We observed variation in collateral damage emissions among countries with differences slope ranges but overall, slope did not explain much variability in emissions, (Fig. 4) as reported elsewhere (Griscom et al. 2014; Putz et al. 2018). However, in DRC with wide range of slope angles (7–30%), collateral damage emissions were higher on steep areas (Fig. 4), as expected since slopes may affect many physical processes due to gravitational acceleration and geometry (Putz et al. 2018). To our surprise, emissions were not higher on the steepest slopes in RoC (20–28%) or in Gabon (7–10%).

### 4.2. RIL-C impact performance methodology

The substantial carbon benefits from improved tropical forest management demonstrated in this study justify payments for emissions reductions by REDD + and other climate change mitigation programs. One advantage of this "natural climate solutions pathway" (Griscom et al., 2017) is that because no reductions in timber yields are required, it entails no risk of leakage due to displacement of logging. In our RIL-C study, the relationship between carbon emissions per m$^3$ of wood extracted and harvest intensity followed similar negative curvilinear trends in all three countries, while there was no indication that FSC certification was associated with reduced emissions (Fig. 6; see S2). RIL-C impact performance promotes increased production rates and profits to support economic development through fulfillment of social obligations while achieving low carbon emissions by not felling trees that yield no timber and by increased wood recovery from the trees that do. These RIL-C practices allow higher timber yields with fewer trees felled, less skidding induced mortality, and reduced emissions from forest clearing of for haul roads and log yards (Feldpausch et al., 2005; Pearson et al., 2014).

In Gabon, more than half non-certified concessions showed high total carbon emissions (Mg C m$^{-3}$) despite low harvesting intensities, while in RoC and DRC, non-certified concessions emitted relatively little. While emissions (Mg C m$^{-3}$) varied greatly among concessions, there was no difference between those that were FSC certified and those

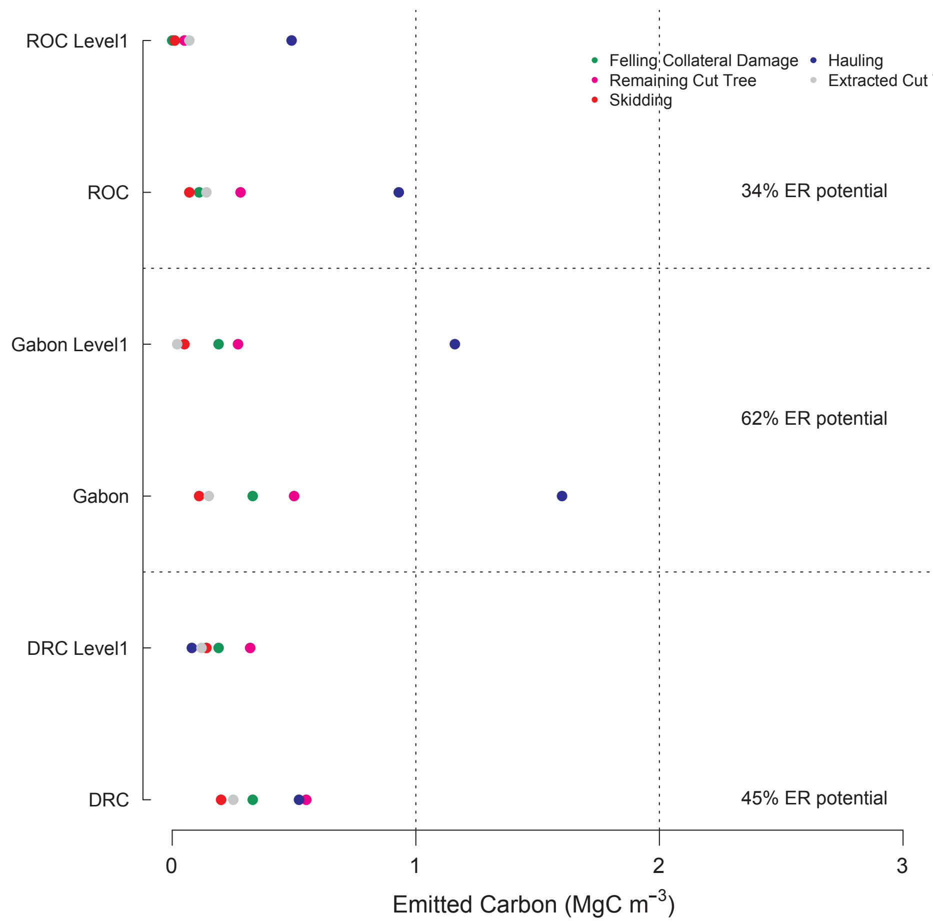


**Fig. 5.** Committed emissions per cubic meter of timber extracted from existing practices and with implementation of the four RIL-C practices described in Table 6. Mean emissions from existing practices can be reduced by 51% through implementation of RIL-C practices Level 1. ER = emission reductions.

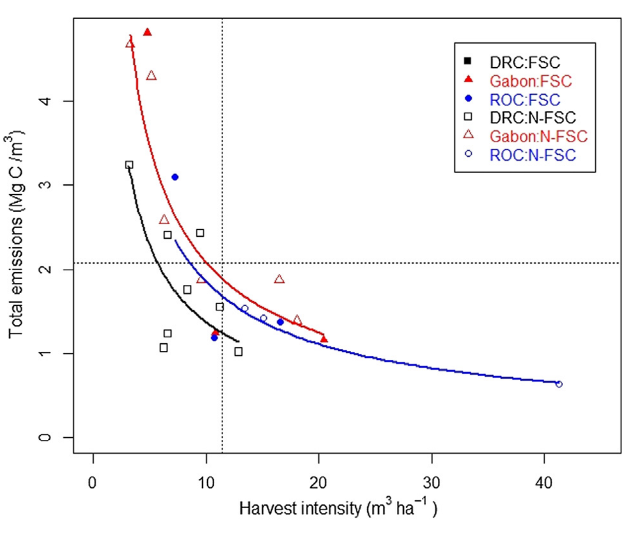


**Fig. 6.** Carbon emissions (Mg C m$^{-3}$) versus harvest intensity in DRC, Gabon, and RoC for FSC-certified and non-certified concessions (N-FSC; for model structure and ANOVA see Table S3; for the statistical method see Gregoire (2015).

that were not at least partially due to high variation coupled with small sample sizes and potential positive sampling bias (i.e., only good performing concessions were sampled). This variation can be explained by differences in logging practices driven by management status or other factors that remain to be investigated. Due to the large variation in logging emissions from FSC-certified concessions, we suggest that FSC criteria and indicators (FSC and Council, 2002) be coupled with a monitoring approach such as the RIL-C to clarify what practices deserve attention and to increase assurance of responsible management.

Results in this study also suggest that by reducing road corridor widths and by maximizing timber extraction, substantial emissions reductions are possible. Road corridors are wide to promote surface drying, but better road drainage and surfacing with gravel are suitable substitutes, especially if coupled with better layouts and overall engineering. Thus, opportunities for reduced emissions depend in part on willingness to invest in high quality roads. While logging roads are easily monitored with remote sensing or by FSC auditors in the field, it will be harder to track felling emissions from abandoned logs and poor bucking (Pearson et al. 2014), both of which are tracked with the RIL-C methodology. We recommend that some form of this methodology be incorporated into national standards to quantify logging emissions if national emission reduction targets are to be met in these high forest cover countries.

### 4.3. *Committed emissions from selective logging vs. deforestation*

Selective logging of merchantable timber, which takes place over the whole Central African region, emits little carbon per hectare because the harvest intensities are low, but the total emissions are substantial. To estimate these emissions at national scales we used reported industrial roundwood production data from FAO FRA 2015 and applied the relevant emission factors obtained in this study (Table 7). To contextualize these values, we compared the gross emissions with those

**Table 7**
Gross committed emissions from selective logging of natural forests based on concession averages from each country, emissions from deforestation, and the maximum mitigation potential from implementing RIL-C practices generated from this study.

| Country | Roundwood production* ($10^3$ $m^3$ $yr^{-1}$) | Total emissions from logging+ (Tg C $yr^{-1}$) | Total emissions from deforestation# (Tg C $yr^{-1}$) | Ratio of logging to deforestation | Maximum mitigation potential with RIL-C (Tg C $yr^{-1}$) |
|---|---|---|---|---|---|
| DRC | 4,611 | 5.99 | 23 | 0.27 | 2.70 |
| Gabon | 1,987 | 2.15 | 3.97 | 0.54 | 1.33 |
| RoC | 1,779 | 1.1 | 3.29 | 0.33 | 0.37 |
| CAR | 623 | 0.65 | 4 | 0.16 | 0.33 |
| Cameroon | 3,264 | 3.4 | 7 | 0.48 | 1.73 |
| Equatorial Guinea | 750 | 0.8 | 1.2 | 0.6 | 0.40 |
| Region | 2,169 | 2.34 | 7.0 | 0.4 | 1.14 |

* Round wood harvest data from FAO's Forest Resources Assessment reported in 2015.
\# Total emissions from deforestation are from Harris et al.2012.
\+ Total emissions excluding logging roads.

from deforestation using data from Harris et al. (2012). Such estimates would be more reliable if based on country-specific emissions factors and of course if based on more accurate estimates of harvested volumes from natural forests (Pearson et al. 2014). For this analysis, we excluded hauling emissions because Harris et al. (2012) may have already included these areas as deforestation (Pearson et al. 2014). We then applied the potential emissions reductions from RIL-C implementation in each country. We applied regional average for countries with no field sampled concessions from our study.

An average of 40% of total emissions from deforestation and forest degradation are from harvesting timber in the six countries Congo Basin countries (Table 7). The DRC, with the highest emissions from deforestation, logging emissions still represent 27% of total land-use change emissions. In countries with low deforestation emissions, such as Equatorial Guinea, RoC, Gabon, and Cameroon, logging emissions contribute higher proportions to the totals, from 33% in RoC to 60% in Equatorial Guinea. To meet their Nationally Determined Commitments (NDCs), these countries might focus on opportunities to reduce logging emissions through implementation of RIL-C practices. We estimate 1.14 (Tg C $yr^{-1}$), an equivalent of 51% of maximum mitigation potential to reduce emissions from degradation.

### 4.4. Limitations of the study

The opportunistic nature of sampling concessions may insinuate a bias into our results, especially if the concessions that granted access to us maintained management practices that were above average. We recognize this possibility but lack any means to validate whether or not it affected in our results. We regard the trends revealed by the 23 concessions that were studied are of great value, notwithstanding the possibility of sampling bias. We also note that the bias is likely positive, which means that our estimates of potential emissions reductions from use of RIL-C practices are conservative.

## 5. Management implications

Future timber yields from selectively logged tropical forests, which are critical for the long-term economic well-being of countries in Central Africa, will vary with harvest intensities and the manners in which timber is harvested. Forest industries contribute up to 7% to the economies of Congo Basin countries, and, in Gabon, they are the second largest employer after the government (de Wasseige et al., 2009). If logging is wasteful, timber stocks will decline rapidly, thereby compromising the ability of the forest to support future extractive economic activities (Umunay et al., 2017). The design of possible actions for reducing logging damage and associated emissions by improving logging practices depend on detailed data about the practices and their consequences. As such, direct measurements, like those employed in this study, allow quantification of damage and associated emissions from each source. Hauling emissions (50%) and emissions from felling damage (43%) are the largest sources of emissions in most of the Congo Basin concessions studied. We suggest that efforts to reduce emissions from these sources include extracting more timber per felled tree and reducing waste. Felling damage would also be reduced by improved directional felling and minimization of incidental damage to surrounding trees through pre-felling liana cutting. Emissions from infrastructure could be reduced by better road planning, shorter roads, and narrower road corridors; efforts should be made to find the optimal ratio between lengths of roads and skid trails. Finally, especially in areas that are steep or where soils are particularly erosion-prone, cable yarding of timber could replace the opening of skid trails up to the stump of each felled tree. We estimated that by applying these RIL-C Level 1 improved practices, emissions could be reduced by 51%. We also believe that the RIL-C monitoring protocol employed in this study represents a robust and cost-effective accounting system that can be used in the design and implementation of performance-based emissions reductions mechanisms. Other improved forest management practices that do not necessarily reduce carbon emissions (e.g., safety gear for forest workers and use of post-logging silvicultural treatments) also deserve attention if countries in the region are to move towards sustainable forest management.

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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.2019.01.049.

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