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MODEST TRADE-OFFS BETWEEN TIMBER MANAGEMENT AND FIRE SUSCEPTIBILITY OF A BOLIVIAN SEMI-DECIDUOUS FOREST

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Abstract. Fire threatens to undermine the conservation potential of tropical production forests. Expecting seasonally deciduous forests that require intensive silviculture to secure sustained yields of commercial species to be especially fire prone, I assessed fire susceptibility in a Bolivian semi-deciduous forest subjected to four management intensities: no logging control; selective harvest only; and two harvest treatments with additional silviculture. I quantified treatment effects on fuel loads, vegetative cover, dry-down rates of 10-h fuels, and fire spread in 4-m^2 test plots. With these data and daily rainfall records, I estimated the number of fire-prone days per month associated with each treatment.

Fuel loads increased with management intensity, but principally in the 1000-h size class. Treatment impacts on vegetative cover were modest, in part because only 30% of the control forest comprised mature stands with closed canopies >16 m high. Fuels dried enough to ignite in 3–5 days in sites with sparse cover, but within 11 days in sites with dense cover. Given that rainless periods of 20 days are common throughout the dry season, fuels are dry enough to burn for long periods in this forest. In the late dry season in forest logged 2–4 months previously, total cover had little effect on whether test plots burned. Plots in recently logged forest burned more readily than those in forest logged one and three years previously.

The model developed for calculating fire-prone days indicated that, unlike intact evergreen Amazon forests that typically remain fire resistant, this forest is very fire prone during most dry seasons. The similar number of fire-prone days among treatments suggests that forest managers need not worry about elevating fire susceptibility with their silviculture.

These results suggest that timber management and fire susceptibility trade-offs are modest in this forest because it is already fire prone and because the intensity of silvicultural treatments applied was low compared to other tropical production forests. Fire severity, however, would likely increase with management intensity due to increases in 1000-h fuels. Fire prevention efforts must complement silviculture treatments to achieve sustained yields if these and similar forests are to serve both production and conservation goals.

Key words: Amazon; Bolivia; deciduous; fire susceptibility; logging impacts; trade-offs; tropical forest management; timber.

Introduction

Forest managers have long recognized that not all forest uses or objectives can be simultaneously maximized (Dana 1943, Toman and Ashton 1996). Despite this realization, sustainable forest management, which promises continuous delivery and maintenance of multiple goods, services, and processes, has become the predominant management paradigm in tropical countries. Although research into the compatibility among different objectives of forest management has advanced substantially in temperate forests (e.g., Johnson et al. 2002, Stevens and Montgomery 2002), such research is scarce in tropical forests. Elucidation of the trade-offs between management for sustained timber production and fire susceptibility is especially important considering the large proportion of tropical forests designated for timber production, the potential for such forests to contribute to conservation and development objectives, and the increasing prevalence of wildfire in these forests.

Despite increasing attention to the problem of fires in tropical forests (Goldammer 1990, Nepstad et al. 2001, Cochrane 2003) and the recognized role of logging in exacerbating the fire problem (e.g., Woods 1989, Holdsworth and Uhl 1997, Nepstad et al. 1999*a*, Cochrane 2003) especially during El Niño-related droughts (Siegert et al. 2001), few studies have determined the extent to which increased fire susceptibility is an inevitable consequence of intensifying management to achieve silvicultural objectives. Holdsworth and Uhl (1997) demonstrated that fire susceptibility (i.e., likelihood of fires starting and spreading in a forest) decreases when logging impacts are reduced in eastern Amazonian evergreen forests, where deep roots help most trees retain their foliage during the marked

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dry season (Nepstad et al. 1995). Unfortunately, reducing logging damage will not sustain timber yields, let alone achieve sustainable forest management, in seasonally dry, semi-deciduous forests that require post-harvest silvicultural treatments (e.g., liana cutting, felling gap enlargement, and soil scarification) to promote regeneration and growth of commercial tree species, many of which are shade intolerant and lack adequate regeneration (Mostacedo and Fredericksen 1999, Fredericksen and Mostacedo 2000, Fredericksen et al. 2003). Considering that seasonally dry tropical forests encompass more area and are more affected by people than wet forests (Mooney et al. 1995), it is important to understand whether the intensive management regimes thought necessary to sustain commercial timber species and hence prevent conversion to other land uses, might elevate fire susceptibility and inadvertently promote forest conversion. This study was conducted in a region of the Bolivian Amazon where forest management is hoped to provide an economically viable alternative to conversion of forests to pasture land, which has increased dramatically in recent decades (Steininger et al. 2001).

Studies throughout the tropics have shown that logging increases forest susceptibility to fire (Kauffman and Uhl 1990, Siegert et al. 2001, Cochrane 2003) as well as fire severity (i.e., fire behavior and its ecological effects; Kauffman 1991) because logging results in a drier understory and increased fuel loads (Uhl and Kauffman 1990). Because additional silvicultural treatments beyond harvesting probably exacerbate the factors that drive fire susceptibility and influence fire severity, it seems reasonable to expect that intensively managed forests would be more prone to wildfires of greater severity than undisturbed or less-intensively managed forests. Moreover, because more radiation reaches the forest understory in deciduous forests, they are more likely to be fire prone than wetter, evergreen forests (Swaine 1992).

The purpose of this study was to elucidate the nature and extent of trade-offs between sustaining commercial timber yields and increasing fire susceptibility in a dry tropical forest and to contrast these findings with published studies from moister sites. I expected that more intensive management would (1) increase the proportion of the forest that is fire prone on any given day during the dry season; (2) extend the number of fire-prone days during the dry season; (3) increase the potential for severe or catastrophic fires; and (4) increase the number of months or years of elevated fire susceptibility above background levels (i.e., compared to unlogged control areas).

SITE DESCRIPTION

The study was conducted in a 100 000-ha Forest Stewardship Council-certified timber concession operated by Agroindustria Forestal La Chonta Ltda. in Guarayos Forest Reserve (15°45′ S, 62°60′ W) in the Bolivian lowlands (200–400 m above sea level). According to the Holdridge classification system, the concession (hereafter La Chonta) is covered by subtropical humid forest. Seasonally deciduous and semi-deciduous forests like La Chonta provide about 45% of Bolivia's timber and encompass about 35% of its designated forest management area (Superintendencia Forestal 2001). Biomass estimates for the region are 73–190 Mg/ha (Dauber et al. 2000). Mean annual temperature is ~24.5°C and mean annual rainfall is ~1500 mm, 77% of which falls between November and April. During the peak of the fire season (July–September) in average years, only 43 mm of rain falls monthly and understory vapor pressure deficits range from 0.6 to 0.8 kPa. Soils are moderately fertile inceptisols, but 10–15% of the area has black anthrosols enriched by humans several hundred years ago (Paz 2003).

The fire history of the region is unknown, but evidence that people extensively inhabited much of La Chonta and the presence of charcoal in the subsoil (Paz 2003) both suggest that the forest was historically subjected to fire. In 1995, an escaped fire burned about 30% of the La Chonta concession (Pinard et al. 1999, Mostacedo et al. 2001, Gould et al. 2002) killing 23% of the trees (dbh $>$ 10 cm) and 75% of the lianas, and causing a proliferation of herbaceous vines (Pinard et al. 1999). Commercial tree regeneration remained scarce five years after the fire (Gould et al. 2002). Another fire in 1999 nearly destroyed the town on La Chonta's southwest border but did not otherwise affect the concession. These fires occurred between July and September when people in the fragmented matrix of fire-maintained anthropogenic palm savannas and active agricultural fields surrounding La Chonta set fires to clear woody vegetation.

La Chonta is situated in a transitional zone between wetter forests to the north and drier forests to the south and southeast, and is dominated by canopy tree species characteristic of humid forests including *Ficus boliviana*, *Hura crepitans*, and *Pseudolmedia laevis*. Tree species common in drier forests (e.g., *Centrolobium microchaete*, *Chorisia speciosa*, and *Cedrela fissilis*) are also present in La Chonta. Although only a few high-value timber species (e.g., *Swietenia macrophylla* and *C. fissilis*) were harvested between 1980 and the mid-1990s, 10–12 tree species were harvested during this study (2001–2003). About 7–20 m^3/ha of wood (3–5 trees/ha) were harvested from annual management units that each encompassed about 2300 ha. Harvest activities are planned based on a 30-yr cutting cycle and implemented in accordance with Forest Stewardship Council certification standards and criteria. The minimum diameter for felling set by law is 70 cm for *H. crepitans* and *F. boliviana*, and 50 cm for all other species. Approximately 20% of trees above the diameter limit are left as seed trees.

METHODS

Design

This study was conducted within and adjacent to 27-ha permanent plots established as part of a long-term silvicultural research project (LTSRP; IBIF 2004). The LTSRP applied four treatments representing a range of management options and intensities: control = no logging; normal logging = planned logging with no other silviculture; improved management = normal logging with liberation of future crop trees from vines and overtopping noncommercial trees; and intensive management = improved management with double the harvest intensity, additional future crop tree liberation, and soil scarification in selected felling gaps. The improved and intensive treatments aimed to promote the regeneration and growth of commercial timber species, most of which are light demanding (Mostacedo and Fredericksen 1999, Pariona et al. 2003). Treatments were randomly applied to 27-ha plots in each block, which were situated in three different harvest units (4 treatments × 3 blocks = 12 plots).

The present study was conducted in and adjacent to Blocks 2 (harvested between May and July 2001) and 3 (harvested between February and July 2002). Because roads can act as fire conduits (Dell 1970, Wilson 1979), it is important to note that although skid trails were included, roads did not traverse the treatment plots. Although the forest appeared disturbed, signs of previous fire were only evident in a few small patches of the intensive plot and no old stumps from previous logging entries were found in any of the plots.

Treatment effects on forest structure and vegetative cover

To compare harvest treatment impacts on forest structure, I compared the harvest volumes and basal area removed as well as the corresponding ground and crown area disturbed by harvest operations. Residual tree densities and basal areas were also compared based on post-harvest censuses of the three harvest treatment plots and the control plot. To estimate the impacts of each treatment on vegetative cover, I measured cover at 5-m intervals along four transects (spaced 75 m apart) per treatment previously established in Block 2. The total number of sample points was 327 for the intensive treatment, 363 for the improved treatment, 338 for the normal treatment, and 377 for the control treatment. The transect lengths varied between 400 and 500 m depending on the distance from the southern to the northern border of each treatment plot. All cover estimates were made in early December 2001 by which time deciduous trees were in full leaf.

Vegetative cover (%) was estimated in six vertical strata (0–1 m; 1–2 m; 2–4 m; 4–8 m; 8–16 m; and >16 m) by viewing upward through a clear grid of 25, 3 cm × 3 cm squares (Mostacedo and Fredericksen 2000). I counted the number of squares covered and half covered with vegetation in each stratum. To increase the accuracy of ocular estimates of vertical heights, a 14-m telescopic pole was used for daily calibration. Where total cover is reported, it is shown as a percentage and is simply the sum of the six percentages of cover (one per stratum).

At each sample point, I also estimated the horizontal distance to the nearest gap (felling or natural) and classified each point by habitat type. I defined a gap as any area $\geq$10 m^2 in which the highest vegetation was $\leq$2 m tall (Brokaw 1982). Habitat classes were (1) undisturbed; (2) felling gap; (3) felling gap edge (0–20 m from gap); (4) skid trail; (5) skid trail edge (0–20 m from edge); (6) natural gap; and, (7) natural gap edge (0–20 m from gap).

The means from each transect per treatment were used to test for treatment differences in a one-way ANOVA; separate tests were conducted for each cover stratum, total cover, and distance to gap. Because the four transects per treatment were all located in one block, they do not constitute true replicates. Nevertheless, inferential statistics were used to provide an objective indication of whether cover differed by treatment (Oksanen 2001).

Treatment effects on fuel loads

To assess treatment impacts on fuel loads, censuses were conducted six and 15 months post-harvest in Block 2 using the planar transect method (Van Wagner 1968, Brown 1974, Uhl and Kauffman 1990). In each census, 36–47 randomly oriented transects were established starting at 50-m intervals in each treatment plot. Transects consisted of vertical planes (extending from the ground to 2.5 m) of variable length depending on the diameter of the woody debris, with planes 11 m long for 1000-h fuels (>7.5 cm), 5 m long for 100-h fuels (2.5–7.5 cm), 2 m long for 10-h fuels (0.6–2.5 cm), and 1 m long for 1-h fuels (<0.6 cm). The fuel time lag concept is based on the observations that as relative humidity changes, fuel moisture changes in an exponential fashion, and that smaller diameter fuels gain or lose moisture faster than larger diameter fuels because of their higher surface area to volume ratio (Agee 1993).

Wood fragments of each size class were tallied if they crossed the sample plane. Separate tallies for 1000-h fuels were made according to three decay classes—sound, intermediate, and rotten—as described by Delaney et al. (1998). Calipers were used to measure diameters of all 1000-h fuels and a sample of smaller woody debris to obtain mean diameters for those size classes. Leaf litter depth was measured at three points along each transect.

To obtain fuel mass estimates, samples of litter and woody debris were collected from the transects. Litter samples (all 1-h fuels down to mineral soil) from quadrats (20 × 20 cm) located at the beginning of each transect were oven dried at 80°C to constant weight.

The first three pieces of 1-, 10-, and 100-h fuels were collected from each transect to determine average wood density for each size class. Random samples of larger pieces in each decay class were obtained elsewhere in each treatment plot.

Wood densities were calculated from measurements of the fresh volume (by water displacement) and the oven dry mass of each sample. In the case of large sections of trunk, heartwood, sapwood, and bark were included. Masses for each size class were computed on a tons per hectare basis as per methods described by Brown (1974) using the combined data from all transects within each treatment. To compare differences among treatments, the log-transformed values for each transect within each treatment were used in an ANOVA. Although the transects within each treatment did not constitute true replicates, the only way to objectively compare the effect of the treatments on fuel loads was to use inferential statistics. Treatment impacts on leaf litter depth and litter mass were compared in a similar manner.

Vegetation cover–dry-down relationships

I determined the number of days 10-h fuels required to dry to 12% moisture content under a range of canopy cover conditions during the early and mid-dry season. Uhl and Kauffman (1990) considered 12% to be the threshold moisture content below which forest fuels could easily ignite. From 10–19 July 2001, I measured dry-down rates of 10-h ‘‘fuel sticks’’ made from a local species (*H. crepitans*), but otherwise identical to the standard pine ‘‘fuel sticks’’—four 35 cm × 1 cm diameter dowels connected in a plane by small dowels and staples—used by other researchers (Uhl and Kauffman 1990, Holdsworth and Uhl 1997).

I placed 10 fuel sticks along each of five variable-length transects (50–75 m) that originated in the centers of logging gaps (50–250 m apart) and extended into undisturbed patches of forest in the intensive treatment plot of Block 2. After soaking overnight in water to simulate a substantial rainstorm, the fuel sticks were suspended ~25 cm above the forest floor in a stratified random manner to represent the range of cover conditions present throughout the four management treatments; sticks within a transect were at least 5 m apart. I repeated this experiment in Block 3 in late May 2002 using standard pine sticks to determine the number of days necessary for 10-h fuels to reach 12% moisture content in the early dry season. For analyses, the moisture contents of the *H. crepitans* fuel sticks were adjusted to values for standard pine fuel sticks based on regression of average moisture contents of both species during controlled drying ($R^2 = 0.98$).

Data collected included vegetative cover estimates, temperature, relative humidity, and moisture content of the fuel sticks. I estimated cover in six vertical strata above each fuel stick using the grid method described above. I recorded temperature and relative humidity at 2-h intervals for two weeks in eight of the sites using Hobo temperature/relative humidity data loggers (Onset Computer Corporation, Bourne, Massachusetts, USA). I calculated vapor pressure deficit as a function of mean maximum temperature and mean minimum relative humidity at 1200 h using standard conversions (Rosenberg et al. 1983). I weighed the fuel sticks to the nearest 0.1 g daily between 1200 and 1400 h until they dried below 12% moisture content.

The data were analyzed using nonlinear regression with vegetative cover as the independent variable and number of days for the fuel sticks to reach 12% moisture content as the response variable. Linear regression was used to relate total cover to mean minimum relative humidity and mean maximum temperature.

Test fires

To further test the influence of treatment-induced changes in micro-environmental conditions on the forest's susceptibility to fire, I carried out a series of test fires in 4-m^2 square plots located just outside of the LTSRP plots. In the first experiment, I set 99 test fires during three consecutive days in early October 2001 (late dry season). Although 4 mm of rain fell two days before the trials, prior to that event no rain fell for one week. Test fire plots were located across the full range of cover conditions found in the treatment plots. All plots were within 25–300 m of the principal logging road and within 5–50 m of primary skid trails to facilitate water transport and for safety.

Using methods adapted from U.S. Forest Service fire research in Brazil (D. Sandberg and E. Alvarado, *personal communication*), I established 33 replicate sites for conducting experimental fires. A replicate consisted of a center point in which I placed a standard 10-h pine fuel stick and a litter sample in a nylon mesh bag for measuring moisture content surrounded by three test fire plots each separated by 1–2 m. I also placed a Hobo data logger at six of the sites to record temperature and humidity over the range of cover conditions among all sites. Test fire replicates were at least 25 m apart and located to avoid steep slopes, dense *Heliconia* patches, and major vine tangles.

Before attempting to burn the plots, I estimated cover in six vertical strata using the grid method described above from the center of each of the 99 test fire plots. To control for variation in the presence of 100-h and 1000-h fuels, I removed woody debris >2.5 cm diameter from several test plots. This step also helped increase my confidence that the results were due to microclimatic factors and the quantity and moisture content of 1-h and 10-h fuels. To assess the quantity of 1-h fuels, I measured litter depth in ten locations (corners, perimeter midpoints, and two points near the plot center) to the nearest millimeter. I also collected a 20 × 20 cm litter sample from the center of each site using the method described above to assess 1-h fuel moisture content. Finally, the percentage of live vegetation below 1 m height (including ferns as well as herbaceous and woody vegetation) covering each sample plot was estimated.

To prevent fires from escaping beyond the plots, a 50-cm safety buffer was established around their perimeter two to three hours before starting the test fires. Specifically, all leaf litter and larger fuels were removed so that any fire reaching the plot edge would encounter mineral soil. Thus, all test fires eventually self-extinguished within the plot's borders.

I started the test fires at 12:00–14:30 each day by igniting 50 mL of diesel that was dripped over a small area (400 cm^2) in the center of each plot. As the fires were set, the fuel sticks and litterbags were weighed, the temperature and relative humidity were measured with a digital thermohygrometer (Thermo-Hygro, Control Company, Friendswood, Texas, USA), and wind speed (m/s) was estimated by measuring the distance a feather dropped from 2 m flew and the time it took to land. Vapor pressure deficit was calculated as described above. The amount of time flames were visible in each plot was recorded. After all the plots burned, I measured the maximum distance (0–90 cm) fire carried from the ignition zone in each plot and visually estimated the percent of each plot that burned. I repeated this experiment in June and July 2002 (in an area adjacent to Block 3 harvested one to three months previously) to quantify the extent to which intensifying management extends the fire-prone season.

After transforming percentage data (arcsine square root), the effects of total cover, litter depth, vapor pressure deficit, wind, and 10-h and 1-h fuel moisture content on the percentage of area of the plots that burned were evaluated with path analysis using SAS version 9.0 (SAS 2002) and procedures described by Mitchell (2001). Path analysis allows hypothesized causal relationships—both direct and indirect—among independent and dependent variables to be tested via a series of multiple regressions (Schemske and Horvitz 1988, Mitchell 2001).

To quantify the persistence of any elevation in fire susceptibility due to intensification of management, I conducted an additional trial to compare the ability of fire to carry in forest logged at three different times. This trial, conducted in August 2002, was carried out near Block 2, near Block 3, and in an area logged in 1999. Block 3 had just been logged and hence was termed the 0-yr treatment. Block 2 was logged one year previously (1-yr treatment) and the 1999 area was logged three years previously (3-yr treatment). Two research teams burned 10 plots per day at 12:00–14:30 in each treatment. In contrast to the criteria described above for selecting plot locations, I placed plots in the most severely disturbed sites (i.e., large felling gaps and primary skid trails) I could find in each of the three areas. After arcsine square-root transformation for percentage data, one-way ANOVA was used to compare the means of total cover, litter depth, 10-h fuel moisture, vapor pressure deficit, and plot area burned among the three treatment blocks. In the two cases with unequal variances among treatments, a Kruskal-Wallis test was used (test statistic, *H*). Post-hoc comparisons (Tukey or Mann-Whitney U) were conducted to specify which treatments differed.

Calculation of fire-prone days

A simple model was used to calculate the number of days La Chonta is prone to fire in response to each management treatment in an average year and a dry year. The model is based on the assumption that the number of consecutive rainless days is a good predictor of fire susceptibility. It also depends on the relationship between canopy cover and the dry-down rate of 10-h fuels that was experimentally derived.

The number of fire-prone days per month (FD) was calculated as a function of f_o, fire-prone days for forest patches with very sparse vegetative cover (= open; total cover <110%); f_m, fire-prone days for patches with intermediate cover (= mid; total cover 110–210%); and f_c, fire-prone days for patches with dense cover (= closed; total cover >210%). Thus,

$$\mathrm{FD} = (f_o\ C_o) + (f_m \times C_m) + (f_c \times C_c)$$

where C_o, C_m, and C_c represent the proportion of each treatment plot consisting of ''open,'' ''mid,'' and ''closed'' vegetative cover, respectively. The values for C were obtained from the assessment of treatment impacts on cover. The model weights the number of fire-prone days for open, intermediate, and closed canopy conditions by the proportion of the forest in each condition.

Fire-prone days for each cover class were calculated with the following procedure. First, I examined the daily rainfall records for La Chonta, which were available for 1998–2002, and defined a rainfall event as being a one-day measurement of at least 5 mm of precipitation, which included 98% of the rainfall records. Second, I counted the number of consecutive rainless days required for 10-h fuels to dry sufficiently to ignite for open, intermediate, and closed forest patches. Based on the results of the cover–dry-down experiments, I assumed that 10-h fuels become flammable after three consecutive rainless days in open forest patches, after six consecutive rainless days in intermediate forest patches, and after nine consecutive rainless days in closed forest patches. For example, if in a particular month two rain events were separated by 10 consecutive rainless days, open patches would be fire prone for seven days, intermediate patches for four days, and closed patches for one day. The monthly tallies of fire-prone days (based on consecutive rainless days) for open, intermediate and closed forest were used as values for f_o, f_m, and f_c, respectively. This equation was used to calculate FD on a monthly basis for each treatment for the five-year period 1998–2002. The results for each treatment were compared by visual inspection

TABLE 1. Impacts of timber harvesting and silvicultural treatments in Block 2 of the Long-term Silvicultural Research Project in La Chonta based on unpublished data from the Bolivian Institute for Forestry Research.

Parameter	Normal	Improved	Intensive
Plot area (ha)	25.9	27.8	25.0
No. trees harvested/ha	3.3	2.8	5.0
Basal area harvested (m^2/ha)	2.1	1.4	2.7
Volume harvested (m^3/ha)	16.8	11.9	18.5
Mean (±SE) dbh of harvested trees	84.3 ± 3.5	77.7 ± 2.8	70.7 ± 2.1
Reduction in tree density (%)†	7.8 (11.8)	7.3 (11.1)	12.5 (17.9)

† Total percentage of trees harvested and killed (≥10 cm dbh; based on differences in census 1 and 2). The number in parentheses refers to the proportion of trees ≥40 cm dbh that was harvested.

of box plots of these values and of summary statistics. Because the interannual, within treatment variation greatly exceeded variation among treatments, treatment effects were not compared with inferential statistics.

RESULTS

Treatment effects on forest structure

Between 35% and 44% more trees were harvested per ha from the intensive treatment plot than from the other two harvest treatment plots (Table 1). The corresponding basal area and volume harvested from the intensive plot was also greater than the other treatments, but the difference between the normal logging and intensive treatments was smaller than expected due to the greater average diameter of harvest trees in the normal treatment than in the intensive treatment plot (Table 1). The intensive treatment killed 41% more trees (≥10 cm dbh) than the improved treatment and 33% more than the normal treatment (Table 1).

Treatment impacts on forest structure were relatively modest. Six months following treatment, the harvest treatment plots had only 10–25% more gaps and building-phase forest (vegetation ≤ 8 m) than did the control plot. Similarly, the proportion of the plots with mature forest (vegetation > 16 m) was 20% less in the harvest treatments than in the control treatment, but only 30% of the control plot comprised mature forest. Average horizontal distances to gaps were shorter in the intensive management than in the improved harvesting and control treatments ($F_{3,12} = 6.3$, $P < 0.01$), but were similar in the intensive management and normal harvest treatments. The area disturbed by felling and skid trails was similar among the harvest treatments (Table 2). The harvest treatments retained less cover than the control plot in the 8–16 m stratum ($F_{3,12} = 8.9$, $P < 0.01$), but cover in this stratum was similar among the harvest treatments. When all cover strata were combined (maximum cover = 600%), only the normal harvest and intensive management treatments retained less cover than the control ($F_{3,12} = 7.7$, $P < 0.01$); total cover was similar in the intensive management and normal harvest treatments (Appendix A). Only 6% of the intensive treatment plot comprised patches with sparse cover (≤110%).

Treatment effects on fuel loads

Based on 3575 m (325 transects) inventoried for woody debris six and 15 months post-harvest, the treatment plots differed most notably in the quantity of coarse woody debris encountered. The intensive management plot contained twice the quantity of 1000-h fuels as the normal and improved harvest plots and 25 times the quantity as the control plot. In addition, about 60% more 100-h fuels were encountered in the intensive management plot than in the control plot and about 30% more were tallied in the intensive management plot compared to the normal and improved harvest plots (Appendix B). Similarly, the variation in spatial distribution of fuels increased with treatment intensity. Compared to the control treatment, the intensive man-

TABLE 2. Percentage of each treatment plot in Block 2 of La Chonta observed in corresponding habitat classes, based on point sampling along four 400–450 m transects in each treatment plot six months post-harvest.

Habitat class	Control	Normal	Improved	Intensive
Undisturbed	62.3	35.8	39.2	28.4
Skid trail	0	5.9	5.2	4.9
Skid trail edge	0	12.4	10.5	9.8
Felling gap	0	16.0	9.9	15.0
Felling gap edge	0	15.1	14.9	22.6
Total harvest disturbed	0	49.4	40.6	52.3
Natural gap	7.7	4.1	3.0	5.5
Natural gap edge	30.0	10.7	17.1	13.8
Total natural disturbed	37.7	14.8	20.1	19.3
Total	100.0	100.0	100.0	100.0

TABLE 3. Densities (g/cm^3) and mass estimates (Mg/ha) (mean ± SE) for each size and decay class of woody debris in La Chonta based on averages from two censuses (six and 15 months post-treatment).

			Mass (Mg/ha)			
Fuel size/decay class	Wood density	N	Control[a]	Normal[b]	Improved[b]	Intensive[b]
1-h	0.34 ± 0.01	174	1.4 ± 0.1	1.7 ± 0.1	1.9 ± 0.1	1.7 ± 0.2
10-h	0.35 ± 0.03	146	4.3 ± 0.3	4.1 ± 0.4	3.8 ± 0.2	3.4 ± 0.3
100-h	0.30 ± 0.01	144	1.6 ± 0.2	2.9 ± 0.3	2.8 ± 0.3	3.8 ± 0.4
1000-h sound	0.66 ± 0.06	86	0.3 ± 0.2	11.9 ± 4.0	11.2 ± 3.4	35.8 ± 12.5
1000-h intermediate	0.59 ± 0.06	72	7.3 ± 4.7	12.4 ± 6.3	11.4 ± 5.5	14.8 ± 5.3
1000-h rotten	0.47 ± 0.09	63	7.1 ± 1.9	8.3 ± 2.4	6.1 ± 1.4	3.7 ± 1.1
Total			22.0 ± 5.0	41.3 ± 8.0	37.1 ± 6.4	63.1 ± 13.9

Notes: Fuel sizes classified by diameter according to the fuel time-lag concept: 1-h class (<0.6 cm); 10-h class (0.6–2.5 cm); 100-h class (2.5–7.5 cm); and 1000-h class (>7.5 cm). Decay classes follow Delaney et al. (1998). Different letters next to treatments indicate significant differences based on one-way ANOVA with masses $\log_{10}$ transformed ($F_{3,321} = 3.81$, $P = 0.01$; $N = 79$ for control, 77 for normal harvest, 82 for improved harvest, and 87 for intensive management). Values shown are based on actual data, not the back-transformed data.

agement treatment increased the variation in the quantity of 1-h fuels by 58%, 100-h fuels by 101%, and 1000-h sound fuels by 121% (Appendix B).

Because the results of the 6-mo and 15-mo post-harvest woody debris assessments were similar ($F_{1,317} = 1.3$, $P = 0.27$), the data from both were pooled. The assessments revealed that greater fuel loads were present in the harvest treatments than in the control treatment (Table 3), and total mass of woody debris (all size and decay classes) was greatest in the intensive treatment (Table 3), but differences among harvest treatments were not significant. The greater mass of sound 1000-h fuels in the harvest (especially the intensive) treatments compared to the control treatment accounted for most of the difference in mass of woody debris.

The harvest treatments reduced leaf litter depths ($H = 31.0$, $P < 0.01$, Fig. 1a) relative to the control treatment six months after logging (during the early rainy season), but among harvest treatments, litter depth did not differ (Fig. 1a). In contrast, litter depth did not differ among any of the treatments at the beginning of the subsequent dry season (15 months post-harvest; Fig. 1b) although the trend was similar. Only the intensive harvest treatment had lower litter mass 15 months post-harvest than the control.

Effect of cover on fuel dry-down rates

Vegetative cover had the expected effects on both microclimate and fuel dry-down rates. Maximum understory temperatures were lower and minimum relative humidities remained higher with increasing vegetative cover during the dry season (Fig. 2a). Despite faster dry-down rates of fuels in sites with sparse cover ($F_{1,46} = 16.1$, $P = 0.0002$), 10-h fuels dried down enough to ignite in all sites (Fig. 2b). Specifically, during the mid-dry season, 10-h fuels dried down to 12% moisture content within three to six days after wetting in open sites (total cover < 110%) and within seven to 10 days in shaded sites (total cover > 210%; Fig. 2b).

During the early dry season of 2002, vegetative cover similarly slowed dry-down rates, but it was not possible to determine by how many days. A wetter than average May caused the moisture content of 10-h fuels under most cover conditions to remain well above 12%

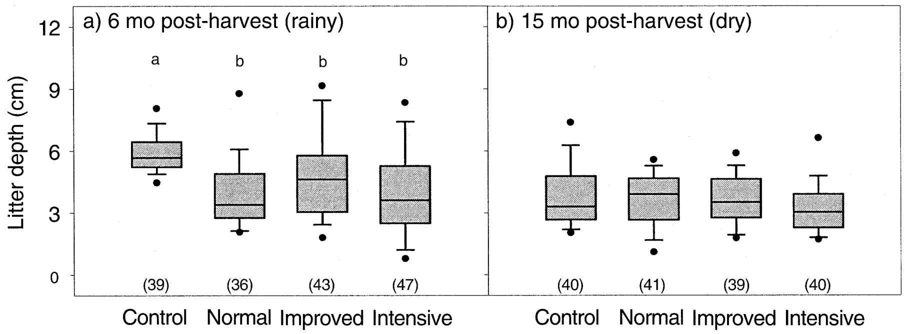

FIG. 1. Litter depth (a) six months and (b) 15 months post-harvest in the study plots at La Chonta, Bolivia. Boxes represent quartiles, whiskers the 10th and 90th percentiles, and dots the 5th and 95th percentiles. The solid line shows the median. Different letters indicate significant differences between the treatments, with sample sizes in parentheses. Treatments are: control, no logging; normal, planned logging with no other silviculture; improved, same as normal with liberation of future crop trees (FCT) from vines and overtopping noncommercial competitors; intensive, same as improved with double the harvest intensity, additional FCT liberation, and soil scarification in selected felling gaps.

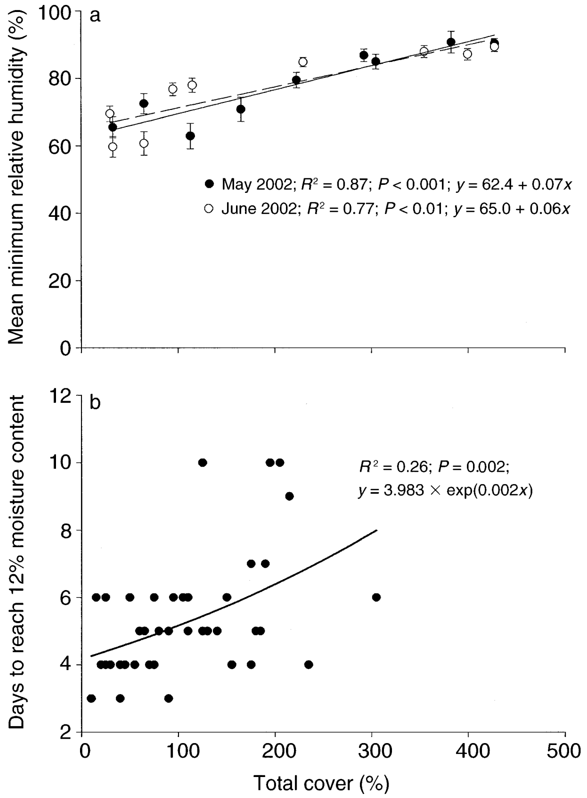

FIG. 2. (a) Mean minimum relative humidity and (b) the number of rainless days required for 10-h fuels to dry down from saturation to 12% moisture as a function of total cover in La Chonta during (a) the early dry season of 2002 and (b) the mid dry season of 2001. Total cover is the sum of percent cover estimates for six vertical strata. Points in (a) represent the means of midday relative humidity (%) measured with Hobo data loggers placed under different cover conditions 1–4 months post-harvest in Block 3. Error bars represent ±SE. Points in (b) represent the number of days each 10-h "fuel stick" required to reach 12% moisture content in July 2001. The R^2 and P values are based on regression analysis.

throughout the experiment. Ten-hour fuels dried down to 12% moisture content (two to three days after soaking) only in the most open sites.

Fire trials

Late dry season.—During the early October 2001 fire trials, the area of each plot burned varied substantially with some plots burning entirely and others not at all. Of the 99 plots tested, only 21% burned completely (>90% charred). However, fire carried to at least one plot edge in 57% of the plots. In cases where fires did not reach the plot edge, only 15% of the plot burned on average (range: 5–35%). Fires did not carry at all in 18% of the plots.

The plot area that burned differed among the three days of the 2001 trial (Table 4, $H = 9.2$, df = 2, $P = 0.01$). Because neither cover nor litter depth varied over the three days, the variation in area burned among days was probably attributable to the cooler, more humid, less windy, and cloudier weather on the third day compared to the first two days of the trial (Table 4). Because the principal aim was to quantify the effects of key factors on area burned across sites, the three-day averages per site were used in the path analysis.

Path analysis confirmed the expected effects of total cover, litter depth, vapor pressure deficit, and 1-h fuel moisture content on percent area of test plots burned (Fig. 3, Appendix C). Despite the influence of these factors on area burned, a large proportion of unexplained variance remained (Fig. 3), which was consistent with the observation that several plots in deep shade burned while some plots with sparse cover and apparently ample fuel did not. The moisture content of 10-h fuels in all sites tested was at or below the theoretical threshold for combustion (Table 4) and did not affect area burned (Fig. 3, Appendix C). Wind speeds throughout the trial were low (Table 4) and also did not directly affect area burned (Fig. 3, Appendix C).

Early dry season.—During the 11–12 June 2002 fire trials, no test plots burned. Despite 12 rainless days, mean minimum relative humidity remained above 70% during the trials.

In July 2002, only three of the 30 plots tested burned completely, whereas less than 30% of the test area was charred in the remaining plots. Total cover was sparse (35–110%) in the three plots that burned, whereas in the plots that did not burn total cover ranged from 30 to 415% (mean ± SE: 254 ± 21%). Analysis of paths for which sufficient data existed indicated that 10-h fuel moisture increased with increasing total cover (partial regression coefficient = 0.87, $P < 0.001$, $R^2 = 0.75$), and, in turn, area burned increased with decreasing 10-h fuel moisture (partial regression coefficient $= -0.79$, $P = 0.01$, $R^2 = 0.69$). Total cover did not affect litter depth and litter depth did not influence area burned.

Persistence of treatment impacts on fire susceptibility.—In the August 2002 fire trials to compare the fire susceptibility of forest areas logged zero, one, and three years previously, only 10 of 94 plots burned. Nevertheless, in the recently logged area (0-yr treatment), 8 of 34 plots burned compared to only 1 of 31 plots in the area logged one year previously (1-yr treatment) and 1 of 30 plots in the area logged three years (3-yr treatment) previously.

When the data for the three days of the trial were averaged by time since logging, the mean area of the test plots burned was nearly three times greater in the 0-yr treatment (27%) than in the 1-yr (9%) and 3-yr (10%) treatments indicating that plots in the recently logged area were more flammable than plots in the older logging treatments ($F_{4,45} = 41.5$, $P < 0.0001$; Table 5).

Analysis of paths (by time since logging) for which sufficient data existed indicated greater total cover increased 10-h fuel moisture and litter depth only in the 1-yr treatment. Litter depth, but not 10-h fuel moisture,

TABLE 4. Summary of 7–9 October 2001 (late dry season) test fires in La Chonta showing means (SE) for measured variables for each of the three consecutive days of the trial and the three-day averages.

Parameter	Max. burn (cm)	Area burn (%)	Rel. humidity (%)†	Temp. (°C)†	VPD (kPa)†	Wind speed (m/s)	Litter moisture (%)	10-h fuel moisture (%)	Total cover (%)	Litter depth (mm)
N	33	33	5	6	5	33	33	33	33	33
Day 1	74.5	45.0	40.4	35.1	3.5	0.6	17.5	10.2	199.8	32.1
	(5.7)	(5.7)	(4.6)	(0.9)	(0.5)	(0.0)	(1.5)	(0.2)	(10.8)	(1.5)
Day 2	87.0	55.6	38.2	35.5	3.7	0.6	14.9	10.1	200.3	33.6
	(3.9)	(5.4)	(2.5)	(0.8)	(0.5)	(0.0)	(1.1)	(0.2)	(12.6)	(1.6)
Day 3	67.1	34.1	50.4	30.3	2.3	0.4	18.5	12.0	206.3	34.1
	(3.2)	(5.2)	(1.6)	(0.7)	(0.4)	(0.0)	(1.4)	(0.2)	(12.4)	(1.8)
Average	76.2	44.9	43.0	33.6	3.1	0.5	16.9	10.8	202.2	33.1
	(4.2)	(4.3)	(2.9)	(0.6)	(0.5)	(0.0)	(1.1)	(0.2)	(6.8)	(0.9)

Notes: Test fires were set at 12:00–14:30 in 33 sites per day, representing the range of cover conditions found throughout the four management treatments 2–3 months post-harvest. Max. burn = maximum linear distance from the center toward the edge of the 2 × 2 m plot that burned; area burn = percentage of the surface area of each plot that burned; total cover = sum of the percent vegetative cover estimates for six vertical strata (maximum = 600%).

† Data are daily mean minimum relative humidity and mean maximum air temperature among six data loggers (at a height of ~25 cm) at sites across the cover range. The humidity sensor malfunctioned in one of the data loggers, hence $N = 5$. Vapor pressure deficits (VPD) were calculated from temperatures and relative humidities.

in turn influenced area burned but only in the 3-yr treatment. Litter in the 0-yr treatment was about twice as deep as in the 1- and 3-yr treatments (Table 5) and about the same as the litter depth measured 3 months post-harvest during the late dry season of the 2001 fire trials (3.3 ± 0.9 cm [mean ± SE]; $n = 99$). Fuel moisture did not influence area burned in any of the treatments. Although fuels were drier in the 0-yr treatment, 10-h fuel moisture was at or below the theoretical ignition threshold in all treatments (Table 5).

Fire-prone days

Analysis of five years of rainfall records revealed that long (~20 days) rainless periods are common in La Chonta. About 198 ± 52 mm (mean ± SE) of rain falls each month during the wet season, but only 60 ± 31 mm of rain falls monthly during the six-month dry season and only 36 ± 20 mm of rain falls in La Chonta during each of the driest months (June–August).

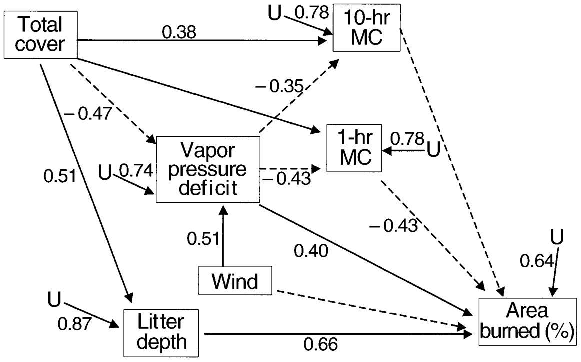

FIG. 3. Path diagram for the effects of total cover, vapor pressure deficit, litter depth, wind, 10-h fuel moisture content (10-h MC), and 1-h fuel moisture content (1-h MC) on area burned (%) in the 7–9 October 2001 test fires in La Chonta. Arrows illustrate hypothesized paths of causation: solid arrows indicate positive effects, and broken arrows negative effects. Arrows with adjacent values indicate significant effects at $P < 0.05$. Magnitude of the values indicates strength of the effects illustrated. Unmeasured factors affecting the variables are represented by ''U.'' See Appendix C for actual P and R^2 values.

Long rainless periods in all months strongly influenced the results obtained from the model used to forecast fire-prone days. The number of fire-prone days ranged from five in February (the wettest month) to 26 in July and August for open sites (cover < 110%), from one in February to 24 in August for intermediate sites (cover 111–210%), and from 1 in February to 22 in August for closed sites (cover > 210%). When these data were used to forecast fire-prone days for each cover class, the number of fire-prone days in any given month was similar among treatments and depended much more on the strength of the dry season than on the treatments (Fig. 4). For example, in an average year the number of fire-prone days in August ranged from 19.1 in the unlogged control plot to 19.5 in the intensive plot. In a drier-than-average year, all plots would be fire prone for 31 days in August. These estimates of fire-prone days were based on the cover conditions in the treatment plots six months post-harvest, after which the small differences among treatments further diminished.

DISCUSSION

Treatment effects on forest structure

Impacts of the silvicultural experiment in La Chonta on forest structure were modest and similar among treatments despite the greater number of trees and lianas killed in the intensive management treatment. This similarity in experimental treatment impacts was attributable in part to the smaller average diameter of harvested trees in the intensive management plot compared to the normal and improved logging plots. In

TABLE 5. Summary of August 2002 fire trial in La Chonta showing means, standard errors, and ANOVA or Kruskal-Wallis results for five measurements on 4-m^2 plots by year post-logging.

Measure	Treatment (years post-logging)			F	df	P	H
	0 yr†	1 yr	3 yr				
Total cover (%)	119.9^{a} ± 16.4	192.5^{b} ± 12.0	204.3^{b} ± 8.7	12.9	2, 47	$<$0.001	
VPD (kPa)‡	5.4^{a} ± 0.2	3.2^{b} ± 0.1	3.2^{b} ± 0.1	88.1	2, 6	$<$0.001	
Area burned (%)	26.7^{a} ± 5.5	8.7^{b} ± 3.3	9.8^{b} ± 2.6	7.2	2, 48	0.002	
Litter depth (cm)	3.5^{a} ± 0.3	1.4^{b} ± 0.1	1.5^{b} ± 0.1			$<$0.001	29.6
10-h fuel moisture (%)	9.0^{a} ± 0.4	12.2^{b} ± 0.5	12.5^{b} ± 0.4			$<$0.001	23.1

Notes: N = 17 plots per treatment, except where noted otherwise. Percentages were arcsine square-root transformed. Different letters indicate differences between treatments based on post hoc comparisons with Tukey or Mann-Whitney U tests.

† For this treatment, N = 15 for 10-h fuel moisture, and N = 16 for total cover.

‡ Means for VPD are based on three data loggers per treatment for the three days of the trial.

addition, although the intensive management treatment doubled the harvest intensity relative to what is typically applied in similar forests in Bolivia, it was mild when compared to other logging operations in the tropics where harvest volumes are 2–10 times greater than those observed in this study (Putz et al. 2001).

Although the intensive management treatment had more gaps than the normal or improved logging treatments, the average distance to gaps differed by only a few meters among the treatments. Considering that edge effects on understory microclimate can penetrate at least 40–60 m (Kapos 1989, Didham and Lawton 1999, Cochrane and Laurance 2002) and the fact that half the canopy trees in La Chonta lose their leaves during the height of the dry season, differences among treatments were probably insufficient to markedly affect fuel dry down rates. Among harvest treatments, vegetative cover differed only in the mid-canopy strata, but the modest differences in total cover need to be considered in reference to the relatively open canopy characteristic of this semi-deciduous forest even before logging. In fact, the most striking result was the high background level of disturbance in La Chonta: 30% of the control plot comprised natural gaps or young forest.

Due to its open canopy, La Chonta is already very susceptible to fire even in the absence of logging. Although elevated fuel loads and decreased canopy cover resulting from mahogany extraction probably exacerbated the severe fires of 1995 (Pinard et al. 1999, Mostacedo et al. 2001, Gould et al. 2002), large swaths of apparently undisturbed forest also burned. Similar fires have occurred in undisturbed forests of the eastern Amazon, but only after several years of drought (Uhl and Kauffman 1990, Nepstad et al. 1995, 1999*b*). In con-

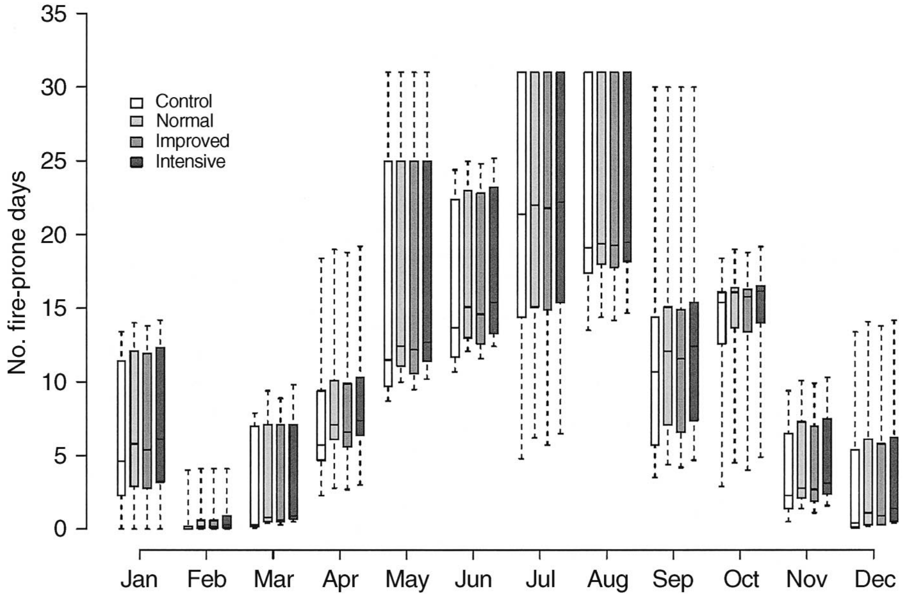

FIG. 4. The number of fire-prone days per month predicted for each management treatment applied in La Chonta based on a model of consecutive rainless days and the proportion of each treatment plot consisting of ''open'' (<110% cover), ''intermediate'' (110–210% cover), and ''closed'' (>210% cover) forest patches (see *Methods: Calculation of fire-prone days* for details). Boxes represent quartiles, the solid line shows the median, and whiskers extend to the maximum and minimum.

trast to these forests, La Chonta receives 300–500 mm less rainfall annually and is semi-deciduous, factors that help explain its fire susceptibility even without logging.

Treatment impacts on fuel loads

The average fuel load (including woody debris and leaf litter) recorded in the unlogged control area in La Chonta (~27.5 Mg/ha) is on the low end of values reported for primary forests in the Amazon. For example, fuel loads twice as great were reported from the eastern Amazon (Uhl and Kauffman 1990) and Venezuela (Kauffman et al. 1988, Delaney et al. 1998). The mass of 100-h fuels in La Chonta was 10 times lower (1.6 vs. 16.8 Mg/ha) than what Cochrane et al. (1999) measured in unlogged forests in the eastern Amazon. The relatively low mass of dead and down fuels in La Chonta is probably attributable to the low tree biomass, which is an expected consequence of lower rainfall (Murphy and Lugo 1986) and high liana density (Alvira et al. 2004). Similarly low fuel loads were found in second growth forests in Brazil (Uhl and Kauffman 1990).

Relative to the control, fuel loads were doubled by the normal logging treatment and tripled by the intensive treatment. These increases were mainly attributable to a greater amount of sound 1000-h fuels resulting from harvest damage and residues that persist for at least 15 months post-treatment. The relative increase in fuel loads from intensive management compared to the unlogged control was similar to that reported by Uhl and Kauffman (1990). In their study, however, the magnitude of woody debris inputs (150 m^3/ha) was much greater than reported here. This difference might be attributable to the size of trees harvested, harvest practices, and to the greater overall volume (50 vs. 18 m^3/ha) and number of harvested trees (8 vs. 5 trees/ha) in their study site in Brazil.

Although the harvest treatments increased woody fuel loads, they decreased leaf litter depth (six months post-treatment) and mass (15 months post-treatment) compared to the control, with the lowest values in the intensive treatment plot. These results differ from those reported by Uhl and Kauffman (1990); in their study site, the mass of fine fuels was 30% greater in the logged vs. the control area. Site factors (e.g., greater leaf area index and litter production in the eastern Amazon) probably explain most of this difference, but the timing of the censuses might also be relevant. Uhl and Kauffman (1990) estimated litter mass a few months post-logging, whereas in this study litter mass was quantified 15 months post-logging, which corresponded to the early dry season when leaf litter is typically sparse (G. M. Blate, *personal observation*).

In this study, it appears that the harvest impacts on fuel loads are more likely to affect potential fire severity than fire susceptibility. The quantity, arrangement, and moisture content of fine fuels, including litter, determine to a large extent the susceptibility of a particular area of forest to fire (Stott 2000, Cochrane 2003). Once a fire ignites, the arrangement, quantity, and moisture content of larger fuels influence whether combustion is sustained and also determine the fire's severity (Stott 2000). Although this study did not assess fire behavior, it is nevertheless reasonable to infer that fire severity would be greatest in the treatments with the greatest quantity of fuels, especially 1000-h and larger fuels. The harvest treatments at La Chonta would increase fire severity relative to the control, but the potential for severe fires would be greatest in the intensive treatment because of the threefold increase in 1000-h fuels relative to the normal treatment. The greater quantity of 1000-h fuels in the intensive treatment plot implies that if a fire were to occur, it would smolder longer and be harder to extinguish (Cochrane 2003), and consequently cause higher tree mortality rates (Kauffman 1991) than in the other treatment plots.

Cover–fuel dry-down rates

As described for forested areas throughout the tropics (e.g., Walsh 1996), understory vapor pressure deficits decreased with greater total cover in La Chonta. That the effect of cover on vapor pressure deficit was strongest early in the dry season and weakest in the mid-dry season indicates that once the forest dries, not even sites with dense cover retain much moisture. Only about half of the canopy species and canopy trees retain their leaves during the greatest period of water stress (i.e., July–August; J. Justiniano, *unpublished data*).

The semi-deciduous canopy of La Chonta differs from the evergreen forests of the eastern Amazon, the canopies of which remain closed—thanks to deep rooting of most tree species—despite equally long and severe droughts (Nepstad et al. 1995). Retention of an evergreen canopy in the eastern Amazon is considered to be the key attribute that provides fire immunity during normal years because it prevents desiccation of the understory vegetation and surface fuels (Nepstad et al. 1995).

Ten-hour fuels in the most open sites dried below the moisture content threshold within three to six days, a result similar to what Holdsworth and Uhl (1997) found in the eastern Amazon. In contrast, 10-h fuels required only seven to 10 rainless days to dry enough to ignite even in the most shaded sites in La Chonta, whereas 10-h fuels remained above threshold levels at which ignition could occur throughout the dry season in unlogged forests of the eastern Amazon (Uhl and Kauffman 1990, Holdsworth and Uhl 1997) and Venezuela (Uhl et al. 1988). These results suggest that the understory microclimate in semi-deciduous forests like La Chonta apparently is much drier than the evergreen forests elsewhere in the Amazon where similar fire studies have been conducted, and that open sites in La Chonta can burn after only three rainless days, while most undisturbed sites can burn after only 10 rainless days.

Fire trials

The extent to which experimental fires carried depended on vegetative cover, litter depth, relative humidity, and fuel moisture content. These factors are well known to influence forest flammability (e.g., Stott 2000), but they only explained 59% of the observed variation. In the late dry season (October 2001) and only a few months after logging, many plots in sites with sparse vegetation and apparently sufficient litter did not burn completely, and conversely, some plots in densely shaded areas burned completely or nearly so. This latter observation contrasts with results from undisturbed evergreen forests in Amazonian Brazil (Uhl and Kauffman 1990, but see Holdsworth and Uhl 1997), Venezuela (Uhl et al. 1988, Kauffman and Uhl 1990), and Indonesia (Siegert et al. 2001, Van Nieuwstadt et al. 2001), which remain fire resistant in the absence of severe disturbances or El Niño associated droughts. The deciduous nature and open canopy structure of La Chonta apparently renders it fire prone even in the absence of logging or severe drought.

In the early dry season, at least at the management intensities tested in this study, La Chonta is not very fire prone. The failure of any plots to burn in June 2002 supports this conclusion. Moreover, few if any ignition sources exist during the early dry season because most small farmers and ranchers wait until July or August to set fires, and lightning initiated fires are rare (Stott 2000, Saarnak 2001). All of the destructive fires of the past four to five years (since a fire monitoring system was established) occurred in August or September (Plan Nacional 2002). Finally, fine fuels are much less available in the early dry season than they are toward the end of the dry season after half the canopy trees shed their leaves.

Factors influencing fire susceptibility.—The key factors explaining variation in area burned varied somewhat during the dry season, but moisture content of fuels, litter depth, and vapor pressure deficit were always important. The lower number of plots that burned on day 3 of the October 2001 fire trial when conditions were overcast and humid exemplified the influence of low vapor pressure deficit, which resulted in higher moisture contents of the short time lag fuels. Low vapor pressure deficit during the July 2002 trial similarly appeared to render most plots nonflammable.

Fuel moisture content, a critical determinant of forest flammability (Stott 2000), influenced the area of plots burned to a different extent during the dry season. Specifically, moisture content of 10-h fuels was a better predictor of the area of plots burned earlier in the dry season because the moisture content of 10-h fuels was about the same regardless of cover in the late dry season. Cochrane's (2003) suggestion that 1-h fuel moisture would be a more appropriate predictor of fire susceptibility than 10-h fuel moisture was supported by the path analysis of the late dry season fire data. Nevertheless, the use of 10-h fuel dry-down rates in the fire-prone days model is considered valid because 10-h fuel moisture did explain whether plots burned in the early-dry season. The packed arrangement of 1-h fuels on the forest surface explains why they may remain moister than 10-h fuels (Uhl et al. 1988), which were suspended 25 cm above the surface.

Differences in litter depth among plots also helped explain whether plots burned. Fuel coverage and quantity are key determinants of whether fires will carry across the forest floor (Stott 2000). Regardless of time during the dry season, few plots burned if they had litter less than 2.1 cm deep. It is conceivable but unlikely that sufficient litter would accumulate by the end of the dry season in the areas logged one and three years previously to render them more flammable because the senesced leaves of the pioneer species occupying the disturbed areas tested were already on the ground.

As reported for other tropical forests (Cochrane 2003), the extent to which plots burned decreased with increasing cover in La Chonta, but this effect was strongest in the early dry season. Apparently, only sites in or very near large gaps are likely to be fire prone early in the dry season. To the extent that intensive management creates more gaps, it will elevate fire susceptibility in the early dry season. This differential effect should be smaller, however, in the late dry season because by then fuels are dry enough to ignite regardless of cover. In summary, intensified management, at least to the extent tested in La Chonta, did not appreciably elevate fire susceptibility compared to the unlogged control or normal management practices, at least in the late dry season.

Persistence of treatment impacts on fire susceptibility.—The modest increase in susceptibility to fire in the early dry season resulting from intensive timber stand management in La Chonta seems to persist only for the year immediately following treatment; almost none of the plots in severely disturbed sites that were logged one and three years previously burned. In contrast, about one-fifth of the plots burned in an area logged two to four months previously suggesting that the elevated fire susceptibility associated with intensifying management in the early- to mid-dry season would become indistinguishable from normal harvest practices within one year. In the eastern Amazon, Holdsworth and Uhl (1997) found that regrowth in 3-yr-old logging gaps slowed fuel dry down rates rendering such gaps fire resistant. In La Chonta, 10-h fuels were drier in the area logged immediately prior to the fire trials than in the older logging areas, but even fuels in areas logged one and three years previously were dry enough to burn. Rather than fuel moisture, depth of fine fuels was the more important factor in the few plots that burned in the areas logged one and three years previously.

Treatment impacts on number of fire-prone days

The most striking result from the model employed to estimate the number of days the forest is fire prone in response to each treatment was that the effects of interannual variability in rainless periods greatly exceed any differences among treatments. For example, only 22 mm of rain fell in two rain events from July to September 1999, which resulted in 76 fire-prone days for closed forest patches according to the model. During the same period in 2000, 215 mm of rain fell in seven rain events, which resulted in only 47 fire-prone days. In an average year, the long rainless periods in the middle of the dry season resulted in very minor differences (maximum of four days) in fire-prone days between open, intermediate and closed sites. Considering the modest treatment impacts on cover, the difference in fire-prone days among treatments regardless of month were negligible.

Among the many assumptions inherent in the model I used to predict the number of fire-prone days, the most important are that 12% moisture content is a valid threshold on which to base fire susceptibility and that the number of consecutive rainless days is the best predictor of fire susceptibility. A more elaborate model might include fuel loads (especially litter depth and arrangement) as well as vapor pressure deficit, both of which helped explain the test fire results.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Four major conclusions can be drawn from the previous discussion. First, unlogged seasonally deciduous forests like La Chonta appear to be very susceptible to fire throughout much of the dry season. This finding contrasts with results reported for intact evergreen forests of the eastern Amazon, which remain fire resistant except during the driest years. Second, the range of timber harvest intensities assessed in this study had a trivial impact on the forest's susceptibility to fire, and this small impact diminished rapidly with time. Therefore, there appear to be only very modest and short-lived trade-offs between doubling the management intensity in an effort to secure adequate regeneration and growth for sustained timber yields and fire susceptibility in these forests. Assuming the forest can be adequately protected from ignition, especially during the year after harvesting, silvicultural activities at the intensities carried out in this study should not be viewed as creating excessively threatening conditions for fire. These conclusions must be considered, however, in the context of the substantial increase in coarse woody debris resulting from intensive management. Should a fire occur, it would be most severe where the forest is managed intensively because of the increased quantity of 1000-h fuels.

Based on these conclusions, it is clear that better control of ignition sources to prevent fires must complement silviculture treatments to achieve sustained yields if these forests are to satisfy both production and conservation goals. To some extent, training forest crews in fire prevention and control techniques will help reduce fire damages to production forests. Vigilance against fires escaping from nearby pastures (or starting within logging areas) should be concentrated in the same year as harvest activities, which is relatively easy if roads are designed as fire breaks. Moreover, forest managers should consider spatial arrangements of harvest units such that sufficiently wide buffers—Holdsworth and Uhl (1997) suggested 1 km—surround each unit at least for one to three years following harvest.

Unfortunately, controlling ignition sources in the Amazon will require a monumental shift in attitudes and practices and an equally large improvement in governance so that the positive economic and biophysical feedbacks that are making the Amazon Basin more fire prone can be broken (Nepstad et al. 2001). A better understanding of fire science across the range of forest types in the Amazon will provide a sound basis for breaking these feedbacks (Cochrane 2003). Equally important is greater emphasis on multi-disciplinary research that elucidates cultural and social uses and attitudes pertaining to fire (e.g., Roman-Cuesta et al. 2003), as well as an increase in inter-agency and intergovernmental cooperation. Considering the rapidly changing land use and climate in the region, unless greater priority is given to better defining and resolving the multiple dimensions of the fire problem in different biophysical and socio-economic contexts, the kind of fire-prone forests found in La Chonta may become more common throughout the entire Amazon Basin.

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APPENDIX A

A table showing a summary of silvicultural treatment impacts on forest structure in La Chonta, Bolivia, is available in ESA's Electronic Data Archive: *Ecological Archives* A015-049-A1.

APPENDIX B

A table showing mean number of woody debris fragments (by fuel and decay class) encountered per meter in La Chonta, Bolivia, is available in ESA's Electronic Data Archive: *Ecological Archives* A015-049-A2.

APPENDIX C

A table listing path coefficients, P values, and proportion of variance explained (R^2) by factors influencing area burned (%) in October 2001 test fires ($N = 33$) in La Chonta determined by path analysis and illustrated in Fig. 3 is available in ESA's Electronic Data Archive: *Ecological Archives* A015-049-A3.