Impacts of selective logging on above-ground forest biomass in the Monts de Cristal in Gabon

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Abstract
Selective logging is an important socio-economic activity in the Congo Basin but one with associated environmental costs, some of which are avoidable through the use of reduced-impact logging (RIL) practices. With increased global concerns about biodiversity losses and emissions of carbon from forest in the region, more information is needed about the effects of logging on forest structure, composition, and carbon balance. We assessed the consequences of low-intensity RIL on above-ground biomass and tree species richness in a 50 ha area in northwestern Gabon. We assessed logging impacts principally in 10 randomly located 1-ha plots in which all trees \( \geq 10 \) cm dbh were measured, identified to species, marked, and tagged prior to harvesting. After logging, damage to these trees was recorded as being due to felling or skidding (i.e., log yarding) and skid trails were mapped in the entire 50-ha study area. Allometric equations based on tree diameter and wood density were used to transform tree diameter into biomass.

Logging was light with only 0.82 trees \( (8.11\, \text{m}^3) \) per hectare extracted. For each tree felled, an average of 11 trees \( \geq 10 \) cm dbh suffered crown, bole, or root damage. Skid trails covered 2.8% of the soil surface and skidding logs to the roadside caused damage to an average of 15.6 trees \( \geq 10 \) cm dbh per hectare. No effect of logging was observed on tree species richness and pre-logging above-ground forest biomass \( (420.4\, \text{Mg ha}^{-1}) \) declined by only 8.1% \( (34.2\, \text{Mg ha}^{-1}) \). We conclude from these data that with harvest planning, worker training in RIL techniques, and low logging intensities, substantial carbon stocks and tree species richness were retained in this selectively logged forest in Gabon.

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1. Introduction
The two million km\(^2\) of Congo Basin forest is high in conservation value and crucial for both national development and the livelihoods of about 100 million people (de Wasseige et al., 2009; FAO, 2011). These forests are among the world’s most intact and provide substantial but seldom measured quantities of carbon (Lewis et al., 2009). Logging by untrained and unsupervised laborers working without the aid of adequate management plans is taking a great toll on Congo Basin forests (Hall et al., 2003; Ruiz Perez et al., 2005; Cerutti et al., 2008, 2011; Ezzine de Blas and Ruiz Perez, 2008; Angelsen et al., 2009; Poulsen et al., 2009). In Gabon, for example, of the 12.4 \( \times 10^6 \) ha of “forêt productive enregistrée” in 2008, management plans were prepared for only about a quarter of the area being logged (WRI, 2009).

Based on studies conducted in tropical forests but not in Africa, employment of reduced-impact logging (RIL) practices reduces collateral forest damage, which results in both substantial reductions in carbon emissions and increased biodiversity retention (see Johns et al., 1996; Pinard and Putz, 1996; van Rheenen et al., 2004; Putz et al., 2008a; van Kuijk et al., 2009; Putz and Nasi, 2009). RIL is a suite of techniques based on scientific and engineering principles that, in combination with worker education, training, and supervision,
improves the efficiency of application of labor and equipment in the harvesting of industrial timber while reducing damage to residual stands (Dykstra, 2002). While definitions of RIL are imprecise and not all of these techniques are used in every site claiming to be applying RIL, studies of areas logged using some or all of these techniques in South America and Asia have shown increased forest carbon retention both immediately after logging and for decades afterwards (Putz et al., 2008b). Unfortunately, the implementation of RIL requires up-front capital investment in timber inventories, staff training, and sometimes machinery, along with substantial modifications in working practices. Logging company managers and owners are unlikely to make these investments without clear indications of their benefits. Evidence for these benefits is scarce in Central Africa where little is known about the extent to which employment of RIL could serve to preserve carbon and tree species diversity.

If poorly implemented, selective logging causes substantial damage to residual stands. Logging directly and indirectly affects all components of biodiversity, from genes to landscapes (Putz et al., 2001; van Kuijk et al., 2009). Even light selective logging affects tree species composition, densities, and size-class frequency distributions, but the deleterious environmental impacts of logging can be substantially reduced if appropriate techniques are used (Bertault and Sist, 1997; Durrieu deMadron et al., 1998; van Kuijk et al., 2009). In a selectively logged forest in Indonesian Borneo, for example, Cannon et al. (1998) found that 8 years after logging the density of trees ≥ 20 cm dbh was lower than in unlogged plots but detected no difference in tree species richness. Similarly, in southwestern Central African Republic, Hall et al. (2003) found that forest sampled 18 years post-logging had lower tree densities than either unlogged stands or stands sampled 6 months post-harvest, but did not detect difference in tree species richness.

Tree harvesting unavoidably opens canopy gaps, reduces overall canopy cover, and disturbs soil surface. In Bolivia, for example, Jackson et al. (2002) found that planned harvesting of 4.3 trees ha⁻¹ (12.1 m³ ha⁻¹) opened the canopy over 25% of their study area. In eastern Brazil, Johns et al. (1996) found canopy reduction of 10% after planned logging of 4.5 trees ha⁻¹ (37 m³ ha⁻¹). In the semideciduous forest of Mbaïki, Central African Republic, Durrieu deMadron et al. (2000) reported 14–22% of area disturbed due to the harvest of 2.6–4.0 trees ha⁻¹ (mean = 118 cm dbh). These results show that the harvest of even small numbers of large trees results in substantial canopy opening.

Selective timber harvesting degrades forests in the sense that it results in reductions in carbon stocks that will need to be accounted for if a reduced-eliminations from deforestation and forest degradation (REDD; Angelsen et al., 2009) program is implemented. If Congo Basin countries are to benefit from REDD and REDD-like programs, data will be needed on the carbon consequences of logging. To fill some of the gaps in knowledge about the effects of logging on forest structure, composition, and above-ground biomass in Africa, we measured the damage resulting from felling and skidding due to low-intensity RIL in Gabon.

2. Methods

2.1. Study site

This study was conducted in the Monts de Cristal region of northwestern Gabon (00°20'N; 10°20'E; Fig. 1) in the 477,033 ha logging concession of Société Equatoriale d’Exploitation Forêsterie (SÉEF). The natural vegetation of this region is dense humid evergreen rainforest (Fuhr et al., 1998; Sunderland et al., 2004). The long-lived pioneer Aucoumea klaineana Pierre (Burseraceae) is the most common tree species. The soils are mostly oxisols, the climate is tropical with a long dry season (July–September), annual rainfall is 2000–2400 mm (Leonard and Richard, 1993), and average temperatures are 24–26 °C (Sunderland et al., 2004).

Logging in what is now the SEEF concession started in the 1950s but due mostly to the undulating topography, elevation (589 m above sea level), and inaccessibility, harvesting was extremely light and spatially patchy until SEEF started more thorough exploitation in 2000. Although we lack maps or other information about the history of the study site, we found no evidence of earlier episodes of harvesting in our study plots.

TIMBER EXTRACTION IN SEEF is selective with A. klaineana alone making up about 60% of the total volume. At the time of this study the concessionaire was preparing management plans for the entire concession with the intention of attaining Forest Stewardship Council (FSC) certification (Ricordo 2010, pers. comm.). With this goal in mind, SEEF allocated 250 ha to the Tropical Forest Foundation (TFF) and FORM International for training, demonstration, and research on RIL as part of an International Tropical Timber Organization project. In this area, harvestable trees of 27 commercial species were tagged, mapped, measured (dbh; diameter at breast height of 1.4 m or above buttresses), and identified to species. Prior to harvesting a total of 104 ha in July 2009 and January–February 2010, skid trails were planned by TFF on the basis of topographic and stock maps prepared by an inventory crew. Each feller received one week of training in directional felling techniques conducted by a professional trainer contracted by TFF. Trees were felled using chainsaws (Stihl MS 880) and yarded by a trained worker with a tracked skidder (Caterpillar D527); both operations were coordinated and supervised by TFF. Logging intensity in the 104 ha (0.82 trees ha⁻¹ and 8.11 m³ ha⁻¹) was within the typical range (0.7–4 trees ha⁻¹) for Central Africa (Durrieu deMadron et al., 1998; Ruiz Perez et al., 2005).

2.2. Plot-based measurements

Prior to harvesting we established ten permanent 200 × 50 m (1 ha) plots at random locations in 50 ha of the area to be subjected to RIL to capture variability in logging impacts. All trees ≥ 10 cm dbh in each plot were measured, tagged, mapped, classified according to stem quality and crown position (suppressed, sidelightened, sub-dominant, co-dominant and dominant; see Hall et al., 2003), and assessed for the presence or absence of lianas. Trees were identified to the species level where possible based on vegetative characteristics. Voucher specimens were collected for species that could not be identified in the field and then identified at the National Herbarium in Libreville.

2.3. Damage assessment

Logging damage was assessed in the 1-ha sample plots using methods well-established in the literature (e.g., Johns et al., 1996; Whitman et al., 1997; reviewed by Putz et al., 2008b). Damage to roots, boles, and crowns were ranked on a scale from minor to very severe. Crown damage was recorded as severe (>66% crown loss), moderate (33–66% crown loss), or minor (<33% crown). Bole damage was recorded as severe (broken bole), moderate (>100 cm² of bark removed), or minor (<100 cm² of bark removed). Uprooted trees were recorded as such. Root damage was recorded as major (>10% of surface roots injured) or minor (<10% of surface root injured). Crown, bole, and root damage were attributed to felling and/or skidding.

The soil surface area disturbed by skid trails and skidder activities in logging gaps was measured in the entire 50 ha study area. Skid trails were assigned to one of three categories based on the number of logs skidded (one log per pass): primary > 10; secondary 2–10; and, tertiary 1. Skid trail widths were measured every 10 m.
Felling gaps were measured from a central point to the gap edge in the eight cardinal and inter-cardinal directions based on Brokaw’s (1982) definition (gaps = forest canopy openings that are >20 m² and extend down through all foliage levels to a height of <2 m above ground). A total of 31 single-tree felling gaps were measured in the 50 ha block.

2.4. Conversion of above-ground biomass into necromass

To estimate the amount of above-ground biomass (AGB) converted into necromass during logging (="committed emissions" defined here as the estimated equivalent of carbon dioxide to be emitted by killed trees), we estimated the mass of each tree that was harvested or destroyed using one of Chave et al.’s (2005) allometric equations (see below) with published wood density estimates for trees harvested in Africa (Zanne et al., 2009). When more than one wood density value was available, we used the arithmetic mean; in the absence of species-specific wood density data we used the mean value for the genus or family; and, when none of these values were available, we used the plot mean (see Section 2.6.2).

2.5. Data analyses

2.5.1. Tree species richness

Species richness values in the 1 ha plots before and after logging were compared using EstimateS 8.2.0 (Colwell, 2006) with sample-based rarefaction to compute expected species accumulation curves. A randomization test without replacement was run to compute richness estimators and diversity indexes (e.g., Fisher’s alpha, Simpson’s, and Shannon’s) based on the sample size. Randomizations were based on 50, 75, and 100 iterations to produce relatively smooth diversity index curves. We used the outputs for 100 randomizations and Fisher’s alpha, defined by the relation 
\[
S = a \ln(1 + \frac{N}{a})
\]
where \(S\) represents the number of species, \(N\) the number of individuals, and \(a\) the diversity index (Leigh, 2008).

2.5.2. Above-ground biomass estimates

Total above-ground biomass of each tree in the plots was estimated using Chave et al.’s (2005) allometric equation:
\[
\ln(AGB) = -1.576 + 2.179 \times \ln(D) + 0.198 \times (\ln(D))^2 - 0.0272 \\
\times (\ln(D))^3 + 1.036 \times \ln(\rho)
\]
where \(D = \text{dbh} (5–156 \text{ cm range})\) and \(\rho = \text{wood density} (\text{df} = 1501)\). For unidentified species, we applied the mean wood density for each plot weighted by the number of trees from each species (see Lewis et al., 2009). For trees larger than 156 cm dbh, AGB was extrapolated.

2.5.3. Logging damage

Analysis of variance (ANOVA) was used to test for differences among skid trail orders in width and numbers of trees damaged
per unit length. For these tests, the units of replication are skid trails in each category \((n = 5\) for primary, \(n = 16\) for secondary, and \(n = 18\) for tertiary). After an overall difference was detected, Tukey's Honest Difference tests were employed for pairwise comparisons of means. Regression analyses were used to determine the relationships between the dbh of the felled trees and felling gap area and the number of trees damaged.

3. Results

3.1. Tree species richness

A total of 4527 trees >10 cm dbh representing 45 families, 188 genera, and 214 species were encountered in the 10 1-ha plots. Of the inventoried trees, A. klaineana Pierre (Burseraceae), the main harvested timber species in Gabon, represented 0.46% of the trees in the plots. Other important timber species such as Bikinia durandi (Caesalpinaceae) represented 1.3% of the identified trees, Dacryodes igaganga (Burseraceae) 4%, and Dialium angolense (Caesalpinaceae) 4.5%; Dacryodes buettneri (Burseraceae), a species that produces commercial timber but is banned from harvesting due to its high biodiversity value, represented 1.2% of the trees. Coula edulis (Oleaceae), an important non-timber forest product (NTFP) species, constituted 2.9% of the trees. Caesalpinaceae is the dominant family in the area, with 28.9% of the trees, followed by Oleaceae (13.4%), Burseraceae (12.7%), and Euphorbiaceae (8.1%).

In the 10 1-ha plots before and after logging, respectively, average species richness of trees >10 cm dbh were 214 and 206, Fisher's alphas were 47.01 and 46.56, Shannon's index values were 71.38 and 72.85, and Simpson's index values were 40.40 and 41.99. None of these descriptors of species richness and diversity were affected by logging (all comparisons based on \(t\)-tests with \(df = 18\): species richness \(t = 0.33, p = 0.75\); Fisher's alpha \(t = 0.26, p = 0.79\); Shannon's index \(t = 0.05, p = 0.96\); and, Simpson's index \(t = 0.61, p = 0.55\)).

3.2. Above-ground biomass prior to logging

Prior to harvesting, the total AGB estimates for the 10 1-ha plots ranged 293.4–511.1 Mg ha\(^{-1}\) with an average of 420.4 ± 92.95 Mg ha\(^{-1}\) (Table 1). The trees of the main commercial species, A. klaineana, represented 6.9% of the total AGB. Other timber species that contributed substantially to the total AGB included D. angolense (7.2%), Bikinia le-testui (6.3%), B. durandi (3.9%), and D. buettneri (3.2%), and C. edulis (11.9%).

### Table 1

<table>
<thead>
<tr>
<th>Plot</th>
<th>Total number of trees</th>
<th>Number of species(^a)</th>
<th>Maximum tree size (cm)</th>
<th>Total basal area (m(^2) ha(^{-1}))</th>
<th>Total AGB (Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIL-P1</td>
<td>463</td>
<td>89 (12)</td>
<td>198(^a)</td>
<td>31.6</td>
<td>431.1</td>
</tr>
<tr>
<td>RIL-P2</td>
<td>440</td>
<td>95 (5)</td>
<td>113</td>
<td>26.8</td>
<td>315.8</td>
</tr>
<tr>
<td>RIL-P3</td>
<td>432</td>
<td>90 (8)</td>
<td>195(^a)</td>
<td>35.5</td>
<td>508.2</td>
</tr>
<tr>
<td>RIL-P4</td>
<td>445</td>
<td>91 (7)</td>
<td>116</td>
<td>26.3</td>
<td>293.4</td>
</tr>
<tr>
<td>RIL-P5</td>
<td>520</td>
<td>99 (6)</td>
<td>152</td>
<td>36.6</td>
<td>508.2</td>
</tr>
<tr>
<td>RIL-P6</td>
<td>471</td>
<td>90 (4)</td>
<td>144</td>
<td>33.4</td>
<td>468.3</td>
</tr>
<tr>
<td>RIL-P7</td>
<td>478</td>
<td>86 (2)</td>
<td>150</td>
<td>27.3</td>
<td>357.3</td>
</tr>
<tr>
<td>RIL-P8</td>
<td>462</td>
<td>88 (1)</td>
<td>122</td>
<td>24.7</td>
<td>205.0</td>
</tr>
<tr>
<td>RIL-P9</td>
<td>391</td>
<td>81 (2)</td>
<td>146</td>
<td>34.3</td>
<td>506.1</td>
</tr>
<tr>
<td>RIL-P10</td>
<td>425</td>
<td>86 (2)</td>
<td>169(^a)</td>
<td>34.2</td>
<td>511.1</td>
</tr>
<tr>
<td>Mean(^b)</td>
<td>452.7 ± 34.83</td>
<td>89.5 ± 4.97</td>
<td>150.5 ± 29.91</td>
<td>31.1 ± 4.37</td>
<td>420.4 ± 92.95</td>
</tr>
</tbody>
</table>

\(^a\) Includes AGB of trees larger than those used to generate the allometric equation with which AGB was estimated (i.e., extrapolated estimates).

\(^b\) Number of unidentified species noted in parentheses.

\(^c\) Values are mean ± 1 standard deviation.

3.3. Logging damage

The size of the harvested trees in the 104 ha ranged 60–216 cm dbh with a mean of 85 cm; harvest intensity was light with 0.82 trees ha\(^{-1}\) (8.11 m\(^3\) ha\(^{-1}\)) extracted. Of the 10 intensively monitored 1-ha plots, five yielded one harvested tree and three other plots in which there was no felling contained trees damaged due to skidding; the other two plots suffered no damage from either felling or skidding (Table 2). Based on data from the 10 1-ha plots, the felling of one tree resulted in damage to an average of 11.0 other trees >10 cm dbh while skidding to the log landing resulted in damage to an additional 15.6 trees >10 cm. One plot was severely damaged due to both felling and skidding with 103 trees damaged (22.2% of trees >10 cm dbh) and 17 trees completely destroyed (i.e., uprooted) and converted into 32.9 Mg of necromass (Table 2).

The 39 skid trails in the 50 ha study area covered 2.8% of the ground surface (Table 3). Machine maneuvering resulted in an additional 2.6% of the ground surface being disturbed. Thus, a total of 5.4% of the ground was disturbed by log yarding activities. Of the trees damaged by skidding, about 26% were uprooted, 6% suffered severe bole damage, and 1% suffered severe root damage. Therefore, skidding was a major cause of tree uprooting and injuries to tree boles and roots (Fig. 2). No differences were detected among the numbers of trees damaged per length of primary (0.11 trees m\(^{-1}\)), secondary (0.12 trees m\(^{-1}\)), and tertiary (0.10 trees m\(^{-1}\)) skid trails \((F = 0.68; df = 36; p = 0.88)\). The widths of the three orders of skid trails also did not differ \((F = 0.70; df = 342; p = 0.50; Table 3)\).

Felling activities that occurred in five of the 10 1-ha plots damaged a total of 110 trees >10 cm representing an average of 11.0 trees ± 5.93 damaged per felled tree (Table 2). Of the trees damaged during felling, 56% suffered severe crown damage, 7% suffered moderate crown damage, and 15% suffered minor crown damage. Some trees were uprooted during felling operations (10%) and a few suffered root damage (9%; Fig. 2). Therefore, felling activities constituted a major source of tree crown loss and bole damage, but also resulted in a complete destruction of trees (i.e., uprooted) and severe root injuries (Fig. 2). Felling gap area increased exponentially with dbh of the felled tree (Fig. 3a) with a mean gap area per felled tree of 320.3 ± 44.29 m\(^2\) (mean ± SE). The number of damaged trees also increased with the size the felled tree (Fig. 3b).

3.4. Above-ground biomass converted into necromass (i.e., committed emissions)

Trees destroyed during felling and skidding (25.6 Mg ha\(^{-1}\)) plus the AGB in the harvested trees (8.6 Mg ha\(^{-1}\)) resulted in an average biomass loss of 34.2 Mg ha\(^{-1}\). Due to extreme heterogeneity in
logging intensity, AGB of the trees that were completely destroyed per hectare ranged from 0 to 32.9 Mg ha\(^{-1}\) with an average of 8.4 Mg ha\(^{-1}\). Overall, the total committed emissions due to harvesting of 0.82 trees ha\(^{-1}\) (8.11 m\(^2\) ha\(^{-1}\)) from the 10 monitored 1-ha plots averaged 17.0 Mg ha\(^{-1}\) or 4.05% of the pre-logging total (Table 2).

### 4. Discussion

#### 4.1. Tree species richness

The modest impacts of low-intensity selective logging using improved techniques (RIL) on species richness and other measures of tree diversity in the Monts de Cristal in Gabon is similar to results reported for forests elsewhere in the tropics. For example, Hall et al. (2003) found very similar Shannon diversity indices for trees in an unlogged forest stand and in nearby stands 6 months and 18 years post-harvest in the Central African Republic. While comforting from a biodiversity conservation perspective, it is important to note that such measures cannot indicate changes in species composition, and do not address the longer-term impacts of repeated harvesting (Kariuki et al., 2006).

#### 4.2. Above-ground biomass

Immediately after the harvest of 0.82 trees ha\(^{-1}\) (8.11 m\(^2\) ha\(^{-1}\)), above-ground biomass declined from the pre-logging average of 420.4 Mg ha\(^{-1}\) (Table 1) to 386.2 Mg ha\(^{-1}\) (Table 2) with an additional biomass of 17.2 Mg ha\(^{-1}\) in trees that suffered minor to moderate damage. Compared with other studies on logging damage, the impacts in the Monts de Cristal were small most probably due to both the use of RIL techniques and the low logging intensity (Table 4). The likely benefits of RIL impacts varied with logging practices and intensities in the tropics. For example under RIL practices in Brazil, Mazzei et al. (2010) reported AGB loss of 94.5 Mg ha\(^{-1}\) due to the harvest of 6 trees ha\(^{-1}\) (21.3 m\(^3\) ha\(^{-1}\)). Similarly in Malaysia, Pinard and Putz (1996) found AGB loss of 90 Mg ha\(^{-1}\) due to the RIL harvest of 8.7 trees ha\(^{-1}\) (104 m\(^3\) ha\(^{-1}\)). Under RIL in the Republic of Congo, with a logging intensity even lower (0.53 trees ha\(^{-1}\)) than in our study site (0.82 trees ha\(^{-1}\)) Brown et al. (2005) reported AGB loss of 20.4 Mg ha\(^{-1}\), not accounting for AGB of extracted logs, slightly greater than our value (17.0 Mg ha\(^{-1}\); Table 4). These results suggest that residual stand damage reduction and biomass retention vary with both the intensity of logging and the harvesting practices employed.

Although large trees (i.e., trees >200 cm dbh) occurred at low densities in our study area (0.2% of all trees >10 cm dbh; 1 individual/2.5 ha), they contained substantial AGB. The diameter of harvested trees in the 104 ha subjected to RIL ranged up to 216 cm dbh, which slightly exceeds the legal limit in Gabon of 200 cm dbh (Ndouna 2010, pers. comm.). Given the difficulty of making accurate measurements of buttressed trees and the presence of many extremely large trees of commercial species in our study area, this minor infraction is understandable and perhaps pardonable. In light of the exponential increase in residual stand damage with increasing dbh of harvested trees (Fig. 3b), such upper bounds on harvestable tree size are justifiable from a carbon-balance perspective. On the other hand, given that the conversion efficiency of round wood into veneer and saw timber and hence the commercial value of logs increases with their diameter, the opportunity costs of foregoing the harvest of very large trees will remain a controversial issue in managed natural forests.

While we used what we deemed the most robust allometric equation available for estimating AGB from dbh and wood density (Chave et al., 2005), no African trees were included in the dataset on which the equation was based. Nevertheless, similar results were obtained when we used the equations of Brown et al. (2005) and Djomo et al. (2010) that include African data but do not include wood density as an independent variable. A bigger problem is that some trees in our study area were substantially larger than any used to develop any of these equations (156 cm dbh). Extrapolation beyond the range of modeled data is questionable practice but truncation at the AGB of the largest tree used to generate the allometric equation results in obvious underestimate and thus does not seem like an appropriate alternative (e.g., Mazzei et al., 2010).

#### 4.3. Logging damage

##### 4.3.1. Damage due to felling

The severity of felling damage increased substantially with the size of trees harvested (Fig. 3a). Mean gap size per felled tree in our

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**Table 2**

Number of damaged trees (>10 cm dbh) per 1-ha plot and associated above-ground biomass (AGB) losses in the RIL study area in the Monts de Cristal, Gabon.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Number of trees harvested (Mg)</th>
<th>AGB of trees damaged by felling (Mg)</th>
<th>Number of trees damaged by skidding</th>
<th>AGB of trees damaged by skidding (Mg)</th>
<th>Number of completely destroyed trees</th>
<th>AGB completely destroyed (Mg)</th>
<th>AGB converted into necromass (Mg)</th>
<th>AGB damage &amp; trees harvested (Mg)</th>
<th>Total AGB after harvest (Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIL-P1</td>
<td>48.3</td>
<td>58</td>
<td>93.9</td>
<td>45</td>
<td>32.4</td>
<td>17</td>
<td>32.9</td>
<td>81.2</td>
<td>174.6</td>
</tr>
<tr>
<td>RIL-P2</td>
<td>12.7</td>
<td>27</td>
<td>35.8</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>15.5</td>
<td>28.2</td>
<td>48.5</td>
</tr>
<tr>
<td>RIL-P3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>17</td>
<td>5.6</td>
<td>9</td>
<td>1.0</td>
<td>1.0</td>
<td>5.6</td>
</tr>
<tr>
<td>RIL-P4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RIL-P5</td>
<td>6.7</td>
<td>2</td>
<td>7.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.9</td>
<td>13.6</td>
<td>13.8</td>
</tr>
<tr>
<td>RIL-P6</td>
<td>10.5</td>
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<td>23.6</td>
<td>10</td>
<td>4.8</td>
<td>7</td>
<td>18.3</td>
<td>28.8</td>
<td>38.9</td>
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<td>-</td>
<td>-</td>
<td>22</td>
<td>13.9</td>
<td>4</td>
<td>0.3</td>
<td>0.3</td>
<td>13.9</td>
</tr>
<tr>
<td>RIL-P8</td>
<td>8.1</td>
<td>9</td>
<td>2.2</td>
<td>30</td>
<td>20.1</td>
<td>8</td>
<td>1.8</td>
<td>9.9</td>
<td>30.4</td>
</tr>
<tr>
<td>RIL-P9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RIL-P10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>32</td>
<td>16.6</td>
<td>2</td>
<td>7.3</td>
<td>7.3</td>
<td>16.6</td>
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<tr>
<td>Mean</td>
<td>8.6</td>
<td>11.0</td>
<td>16.3</td>
<td>15.6</td>
<td>9.3</td>
<td>5.1</td>
<td>8.4</td>
<td>17.0</td>
<td>34.2</td>
</tr>
</tbody>
</table>

* The AGB converted into necromass (i.e., the committed emissions) includes the entire above-ground biomass of harvested trees plus the AGB of trees that were completely destroyed.

b The AGB damage & trees harvested includes the entire above-ground biomass of harvested trees plus AGB of trees damaged by both felling and skidding.

---

**Table 3**

Number and surface area of skid trails in the 50 ha RIL study area in the Monts de Cristal, Gabon.

<table>
<thead>
<tr>
<th>Category</th>
<th>Number</th>
<th>Total length (m)</th>
<th>Mean width (±SD)</th>
<th>Ground area covered (m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>5</td>
<td>350 m</td>
<td>3.9 m (±1.09)</td>
<td>1365 m(^2) (0.3%)</td>
</tr>
<tr>
<td>Secondary</td>
<td>16</td>
<td>1630 m</td>
<td>4.1 m (±1.45)</td>
<td>6683 m(^2) (1.3%)</td>
</tr>
<tr>
<td>Tertiary</td>
<td>18</td>
<td>1470 m</td>
<td>4.2 m (±1.43)</td>
<td>6174 m(^2) (1.2%)</td>
</tr>
</tbody>
</table>
study was $302.3 \pm 44$ m$^2$ (mean ± SE) with the mean dbh of harvested trees of 85 cm dbh. In contrast, for trees that average 81 cm dbh, Jackson et al. (2002) reported a mean felling gap per tree extracted of using RIL techniques in Bolivia of $591 \pm 92$ m$^2$ (mean ± SE). Using RIL in Cameroon, Jonkers (2000) found a mean felling gap size of 720 m$^2$ per tree extracted. Most of the trees harvested in our study site were okoumé ($A. klaineana$) that do not have large crowns relative to other tree species such as $Bikinia durrandii$ (Caesalpiniaeae). This suggests that gap size likely varies with crown size, the spatial distribution of the felled trees, and the physiognomy of individual tree species.

On average 11 trees suffered minor to severe damage per tree felled in our study site (Fig. 3b). In Bolivia, Jackson et al. (2002) found 14.6 trees were damaged per tree felled. In contrast, Johns et al. (1996) found that even in a planned operation in Brazil, 20.5 trees were damaged per harvested tree. At the other extreme, in a RIL study in the Republic of Congo, Brown et al. (2005) reported only 7.3 trees damaged per felled tree with a mean dbh of 123 cm. Similarly, in Southern Cameroon, Jonkers (2000) found 19.3 trees damaged per felled tree with mean dbh of 91 cm. Even when carried out with care, felling still results in stand damage, but the number of trees damaged likely varies with stem density, the abundance of lianas connecting tree crowns, crown dimensions, and terrain. For example, the lower damage per felled tree reported by Brown et al. (2005) for their study in the Republic of Congo may result from the relatively flat terrain in their study area compared to the rolling terrain in our study site in Gabon.

4.3.2. Damage due to skidding

Although skid trails were planned in advance, skidding still caused residual stand damage. Most trees damaged during skidding were uprooted but some suffered severe bole damage (Fig. 2). Overall, skid trails and machine maneuvering disturbed 2.8% and 2.6% of the ground surface, respectively, during the harvest of 0.82 trees ha$^{-1}$. During a planned harvest of 4.5 trees ha$^{-1}$ in Brazil, Johns et al. (1996) reported 5.4% of the logging area in skid trails and 0.4% affected by machine maneuvering. Similarly, in a RIL harvest of 6 trees ha$^{-1}$ in Eastern Amazon, Brazil, Sist and Ferreira (2007) reported that skid trails occupied 7% of the surface area. In a study on RIL harvest in Cameroon, Durrieu de Madron et al. (1998) reported that skid trails occupied 3.0% of the surface area due to the harvest of 0.5–1 trees ha$^{-1}$ (5–15 m$^3$ ha$^{-1}$); in the same country, Jonkers (2000) reported 3.9% of area disturbed resulting from the planned harvest of 1.4 trees ha$^{-1}$. In Southern Central African Republic, skid trails covered 7.4% of the surface area due to the harvest of 3.7 trees ha$^{-1}$ (Durrieu de Madron et al., 1998). In a RIL study in Malaysia, Pinard and Putz (1996) reported that skid trails occupied 3.5% of the surface area where 8.7 trees ha$^{-1}$ were harvested. While these values vary with logging intensity, they suggest that well-planned skidding operations result in relatively little damage to the ground surface.

Despite efforts to minimize residual stand damage, collateral damage to trees >10 cm dbh during RIL of 0.82 trees ha$^{-1}$ (8.11 m$^3$ ha$^{-1}$) in Gabon resulted in an average AGB impact of 34.2 Mg ha$^{-1}$ (8.1% of pre-harvest AGB) of which 17.0 Mg ha$^{-1}$ (4.05% of the pre-harvest AGB; Table 2) was converted into...
neocmass. In a study conducted in Eastern Amazon, Mazzei et al. (2010) reported that with RIL of 6.0 trees ha⁻¹ (21.3 m³ ha⁻¹), 94.5 Mg ha⁻¹ (23% of the pre-harvest AGB; includes harvested and destroyed trees) were converted into necromass, which is much greater than the value reported here. It is important to note that an average of 8.6 Mg ha⁻¹ was in the trees harvested from our plots, of which a portion will be converted into end forest products with long carbon storage, but we do not account for this retained carbon.

4.3.3. Management implications

Future timber yields from selectively logged tropical forests will vary with the ways forests are harvested. Yield sustainability is crucial in Central Africa where timber production is of great economic importance. 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 (Minnemeyer et al., 2002; 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.

While the focus of this study was on logging damage and carbon losses when RIL practices are used in selectively harvested forest, sustainability of management was the underlying motivation. One concern is that by implementing RIL, regeneration of disturbance-dependent species will be disfavored. In particular, managing for the sustained yield of okoumé (A. klaineana), the main timber species in Gabon, is problematic because it is light-demanding and unlikely to regenerate under the small canopy gaps that are the objective of RIL and that favor carbon retention. To retain this and other light-demanding species, silvicultural treatments such as liberation thinning or even scarification of the surface soil in felling gaps may be required (Fredericksen and Putz, 2003; Sist and Ferreira, 2007; Peña-Claros et al., 2008). Clearly needed is research on forest management strategies that mitigate carbon emissions while ensuring the maintenance of timber stocks. Given the many environmental and social benefits of RIL and the fact that the adoption of good timber harvesting practices in the Congo Basin is still facing challenges (Ezzine de Blas and Ruiz Perez, 2008; Cerutti et al., 2011), perhaps concerns about species-specific sustainability of volume yields need to be considered in light of the carbon and biodiversity benefits of sound harvesting practices. Thus, with economic development as part of the “development adjustment factors” set by the Central African Commission for Forests (COMIFAC) countries and efforts to reduce emissions from deforestation and forest degradation and enhancing forest carbon stocks (REDD+), the implementation of better forest harvesting techniques is timely for the sub-region.

Acknowledgements

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References


Table 4

<table>
<thead>
<tr>
<th>Logging practices</th>
<th>AGB before logging (Mg ha⁻¹)</th>
<th>AGB loss from logging (Mg ha⁻¹)</th>
<th>Percent loss (%)</th>
<th>Trees harvested (trees ha⁻¹)</th>
<th>Volume extracted (m³ ha⁻¹)</th>
<th>Study site</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>CL</td>
<td>331.4</td>
<td>159.4</td>
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<td>27.5</td>
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<td>104</td>
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<td>Pinard and Putz (1996)</td>
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<tr>
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<td>94.5</td>
<td>23.0</td>
<td>6.0</td>
<td>21.3</td>
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<td>Mazzei et al. (2010)</td>
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<tr>
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<td>170.0</td>
<td>40.1</td>
<td>10.4</td>
<td>32.5</td>
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<td>3.7</td>
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<td>Brown et al. (2005)</td>
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<td>17.0</td>
<td>4.1</td>
<td>0.82</td>
<td>8.11</td>
<td>Monts de Cristal, Gabon</td>
<td>This study</td>
</tr>
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</table>

(continued)


