Forest damage caused by selection logging of mahogany (Swietenia macrophylla) in northern Belize

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Abstract

We assessed the damage caused by selection logging of mahogany in a tropical forest in northern Belize and compared it with damage reported in other Neotropical logging and disturbance studies. We mapped skid roads and tree felling sites, and assessed soil compaction, loss of canopy cover, damage to saplings and trees, seedling survival and seedling height growth. Logging had been conducted using hand crews with chain saws and cable skidders. Logging directly affected 11.9 ha (12.9%) of the 92.3 ha logging area. Canopy cover decreased the most at logging gaps, and soils were most compacted on skid roads. Soil compaction was much greater on roads where more than one tree had been skidded. For the whole logged area, canopy cover declined 2% and compacted soils covered 3.8% of the area. Seedling height growth was unaffected by soil compaction, but seedling survival was less on compacted sites. About 50% of the trees and about 15% of the saplings were damaged in gaps and along skid roads. However, only 4.8% of the trees and 1.9% of the saplings were damaged for the logged area as a whole. The most common kinds of damage included scraped bark, snapped tops, and run-over stems. Although this logging operation had relatively low impacts compared with other logging operations in the Neotropics, it may not be silviculturally sustainable because its disturbance may be insufficient to promote adequate mahogany regeneration.

Keywords: Canopy openness; Soil compaction; Tree damage; Seedling growth; Disturbance; Neotropical forest

1. Introduction

Increasing rates of deforestation in the tropics have created significant pressure to find alternatives to deforestation that are economically competitive (Anderson, 1990). Selection logging, where isolated, large trees are logged, is one management strategy that might shift the economic balance away from land uses that require clear felling and toward land uses that maintain healthy forests (Bushbacher, 1990). To be an attractive alternative to clear felling for conservationists and foresters, selection logging must be: (1) ecologically sustainable (maintain ecosystem structure and function) and; (2) silviculturally sustainable (harvest rates equal regeneration and growth of a resource).

However, selection logging in tropical forests often heavily damages the residual stand. Damage to the remaining trees, including species of economic importance, can range from 26 to 75% of the stems (Johnson and Cabarle, 1993), although the area actually in tree felling areas, skid roads, and haul roads can be a small percentage of the forest area (e.g. Gullison and Hardner, 1993). Logging equipment
also can affect the forest by compacting soils, thereby reducing seedling recruitment and growth (Reisinger et al., 1988), and which can take up to 35 years for recovery (Geist et al., 1989). Thus, it is essential to evaluate the amount of damage caused by selection logging to determine if damage levels are acceptable and meet criteria of sustainability.

We assessed the impact of selection logging for mahogany in a tropical forest in northern Belize. We had two objectives: (1) to determine the extent of forest damage from this logging operation; and (2) to use the results of other Neotropical selection logging and disturbance studies as a guide for evaluating the relative degree of damage assessed in this study. Specifically, we (1) mapped skid roads and tree felling areas to determine the amount of area affected by logging; (2) measured soil compaction and canopy openness in tree felling areas and skid roads to determine the intensity of damage caused by logging; (3) assessed damage to residual trees and advance regeneration in tree felling areas and near skid roads; and (4) compared seedling growth and survival on sites of high and low soil compaction.

2. Methods

2.1. Study area

The study area was near Hill Bank (88°42' W, 17°36' N), Orange Walk District, northern Belize. It is in the 'subtropical moist' life zone (Hartshorn et al., 1984) and receives a mean annual rainfall of 1600 mm. The 'dry' season usually extends from January to May and the remainder of the year is relatively wet, although the amount of rainfall in the dry and wet seasons may vary significantly from year to year. Soils are moderately deep, well drained and are derived from porous limestone. The topography is flat with a few small, low hills. Most streams are seasonal (Brokaw and Mallory, 1993). The study site was in upland evergreen, broadleaf forest (canopy height 15-25 m) with patches (0.25 - 1 ha) of low swamp forest. Dominant tree species included: Pouteria reticulata, Aspidosperma cruenta, Manilkara chicle, Sabal mauritiiformis, Orbignya cohune, Ampelocera hottlei, and Terminalia amazonia.

Forests in northern Belize have been struck with moderate frequency by hurricanes and occasional, subsequent fire have struck (Wolffsohn, 1968) and may have been cleared by the Maya during the period 0-1000 AD (Brokaw and Mallory, 1993). Since the early 1800s, selection logging for mahogany (Swietenia macrophylla) and Spanish cedar (Cedrela odorata) has occurred infrequently and at low intensities throughout northwestern Belize. Stands such as our study site, which were logged 10 or more years ago have an intact canopy. Logging has reduced abundance of mahogany and Spanish cedar only, and thus does not appear to have altered the forest significantly (Brokaw and Mallory, 1993), although a reduction in numbers of these species may have reduced the overall density of canopy emergents. The study site had been logged for mahogany in March and April 1992. Trees were felled, limbed, and topped by hand crews using chain saws and logs were extracted by cable skidders with rubber tires. We conducted this study from 2 April to 11 May 1993.

2.2. Mapping

We mapped skid roads and tree felling sites ('logging gaps') in 4 km² using a tape and compass. The width of a skid road was the maximal extent of damaged vegetation according to visual assessment. We determined the area of logging gaps from measurements of the longest axis from edge to edge in the gap and of axes placed every five meters along and perpendicular to, the long axis. Gap edge was defined as the outermost limit of damaged vegetation or canopy opening, whichever was greatest.

2.3. Measurement of soil compaction and canopy cover

After mapping, we assessed soil compaction and loss of canopy cover in 14 randomly selected logging gaps and at 13 randomly selected points along skid roads. Gaps were selected randomly by drawing gap identification number from a hat. On skid roads, we measured soil compaction and canopy cover at points on three types of skid roads: (1) single tree skid roads from a logging gap where one tree was harvested (n = 4); (2) secondary skid roads where two to ten trees had been skidded (n = 5); and (3)
primary skid roads where > 10 trees had been skid-
ded (n = 4). From these three treatments, we se-
lected points along skid roads randomly by drawing
skid road identification numbers from a hat and then
selecting a number from a random numbers table to
determine the distance along the skid road for further
study. Lack of time did not permit equal sample
sizes. In logging gaps we measured soil compaction
in high disturbance areas (the skidding zone near the
mahogany stump), moderate disturbance areas (at the
gap edge in an area possibly used by a skidder or
affected by the falling tree), and low disturbance
areas (5 m away from the gap edge, into the logging
gap, in an area not used by skidder). In these same
logging gaps at the gap end opposite from the skid-
ding area we measured canopy cover in low distur-
bance areas (5 m from the edge of the gap, in forest),
moderate disturbance areas (at the gap edge), and
high disturbance areas (5 m from the gap edge, into
the logging gap). At each point on skid roads, we
measured soil compaction and canopy cover in the
skid road ruts created by the skidder and in forest at
5 m away. Soil compaction was measured using a
soil penetrometer ('Pocket Penetrometer', Forestry
Suppliers, Jackson, MS), and canopy cover was mea-
sure using a spherical densiometer (Lemmon, 1957).

For logging gap data, we used an Analysis of
Variance (ANOVA) and Tukey’s test to determine if
soil compaction and canopy cover were similar at
high, moderate, and low disturbance areas (Statistical
data, we used the same tests to determine if soil
compaction and canopy cover were similar in skid
road ruts and nearby forest. We used an unbal-
anced ANOVA with Tukey’s test to determine if soil
compaction was similar on different types of skid
roads (single tree, secondary, and primary skid roads).
However, estimates of soil compaction can be biased
depending on local site factors such as soil moisture,
composition, and structure, and these are time-de-
manding factors to measure. Therefore, we used ratio
of compaction values instead of raw compaction
values to control for the effect of site and to deter-
mine if the contrast between skid road soils and
undisturbed forest soils was different among the
three different types of skid roads. The data were
normally distributed (Kolmorgov-Smirnov tests, P
> 0.05).

2.4. Measurement of the effect of soil compaction on
seedlings

We tagged and measured seedling height (cm) of
economically important species (Appendix A) in the
13 skid road sites in 1993 and re-measured the same
seedlings in 1994. The sample plot was a 10 m
section of a skid road plus a 1 m buffer strip on each
side. We noted if a seedling was in the skid road or
the 1 m buffer strip. We also measured soil compa-
c tion (using a soil penetrometer), canopy cover
(using a densiometer) and ground cover (in a 1 m²
plot) in the buffer strip and skid road of each plot.
For soil compaction, and canopy and ground cover,
We used a paired t-test to compare 1 m buffer strips
and skid roads (Statistical Analysis Systems Institute
Inc., 1990). Percent seedling height growth and sur-
vival were compared between 1 m buffer strips and
skid roads with t-tests (Statistical Analysis Systems
Institute Inc., 1990). We were unable to use a paired
t-test because treatment and control plots within a
plot did not always have a species present. We only
analyzed species found in ten or more plots. For both
soil and seedling analyses, the data were normally
distributed (Kolmorgov-Smirnov test, P > 0.05).
When necessary we used a t-test for unequal vari-
ces (Statistical Analysis Systems Institute Inc.,
1990).

2.5. Assessment of damage to saplings and trees

We assessed damage to saplings (stems ≥ 1.4 m
in height and < 10 cm DBH) and trees (stems ≥ 10
cm DBH) at the same logging gaps and skid road
sites where we assessed soil compaction and canopy
cover loss. In logging gaps, we assessed saplings and
trees within the damage zone (defined as the area
where vegetation was damaged) and the area below
the canopy opening. At skid roads sites, we assessed
damage on 100 m lengths of skid roads and within 3
m of the road edge. For each stem, we noted the
species, its location (on or off the skid road), and
categorized the type of damage: run over, killed,
scrapped root, scraped trunk, top broken off, other, or
none. We used ANOVA to determine if the percent
of tree basal area, tree stems, and saplings stems
damaged in gaps, along skid roads, and in skid roads
was similar. We used χ² and G tests to determine if
commercial species were more or less susceptible than other species to damage by logging, and if damage to them was more or less severe than damage to other species (Statistical Analysis Systems Institute Inc., 1990).

2.6. Comparison with other Neotropical studies

Damage assessment data from seven other Neotropical studies that were available for comparison: Johns, 1991, 1992; ter Steege et al., 1994; Thillay, 1992; Uhl et al., 1991; Uhl and Viera, 1989; Verissimo et al., 1995. No study had values for all variables, and no more than five studies had values for any single variable. Hence we were only able to compare the damage assessment values (Table 3) of our study with the values of the five of these studies using a two-tailed one sample t-test (Zar, 1984). Most values from other studies represent a single value measured for the entire study area.

3. Results

3.1. Extent of disturbed area

We mapped 9.64 km of skid roads and 46 logging gaps (Fig. 1). We assumed that the maximum extent of the area searched for mahogany trees extended 100 m from all logging areas. Thus, we estimated that the logging area was 92.3 ha. Logging affected 11.88 ha or 12.9% of this area. Skid roads covered 3.48 ha (3.8%) and affected another 5.78 ha (6.3%) adjacent to the skid roads and thus accounted for 78% of the disturbed area. Logging gaps covered...
2.62 ha (2.8%) and thus accounted for the remaining 22% of the disturbed area.

Light levels in gaps were not related to the size of tree (stump diameter) removed \((r = -0.07, P = 0.823)\) or the gap area \((r = -0.10, P = 0.745)\). Similarly, size of the tree (stump diameter) and logging gap area also were not related \((r = 0.45, P = 0.106)\). Thus, logging of large trees did not necessarily produce larger gaps than logging of small trees.

3.2. Soil compaction and canopy cover

Selection logging moderately affected canopy cover and soil compaction on skid roads and in logging gaps. Canopy cover in gaps was about 10% less than it was 5 m into adjacent forest (Fig. 2.a.1; ANOVA, \(F = 6.61\), df = 2, \(P = 0.003\), Tukey’s test \(P = 0.05\)). Canopy cover on skid roads was 2.8% less than 5 m into adjacent forest (Fig. 2.a.2; ANOVA, \(F = 19.54\), df = 1, \(P < 0.001\)). The different types of skid road (single tree, secondary, and primary) had the same amount of canopy cover (ANOVA, \(F = 1.48\), df = 2, \(P = 0.233\)). Extrapolating from these data, 2% of the canopy in the 92.3 ha logged area was lost due to logging.

At logging gaps, soil hardness was not significantly different in the gap, at the gap edge, or in the skidding area (ANOVA, \(F = 0.49\), df = 2, \(P = 0.615\)) although the soil was most compacted in the skidding area generally (Fig. 2.b.1). Soil was twice as compacted on skid roads than in adjacent forest 5 m away (Fig. 2.b.2; ANOVA \(F = 10.07\), df = 1, \(P < 0.001\)). Although soil compaction was not significantly different on three types of skid road (Fig. 2.c; ANOVA \(F = 1.68\), df = 2, \(P = 0.202\)) it was over 200% greater on roads where more than one tree had been skidded (Fig. 2.c). Extrapolating from these data and given that skid roads covered 3.48 ha, soils were significantly compacted on 3.8% of the 92.3 ha logged area. Overall, while canopy cover decreased the most at logging gaps, soils were most compacted on skid roads.

### Table 1

Differences in habitat variables, seedling growth and survivorship between skid roads and 1 m buffer strips. Differences for habitat variables and growth and survival of all seedlings were compared using a paired \(t\)-test. Growth and survival of individual species were tested using \(t\)-test, correcting for unequal variances when necessary.

<table>
<thead>
<tr>
<th>Category variable</th>
<th>1 m buffer mean (SD)</th>
<th>Skid road mean (SD)</th>
<th>(P)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Habitat variables</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil compaction (kg cm(^{-2}))</td>
<td>0.88 (0.698)</td>
<td>2.13 (1.034)</td>
<td>0.001</td>
</tr>
<tr>
<td>Canopy cover (%)</td>
<td>97.5 (0.92)</td>
<td>96.3 (2.76)</td>
<td>0.007</td>
</tr>
<tr>
<td>Ground cover (%)</td>
<td>41.2 (21.67)</td>
<td>30.8 (30.70)</td>
<td>0.262</td>
</tr>
<tr>
<td><strong>Seedling growth (%)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alseis yucatanensis</td>
<td>26.4 (14.63)</td>
<td>14.1 (15.12)</td>
<td>0.257</td>
</tr>
<tr>
<td>Ampelocera hotteii</td>
<td>13.7 (6.99)</td>
<td>20.3 (25.83)</td>
<td>0.535</td>
</tr>
<tr>
<td>Aspidosperma cruenta</td>
<td>25.3 (15.83)</td>
<td>37.3 (17.93)</td>
<td>0.216</td>
</tr>
<tr>
<td>Calophyllum brasiliense</td>
<td>35.2 (16.02)</td>
<td>29.9 (17.52)</td>
<td>0.530</td>
</tr>
<tr>
<td>Manilkara chicle</td>
<td>24.0 (15.10)</td>
<td>33.4 (17.10)</td>
<td>0.274</td>
</tr>
<tr>
<td>Terminalia amazonia</td>
<td>518.0 (852.11)</td>
<td>84.3 (126.33)</td>
<td>0.321</td>
</tr>
<tr>
<td>All species</td>
<td>143.2 (381.69)</td>
<td>41.3 (26.24)</td>
<td>0.356</td>
</tr>
<tr>
<td><strong>Survival</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alseis yucatanensis</td>
<td>100.0 (0.00)</td>
<td>96.7 (7.45)</td>
<td>0.374</td>
</tr>
<tr>
<td>Ampelocera hotteii</td>
<td>95.2 (7.07)</td>
<td>76.9 (18.47)</td>
<td>0.040</td>
</tr>
<tr>
<td>Aspidosperma cruenta</td>
<td>96.7 (8.16)</td>
<td>77.8 (36.32)</td>
<td>0.166</td>
</tr>
<tr>
<td>Calophyllum brasiliense</td>
<td>100.0 (0.00)</td>
<td>78.8 (33.23)</td>
<td>0.075</td>
</tr>
<tr>
<td>Manilkara chicle</td>
<td>100.0 (0.00)</td>
<td>88.3 (18.70)</td>
<td>0.098</td>
</tr>
<tr>
<td>Terminalia amazonia</td>
<td>100.0 (0.00)</td>
<td>92.1 (11.41)</td>
<td>0.198</td>
</tr>
<tr>
<td>All species</td>
<td>96.7 (4.84)</td>
<td>80.9 (10.95)</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>
3.3. Effect of soil compaction on seedlings

Skid roads had nearly 300% greater soil hardness than 1 m buffer strips but similar levels of canopy and ground cover compared with the 1 m buffer strips (Table 1). Seedling height growth of all species and six individual species was not statistically different between skid roads and the 1 m buffer strips. However, seedling survival was greater in the 1 m buffer strips than in skid roads for all species and this difference was statistically significant for *Ampelocera hottlei* and all species combined.

3.4. Damage to saplings and trees

Logging gaps had a greater percentage of damaged trees and a greater percentage of their total basal area damaged than skid roads but this difference was not statistically significant (Table 2). The percent of sapling stems damaged was significantly lower in logging gaps than on skid roads. Percent of sapling stems damaged off skid roads and in logging gaps was similar (Table 2). Overall, tree species of commercial value and other species were damaged in proportion to their relative abundance along skid roads ($\chi^2$ test, $\chi^2 = 0.163$, df = 1, $P = 0.687$) and near logging gaps ($\chi^2$ test, $\chi^2 = 0.958$, df = 1, $P = 0.328$). Moreover, because commercial and non-commercial species had similar abundance along skid roads, similar numbers of each category were damaged per hectare of skid road and per logged

### Table 2
Mean percent and standard deviation (SD) of the tree basal area, tree stems, and saplings stems damaged in logging gaps, on skid roads, within 3 m of skid roads, and within the total damage area

<table>
<thead>
<tr>
<th>Percent of</th>
<th>Logging gap mean (SD)</th>
<th>On skid road mean (SD)</th>
<th>Along skid road mean (SD)</th>
<th>Damage estimate for logged area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree basal area</td>
<td>56.0 (34.1)</td>
<td>46.0 (43.7)</td>
<td>27.7 (39.7)</td>
<td>4.8</td>
</tr>
<tr>
<td>Trees</td>
<td>65.4 (23.1)</td>
<td>44.1 (44.6)</td>
<td>27.2 (38.0)</td>
<td>4.8</td>
</tr>
<tr>
<td>Saplings</td>
<td>9.3 (13.3)</td>
<td>46.3 (39.7)</td>
<td>8.6 (23.1)</td>
<td>1.92</td>
</tr>
</tbody>
</table>

### Table 3
Average number of damaged stems per logged tree of commercial and other tree species on and next to skid roads ($n = 13$), and in treefall gaps ($n = 14$)

<table>
<thead>
<tr>
<th>Species category</th>
<th>Skid road On</th>
<th>Treefall gap</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial</td>
<td>6.3</td>
<td>17.0</td>
<td>8.3</td>
</tr>
<tr>
<td>Other</td>
<td>6.5</td>
<td>15.9</td>
<td>24.3</td>
</tr>
<tr>
<td>Total</td>
<td>12.6</td>
<td>30.9</td>
<td>49.4</td>
</tr>
</tbody>
</table>

### Table 4
Source of damage to commercially valuable and other tree species on and next to skid roads, and in treefall gaps

<table>
<thead>
<tr>
<th>Damage category</th>
<th>Commercial species</th>
<th>Other species</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Next to skid road</td>
<td>On skid road</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>(n)</td>
</tr>
<tr>
<td>Run over</td>
<td>0.0</td>
<td>(0)</td>
</tr>
<tr>
<td>Killed</td>
<td>0.0</td>
<td>(0)</td>
</tr>
<tr>
<td>Scraped root</td>
<td>6.4</td>
<td>(6)</td>
</tr>
<tr>
<td>Scraped trunk</td>
<td>6.4</td>
<td>(6)</td>
</tr>
<tr>
<td>Top broken off</td>
<td>2.1</td>
<td>(2)</td>
</tr>
<tr>
<td>Other</td>
<td>3.2</td>
<td>(3)</td>
</tr>
<tr>
<td>None</td>
<td>81.9</td>
<td>(77)</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>(94)</td>
</tr>
</tbody>
</table>
mahogany tree (Table 3). However, because other species were nearly twice as abundant as commercial species near logging gaps, twice as many other species were damaged per ha and per logged mahogany tree compared with commercial species (Table 3).

Overall, the most common kinds of damage included scraped bark, snapped tops, and run-over stems (Table 4). Commercially valuable species were less likely than other species to receive serious injuries, such as snapped tops and run-over stems, along skid roads ($G$-test, $G = 15.423$, df = 7, $P = 0.031$) and in logging gaps ($G$-test, $G = 12.946$, df = 5, $P = 0.024$).

3.5. Comparison with other Neotropical studies

For the nine damage assessment variables that could be compared between our study and five other studies, values for four variables were significantly

<table>
<thead>
<tr>
<th>Impact variable</th>
<th>This study</th>
<th>Neotropical studies $a$ mean (SD, n)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean disturbance dimensions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skid road width ($n = 651$)</td>
<td>3.6 (0.1) m</td>
<td>3.6 (--, 2)</td>
</tr>
<tr>
<td>Gap area $b$ ($n = 14$)</td>
<td>583 (171) m$^2$</td>
<td>nd $c$</td>
</tr>
<tr>
<td><strong>Damage rate (per harvested tree)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of damaged saplings</td>
<td>104.3</td>
<td>695 (--, 1)</td>
</tr>
<tr>
<td>Number of damaged trees</td>
<td>38.7</td>
<td>31.0 (16.90, 6)</td>
</tr>
<tr>
<td>Area disturbed (m$^2$)</td>
<td>2500 *</td>
<td>1304 (666.97, 6)</td>
</tr>
<tr>
<td><strong>Harvest density</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of harvested tree ha$^{-1}$</td>
<td>0.50 *</td>
<td>3.0 (2.48, 8)</td>
</tr>
<tr>
<td>Percent of target species</td>
<td>22.1 *</td>
<td>80.3 (17.06, 4)</td>
</tr>
<tr>
<td>Percent of trees $\geq$ 72 cm DBH</td>
<td>100</td>
<td>93.4 (14.76, 5)</td>
</tr>
<tr>
<td>Basal area ha$^{-1}$ (cm$^2$)</td>
<td>554.2</td>
<td>4.4 (--, 1)</td>
</tr>
<tr>
<td><strong>Damage density for logged area (% of total)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basal area of damaged tree</td>
<td>4.8 *</td>
<td>64.0 (16.87, 4)</td>
</tr>
<tr>
<td>Number of damaged trees</td>
<td>4.8</td>
<td>37.0 (250.6, 3)</td>
</tr>
<tr>
<td>Number of damaged saplings</td>
<td>1.9</td>
<td>nd</td>
</tr>
<tr>
<td>Area of damage</td>
<td>12.9</td>
<td>18.3 (19.19, 5)</td>
</tr>
<tr>
<td>Canopy loss</td>
<td>2.0</td>
<td>43.7 (26.27, 3)</td>
</tr>
<tr>
<td><strong>Frequency of damage categories (%)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cut trees</td>
<td>1.6</td>
<td>23.0 (--, 2)</td>
</tr>
<tr>
<td>Broken trees</td>
<td>27.8</td>
<td>43.5 (--, 2)</td>
</tr>
<tr>
<td>Up rooted tree</td>
<td>15.1</td>
<td>25.0 (--, 2)</td>
</tr>
<tr>
<td>Scraped and bruised trees</td>
<td>36.5</td>
<td>8.5 (--, 2)</td>
</tr>
<tr>
<td>Other</td>
<td>19.0</td>
<td>0.0 (--, 2)</td>
</tr>
<tr>
<td><strong>Frequency of damage in value categories (%)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High value</td>
<td>0.9</td>
<td>6.5 (--, 2)</td>
</tr>
<tr>
<td>Medium value</td>
<td>16.7</td>
<td>60.5 (--, 2)</td>
</tr>
<tr>
<td>Low value</td>
<td>20.4</td>
<td>8.0 (--, 2)</td>
</tr>
<tr>
<td>No value</td>
<td>62.0</td>
<td>25.0 (--, 2)</td>
</tr>
</tbody>
</table>


$^b$ Includes canopy openings, area covered by logging debris, and area of damaged vegetation.

$^c$ nd: no data.

$^* P < 0.005.$
different from those in our study (Table 5). Although more area per tree was disturbed in this operation than in the five other Neotropical selection logging studies, this operation study had fewer trees harvested per hectare, took a smaller proportion of the target species, and damaged a smaller proportion of the total basal area. Values from our study were not statistically different from values of other studies for the number of damaged trees per harvested tree, number of large trees of the target species removed, percent of total trees damaged, area damaged, and percent of canopy loss. This probably reflects the wide variation in damage values from other studies.

4. Discussion

To forest conservationists, low-intensity selection logging operations such as the one studied here are attractive. Only a small portion (12.9%) of the total logged area was affected directly by the logging. Although gaps were of moderate size and contained many trees damaged by logging, they accounted for a small proportion of the area and left much of the advance regeneration (saplings) undamaged. Because soil compaction was most severe on skid roads sites where multiple passes occurred, efforts should be made in the planning stages to minimize the length of these types of skid roads (e.g. Gullison and Hardner, 1993). Skid roads were areas with much soil compaction and reduced seedling survival but were narrow and occupied a small proportion (3.8%) of the total area. As a result, only a small part of the residual stand, trees, and regeneration were damaged by this operation. Because the similar numbers of commercial and non-commercial species were damaged, loggers did not appear to make an effort to avoid damaging species of commercial value. In contrast to the positive correlations between sizes of naturally fallen trees and gap sizes found elsewhere (Brokaw, 1982; ter Steege et al., 1994), the felling of large trees did not produce larger disturbance zones and gaps than the felling of small trees. Perhaps, loggers fell trees to reduce the chance of the target stem getting caught in or damaged by the surrounding trees when it is felled, and in doing so reduced variation in the logging gap area. Thus, compared with other Neotropical operations, total damage at our site was low because few trees were harvested per unit area.

Given the interest in natural forest management, it is useful to compare the logging disturbance found in this study to natural disturbance. Although proportion of area damaged (12.9%) was higher than that produced by natural treefalls at four (mean = 3.8%, range: 0.3–6%) of five Middle American sites (fifth site, gap area = 25%), the proportion of canopy loss due to logging, 2.0% was less than natural disturbance (Brokaw, 1985) excepting for a nearby dry forest site (0.3%, Noh Bec, Mexico, D. Whigham personal communication, 1995). And while logging gaps in this study were larger on average, 583 m², than natural gaps (mean = 130 m², range: 86–200), density of logging gaps in this study was less, 0.5 ha⁻¹, than the density of natural treefall gaps in Middle America (mean = 7.1, range 3.2–12.8). Given that loggers revisit logged sites about once every five years (C. Polk, personal communication, 1993), the stand turnover rate would be about 100 years, similar to natural turnover rates in other Middle American forests (mean = 100, n = 3, range = 62–135). Thus, selection logging at the rate observed in this study might double the kinds of disturbance resulting from treefall gaps. Given that this forest is severely disturbed by hurricanes at regular intervals, it is more likely that centuries of large-scale disturbance by hurricanes has had a greater impact on the forest than low-intensity selection logging (e.g. Lynch and Whigham, 1995). Therefore, the impacts of selection logging in Belize at this intensity may be trivial compared to natural disturbance.

However, there are tradeoffs associated with low logging densities (Gullison and Hardner, 1993). Compared with other Neotropical studies, the area disturbed per tree was nearly twice as great as was found in other studies. We attribute this differences to the harvest density. At low harvest densities found in this study, much of the logging disturbance results from skid roads. As the harvest density increases, damage area per tree due to skid roads declines as each additional harvested tree requires less and less new skid road, while damage area per tree due to logging gaps remains constant (Gullison and Hardner, 1993). Thus, logging damage per tree declines as harvest density increases.

Although this logging operation had relatively
low impact compared to other logging operations in the Neotropics and had little impact on the bird community (Whitman et al., 1994), it was not silviculturally sustainable. The complete harvest of the largest and probably most fecund trees may have greatly reduced the seed production potential of the residual stand. Ironically, adequate recruitment and regeneration of mahogany requires disturbances much larger than those created by this logging operation (Snook, 1992). Moreover, elsewhere we determined that the mahogany harvest rate far exceeded the mahogany regeneration and recruitment capacity of the forest (Whitman et al., 1994). Thus, further research is necessary to determine forest practices that will assure the silvicultural sustainability of mahogany. These practices will almost assuredly require disturbing the forest much more than the current logging operations and will also require studies to determine how to maintain ecological integrity and biodiversity of tropical forests at these greater disturbance levels.

Acknowledgements

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Appendix A. The relative economic value of tree species found on plots

<table>
<thead>
<tr>
<th>Economic value</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High</strong></td>
<td><em>Swietenia macrophylla</em></td>
</tr>
<tr>
<td></td>
<td><em>Cedrela mexicana</em></td>
</tr>
<tr>
<td><strong>Medium</strong></td>
<td><em>Aspidosperma cruenta</em></td>
</tr>
<tr>
<td></td>
<td><em>Calophyllum brasiliense</em></td>
</tr>
<tr>
<td></td>
<td><em>Spondias mombin</em></td>
</tr>
<tr>
<td></td>
<td><em>Terminalia amazonia</em></td>
</tr>
<tr>
<td><strong>Low</strong></td>
<td><em>Alseis yucatanensis</em></td>
</tr>
<tr>
<td></td>
<td><em>Ampelocera hottlei</em></td>
</tr>
<tr>
<td></td>
<td><em>Bucida buceras</em></td>
</tr>
<tr>
<td></td>
<td><em>Bursera simaruba</em></td>
</tr>
<tr>
<td></td>
<td><em>Drypetes brownii</em></td>
</tr>
<tr>
<td></td>
<td><em>Ficus spp.</em></td>
</tr>
<tr>
<td></td>
<td><em>Guettarda combsii</em></td>
</tr>
<tr>
<td></td>
<td><em>Manilkara chicle</em></td>
</tr>
<tr>
<td></td>
<td><em>Metopium brownei</em></td>
</tr>
<tr>
<td></td>
<td><em>Coojba arborea</em></td>
</tr>
<tr>
<td></td>
<td><em>Simarouba amara</em></td>
</tr>
<tr>
<td></td>
<td><em>Vitex gaumerii</em></td>
</tr>
<tr>
<td></td>
<td><em>Zanthoxylum juniperum</em></td>
</tr>
</tbody>
</table>

High value species were species desirable for international markets. Medium value species were species currently sought after for domestic and international markets. Low value species were species occasionally harvested or listed in Lamb (1946) and Joseph Loskott (personal communication, 1993) as species of value.

References


