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Selection harvests in Amazonian rainforests: long-term impacts on soil properties

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Abstract

Surface soil properties were compared among disturbance classes associated with a single-tree selection harvest study installed in 1979 in the Brazilian Amazon. Response variables included pH, total N, total organic C, extractable P, exchangeable K. Ca, Mg, and bulk density. In general, concentrations of all elements displayed residual effects 16 years after harvests with N, P, K, and C being inversely related to disturbance intensity while Ca and Mg levels as well as pH were directly related. Elemental contents exhibited fewer residual effects except in the cases of Ca and Mg contents which generally increased with disturbance intensity. Higher intensity disturbance classes were associated with increased bulk density. Soil impacts apparent after 16 years suggest a combination of direct effects of harvests (e.g. as in the case of bulk density) combined with indirect influences of the ecophysiology of the *Cecropia* sp. which dominate disturbed areas © 1997 Elsevier Science B.V.

Keywords: Amazon; Harvesting; Rainforest; Soil

1. Introduction

Sustained integrity and function of forest ecosystems is a major concern world wide. The need to insure the continued satisfaction of human needs derived from forests is especially strong in association with tropical rain forests. These biomes are highly valued for timber resources and non-timber values such as biological diversity, carbon cycling functions, and effects on global climate. Historically, however, these forests have been used in a destructive manner such as slash and burn agriculture, unrestricted logging, and conversion to other land uses. Faced with increasing population pressures and the need for economic growth, countries with tropical forests often turn to these exploitive strategies to make their forests economically productive.

Sustainable development of tropical forests has been defined by FAO (cited by Dykstra and Heinrich. 1992) as "the management and conservation of the natural resource base and the orientation of tech-

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nology and policy to facilitate the attainment of continued satisfaction of human needs for present and future generations''. The wisest strategy for maintaining the integrity of tropical forests is to develop management techniques which promote a mix of timber and non-timber values for present and future human populations (Bruenig. 1992; Dykstra and Heinrich, 1992). However, as Dykstra and Heinrich (1992) have noted, the successful creation and implementation of sustainable management in tropical forest ecosystems are partially dependent on the development of forest operations which are compatible with the sustainability concept. Unfortunately, despite the clear need for ecologically compatible operational techniques in tropical forestry. their identilication and assessment has only minimally progressed (Fearnside. 1989; Heinrich. 1992; Dykstra and Heinrich, 1992; Holloway. 1993).

Initial efforts directed toward development of feasible natural regeneration systems in tropical rain forests took place in Malaysia in the early twentieth century with the development of the Malaysian Uniform System (Bruenig. 1992). This has been followed by other systems such as the Selection Improvement System developed in the Philippines and the Tropical Shelterwood System developed in Nigeria (Bruenig. 1992). All of these have had mixed success due to a combination of biological or economical problems.

A trend in tropical silviculture which may hold significant promise with regard to sustained production is oriented toward the creation of small openings in a fashion that is akin to small group selection in the United States. Several recent reports (Page. 1988; Helm-Nielson et al.. 1989; Ocana-Vidal. 1992; Omiyale, 1992) support the notion that single-tree and/or small group selection may mimic natural gap-phase replacement in tropical systems. The same gap disturbance analogy has been extended to strip-clearcuts in natural forests of Peru (Ocana-Vidal. 1992). The philosophy behind the analogy is that natural processes such as succession continually create disturbances at this spatial scale and may, in fact, be necessary to maintain the integrity of natural forests.

Consequently, harvesting operations which mimic the creation of natural gaps may allow the highly valued functions of these systems to retain their integrity. The above authors suggest that operations could be somewhat concentrated via small group selection and thus made more efficient than in single-tree selection while potentially maintaining natural structure and function. However. the nature and longevity of changes in abiotic factors in openings created by harvests vs natural. small-scale disturbances is very uncertain but reflects a question which is critical to the successful use of these management systems. In particular, we know little about the magnitude and duration of shifts in soil properties within openings with no ground disturbance vs those with traffic.

The creation of single-tree size gaps (whether natural or silvicultural) will alter nutrient circulation through changes in nutrient inputs as well as soil moisture and temperature conditions which control mineralization. The direction and magnitude of changes in mineralization may vary depending on the relationship between substrate quality and conditions affecting microbial populations. The duration of changes following harvests may be chiefly affected by rates of revegetation (Lockaby et al., 1996).

The utilization of single-tree selection harvests **in Brazil generated gap disturbances sufficient to stimulate diameter growth** for approximately 4 years following harvests (Silva et al., 1995). The increased growth was primarily light driven and its longevity differed among species with some exhibiting responses 8 years afterward. As noted by Silva et al. (1995), in spite of a relatively heavy harvest, the growth response was not particularly long lasting. The latter observation suggests that the creation of larger gaps might prove beneficial in that regard.

In general, nutrient availabilities during secondary succession following natural disturbances in tropical systems rapidly increase followed by declines (Vitousek et al., 1989) with the declines controlled by the rate of revegetation (Snedaker, 1980). The duration of such shifts in nutrient availability have been generally short-lived in the tropics (i.e. 3-6 months) whether the disturbance is small- (Vitousek and Denslow, 1986) or large-scale (Steudler et al.. 1991). Similarly, experimental installations of 0.05- to 0.25-ha clearcuts at La Selva have confirmed the trend of rapid, brief increases in nutrient availability (Parker. 1994). In the latter instance. predisturbance nutrient levels were re-attained within 2 years.

It is unclear whether changes in availability reect net changes in quantities and if so. whether they re a critical factor in controlling revegetation paterns (Harcombe, 1980). Alternatively, Jordan and Herrera (1981) have argued that disturbance of tropial forests on low fertility sites such as occur in much of the Amazon River Basin will cause large utrient losses and, subsequently, major decreases in roductivity. Similarly, the degree to which harvestng traffic and subsequent changes in soil physical roperties may affect patterns of nutrient availabily/export after disturbance is uncertain.

Our objective in the current study was to compare urrent soil properties among four disturbance classes n plots which had been selectively harvested in 979. We hypothesized that disturbances associated with single-tree selection harvests using planned acess would stimulate only short-tenn shifts in macronutrient availability and that those would be ndetectable after 16 years. Similarly, we expected hat increases in bulk density and net changes in uantities of soil C. N, P, K, Ca. and Mg would not be detectable after the same time period.

. Study area

The investigation took place on the Tapajós Naional Forest which is located in the state of Pará and near the city of Santarém in the Amazon River Basin. The geographic coordinates of the Tapajós are °40′S to 4°10′S and 54°45′W to 55°00′W. The Tapajós is bordered on the west by the Tapajós river, o the east by the Santarém–Cuiabá highway beween km 50 to 205, to the south by the Santa Cruz nd Cupari rivers. while diminishing to a point on he northern boundary. Soils on the Tapajós may bc ategorized in the orthox suborder in the United States system or Ferralsol in the FAO/UNESCO ystem (SUDAM, 1989) with a solum depth frequently beyond 2 m. Texture is clayey (i.e. approximately 80%) although these soils are usually well drained. permeable, and highly resistant to erosion. Originating from Tertiary sediments of variable texure. the base saturation is usually low. The A horizon is typically weak while the B may average above 50 cm depth (Hernandez et al.. 1993). The geomorphology of the forest can be described as a wide plateau (120– 170 m altitude) on the eastern side of the forest that is gradually dissected into increasingly deeper ravines and steep valleys until reaching the flood plain of the Tapajós river on the west. The study site is located on the eastern side of the forest on flat topography undissected by water channels.

The vegetation is primary high forest and dominant over- and understory species are listed in Silva et al. (1995). A short. dry season exists during August-October when rainfall is less than 60 mm month $^{-1}$ and accounts for about 4% of the annual total of 2100 mm. Monthly rainfall is maximized in March, April. and May with averages above 300 mm month $^{-1}$, corresponding to 48% of annual rainfall (Hernandez et al.. 1993). Average monthly temperatures vary from 24.3 to 25.8°C (Silva et al.. 1995).

3. Methods

3.1. Treatment establishment

In 1979, a single replication of three treatment plots were designated and subjected to the following treatments: control (24 ha). single-tree selection harvest of all commercial timber > 55 cm DBH (25 ha), and selection harvest of all commercial species > **45** cm DBH (39 ha). Harvests were preceded by an inventory and mapping of all commercial species. Layout of primary skid trails was oriented at regular intervals in an east-west direction and that of secondary trails according to locations of individual trees. No soil data were collected prior to or immediately following the 1979 harvests. According to Silva et al. (1995), the logging intensity was heavy relative to that usually observed in Amazonian selection harvests. An average of 16 trees ha $^{-1}$ from 63 species were removed which translates to a volume extraction of 75 m^3 ha^{-1}.

3.2. Field sampling

All field sampling for the current study took place during January, 1995. On harvest plots, three categories of disturbance were designated for sampling and included (a) minimally disturbed (i.e. any area on a harvest plot not falling within a skid trail). (b) between ruts on skid trails. and (c) within ruts on

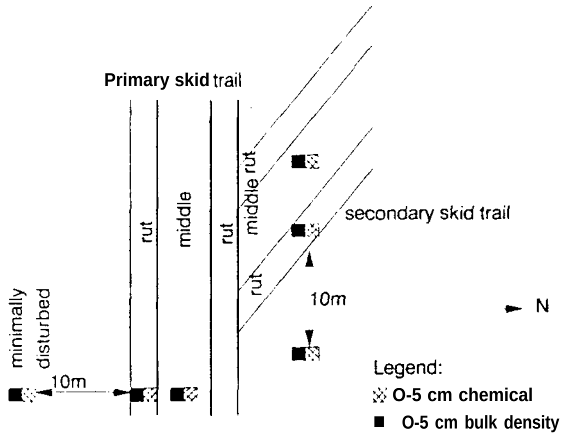

Fig. 1. Schematic of soil sampling subplots located on km 67 harvest plots in the Tapajós National Forest in Brazil.

skid trails. Soil properties on these areas are also contrasted with those of (d) control plots. The two harvesting treatments differ only in terms of the areal extent of each disturbance class rather than the nature of impacts.

On each harvest plot, two primary skid trails were located and 10-m radius subplots were delineated at 50-m intervals (Fig. 1). Two soil samples for chemical and physical analysis, respectively, were randomly collected from disturbance classes a-c within each subplot. An additional subplot was delineated (25 m from the primary trail) on all secondary skid trails as the latter were encountered and was sampled in the same fashion. Totals of 78 and 81 pairs of samples were collected from the 55-cm and 45-cm plots, respectively. Depth of sampling was 7.6 cm in all cases and was chosen because of the well-documented linkage between the shallow fine root mar and nutrient circulation in Amazonian. terra firme forests (Stark and Jordan. 1978). The volume of the bulk density core sampler was 98 cm’.

On the adjacent control plot, two transacts were designated and were sampled at 50-m intervals. At each sampling point, two soil samples were collected and used for chemical and physical analysis. respectively. Twenty-two pairs of samples were collected from the control plot.

3.3. Analysis

Soil samples were taken to the EMBRAPA Laboratory in Belém where analyses for bulk density, pH, total N, total organic C, extractable P, K, Ca, and Mg were performed. Bulk density cores were dried at 105°C for 48 h and weighed. A 1:2.5 soil to water ratio was used for pH and total N was estimated using kjeldahl analysis. Total organic C was performed using the Walkley-Black procedure. Extractable P and exchangeable K were determined calorimetrically and with atomic absorption, respectively, on a Mehlich I extraction solution. Exchangeable Ca and Mg were determined on a KCl extract using atomic absorption.

Since the study was non-replicated, f-tests were used to assess all possible paired comparisons of response variables from disturbance classes a-d. This approach combines data from both 45- and 55-cm plots to create a single data set for each of disturbance classes a-c. As stated, these were compared with the single data set for class d. Statistical significance is discussed as $P < 10\%$.

Table 1

Bulk density (BD) (mg m^{-2}), pH, and concentrations (mg kg^{-1}) of N. P. K. Ca, Mg. and C by disturbance classes on harvested sites in the Brazilian Amazon. Standard errors in parentheses

Class	BD	pH	N	P	K	Ca	Mg	C
Control	0.90	4.0	2600	4.86	43.59	4.21	2.63	35200
	(0.02)	(0.05)	(124)	(0.34)	(2.51)	(0.42)	(0.40)	(1494)
Minimally disturbed	0.94	4.0	2500	4.80	40.83	7.37	4.25	34300
	(0.02)	(0.03)	(97)	(0.17)	(1.51)	(0.86)	(0.31)	(985)
Skid trails middle	1.00	4.2	2400	4.10	38.73	9.46	5.12	32600
	(0.02)	(0.04)	(77)	(0.23)	(1.73)	(1.34)	(0.48)	(1079)
Skid trails ruts	1.06	4.2	2300	4.02	3x.74	9.08	5.00	31800
	(0.01)	(0.04)	(83)	(0.21)	(1.45)	(1.01)	(0.33)	(1066)

4. Results

Ruts in skid trails were still visible after 16 years and the depths and widths of ruts averaged 16 and 97 cm. respectively. In general, skid trails were occupied by *Cecropia* sp., a common pioneer during secondary succession in tropical rainforests (Alvarez-Buylla and Garcia-Barrios, 1991). According to J. Francis (unpublished reports, 1996), the three species of *Cecropia* which occur on the Tapajós include *C. bicolor* Klotzsch, *palmata* Willd., and *sciadolphylla* Mart. There were no significant differences between primary and secondary skid trail data for any response variable and, consequently, those data were pooled by disturbance class.

Comparisons of concentration data for N, P, K, Ca. Mg among classes indicated that levels of all elements remained affected to varying degrees by harvesting after 16 years (Tables 1 and 2). In general. concentrations of N, P, K, and C decreased with disturbance intensity while those of Ca and Mg increased. Bulk density and pH both increased directly with intensity. In addition, there were significant changes in bulk density, Ca, and Mg between the controls vs minimally disturbed areas, a potentially, very important finding in relation to the high proportion of area associated with the latter disturbance class.

Nitrogen, P, and pH effects were most strongly pronounced when skid trail versus non-skid trail samples were compared. There was no difference for N, P, or pH when controls were compared with minimally disturbed areas. Calcium and Mg exhibited tandem behavior and, as mentioned, were altered even in minimally disturbed areas. Carbon concentrations were different only when the most divergent classes were compared. Bulk density data indicated that soils remained compacted in all classes after 16 years. Potassium was the least responsive of any element to disturbance after this time period. Although C/N ratios generally widened as disturbance increased, (i.e. 13.3 to 13.9) differences among classes were not significant.

Comparisons of net changes in elemental content to a depth of 7.6 cm indicated fewer statistically significant shifts than did the concentration data (Tables 3 and 4). There were no significant shifts for N, K, or C. However, significant increases in content of both Ca and Mg were evident as disturbance increased except in the within vs between-rut comparisons.

In 1995. the visible extent of areal disturbance associated with each disturbance class was similar on the 45- and S-cm plots and averaged as follows: primary skid trails, 1%; secondary skid trails, 0.1%; and minimally disturbed areas, 99%. However, the extent of areal disturbance at the time of harvest in

Table 3
Content (g m^{-2} to 5 cm depth) of N. P, K, Ca. Mg, and C by disturbance classes on harvested sires in the Brazilian Amazon. Standard errors in parentheses

Class	N	P	K	Ca	Mg	C
Control	178.6	0.33	2.96	0.29	0.18	2393
	(3.97)	(0.02)	(0.18)	(0.03)	(0.03)	(107)
Minimally disturbed	178.8	0.35	2.91	0.54	0.30	2432
	(3.98)	(0.01)	(0. 11)	(0.06)	(0.02)	(67)
Skid trails middle	178.8	0.31	2.91	0.73	0.40	2446
	(3.58)	(0.02)	(0.11)	(0.10)	(0.04)	(72)
Skid trails ruts	183.4	0.32	3.07	0.75	0.41	2524
	(1.73)	(0.02)	(0.11)	(0.10)	(0.03)	(74)

Table 2
Probability levels associated with paired-comparisons of Table 1 data among disturbance classes on harvested sites in the Brazilian Amazon

Comparison	BD	pH	N	P	K	Ca	Mg	C
Control–rut	0.00	0.03	0.00	0.04	0.08	0.00	0.00	0.06
Control-min. disr.	0.10	0.94	0.31	0.84	0.34	0.00	0.00	0.61
Control-middle	0.00	0.00	0.02	0.07	0.13	0.00	0.00	0.18
Min dist.–rut	0.00	0.00	0.01	0.01	0.32	0.22	0.10	0.09
Min. disc.-middle	0.01	0.00	0.10	0.02	0.36	0.19	0.13	0.25
Middle–rut	0.01	0.32	0.40	0.81	0.99	0.82	0.84	0.61

Table 4
Probability levels associated with paired-comparisons of Table 3 data among disturbance classes on harvested sites in the Brazilian Amazon

Comparison	N	P	K	Ca	Mg	C
Control-rut	0.56	0.75	0.60	0.00	0.00	0.32
Control-min. dist.	0.98	0.49	0.79	0.00	0.00	0.76
Control-middle	0.98	0.44	0.81	0.00	0.00	0.68
Min. dist.-rut	0.46	0.20	0.30	0.06	0.01	0.35
Min. dist.–middle	1.00	0.06	0.98	0.10	0.04	0.89
Middle–rut	044	0.60	0.32	0.90	0.82	0.45

1979 was likely greater and differed between the 45- and 55-cm harvests.

5. **Discussion**

The degree to which soil chemical and physical properties remained altered as a result of harvest disturbance 16 years earlier was unanticipated. The most sensitive soil chemical indicators of disturbance, whether from the standpoint of availability or content shifts, were Ca and Mg.

The tendency for Ca and Mg concentration and content to vary directly with disturbance intensity could be explained by increased weathering, increased mineralization, or decreased plant uptake as disturbance intensity increased. Increased weathering or mineralization might result from a stimulus such as altered microclimate (i.e. increased moisture and temperature). While those conditions may have existed briefly following the harvest, the high rates of revegetation that are characteristic of gap-phase regeneration in tropical rainforests (West et al., 1981) coupled with the short-duration of mineralization pulses in naturally formed gaps (Vitousek and Denslow, 1986; Steudler et al., 1991; Parker, 1994) argue against such an effect being detectable after 16 years.

However, longer term changes in Ca and Mg mineralization rates might be possible if the litter quality associated with the replacement vegetation, *Cecropiu* sp., was conducive to different Ca/Mg dynamics. While no data exist in the present study with regard to base cation levels in *Cecropia* sp. foliage, there is anecdotal evidence that some species of *Cecropia* in the Amazon are associated with base accumulation in the foliage. Apparently, foliage of *Cecropia* sp. is sometimes chewed in conjunction with cocoa leaves to accentuate the 'effect' of the latter. According to Dr. James Duke (personal communication, 1996), the synergism between *Cecropia* foliage ash (known in some localities as 'cal') and cocoa leaves is due to the high Ca content of the former.

In addition, in comparisons of foliar concentrations of macroelements among 4.5 native tree species in the Amazon, *Cecrovia palmata* ranked second highest for N, first for P, second for K. and fourth and third for Ca and Mg, respectively (Natalino Silva. personal communication, 1996). Consequently, we suggest that increased uptake of Ca and Mg coupled with high amounts of both elements in *Cecropia* sp. litterfall offer the best explanation for the trends observed (i.e. the second explanation).

Therefore, it is possible that some species of *Cecropiu* tend to function as calcium 'pumps' in much the same manner as flowering dogwood (*Cornus florida*) in the eastern United States (Kramer and Kozlowski, 1979). If *Cecropiu* sp. foliage does accumulate Ca and Mg to a greater extent than is usually observed in Amazonian species. rapid mineralization of base cations from abscised *Cecropiu* foliage could account for elevated levels in surface soils within disturbed areas.

Similarly, the tendency for N, P, and K to vary inversely with disturbance intensity suggests decreased inputs of organic N, decreased mineralization of P and K, or increased uptake for those elements. The inverse relationship observed for organic C suggests that decreases in organic N are a possibility. One explanation for a decrease in organic N and C could be restricted rooting due to increasing bulk densities as disturbance increases. Residual soil compaction might also contribute to reduced mineralization of P and K through reduced aeration and water holding capacity.

Alternatively, since N, P, and K tend to be associated to varying degrees with internal translocation prior to foliar senescence. quantities returned in *Cecropia* litterfall may be small relative to those of Ca and Mg. However, this explanation alone would not explain an inverse relationship between N. P. and K and disturbance intensity because C. *palmata* appears to be particularly demanding for all macronutrients.

Given these arguments, we suggest that the changes which remain apparent after 16 years are driven by a combination of normal successional as well as impacted soil factors. *Cecropia* sp. may exhibit a markedly different demand for bases compared with the primary species and, consequently, greater quantities of Ca and Mg are returned to surface soils (via decomposition of foliage). A vegetation-driven effect on base cation availability and content would not be unexpected since levels of these elements tend to be more heavily Influenced by tropical forest demands compared with those of N and P (Sanchez, 1992).

Based on the evidence that organic N and C concentrations are reduced in the heavy disturbance classes. we believe that the conversion of above- and/or belowground detritus to soil organic matter (SOM) has been altered in the heavy disturbance classes. This could result from restricted root growth in the upper 7.6 cm of mineral soil due to residual compaction, different root architecture associated with *Cecropia* sp. (i.e. greater tendency for roots to occur in the 0 horizon), or differential quality (i.e. slower decomposition) of *Cecropia* sp. detritus. It is possible that P and K trends are associated with the same SOM linkage.

6. Conclusion

It should not be surprising that long-term effects of harvesting in systems with very strong biogeochemical linkages between vegetation and soil are heavily influenced by the ecophysiology of pioneer vegetation species. However, an interaction between residual soil compaction and vegetation cannot be eliminated as a possible explanation for some of the results presented here. It is apparent that, although soil C was assessed only to a very shallow depth, no evidence of net soil C source or sink behavior existed after 16 years.

Given the tendency for *Cecropia* sp. to colonize natural gaps, it is likely that single-tree selection harvests in the Tapajós mimic processes ongoing in gap-phase regeneration to some degree. This may reflect a major difference between selection harvests vs tropical clearcuts since early successional patterns may be disrupted in the clearcuts (Alvarez-Buylla and Garcia-Barrios, 1991). The combination of small canopy openings and soil disturbance associated with selection harvests may resemble conditions created by an upturned tree, a scenario that is conducive to the establishment of pioneer vegetation such as *Cecropia* sp. (Putz, 1983).

However, a better understanding is needed of the degree to which the soil conditions described here are similar to those associated with gap-phase regeneration. If soil processes differ between the two modes of gap creation, the distinction could be important to the sustained management of these ecosystems since even the minimally disturbed areas (i.e. 99% of the harvested area) continue to show evidence of compaction and biogeochemical differences.

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