Natural Forest Disturbance and Change in the Brazilian Amazon

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ABSTRACT

Landsat Thematic Mapper images covering the entire 3.9 million km$^2$ of forested Brazilian Amazon reveal natural change and disturbance occurring on a scale of decades to centuries. These include: 92,000 km$^2$ of bamboo forests undergoing synchronous mortality and regrowth; 1500 km$^2$ of recently active dune fields; 900 km$^2$ of recent downburst blowdowns; $> 500$ km$^2$ of recent forest fire scars; and an unknown area of forest mortality from flooding of high ground and alluvial forests. Fire subclimax fern savannas created by Yanoama Indians cover an additional 600 km$^2$. Natural and indigenous disturbances and synchronized phenologies are therefore responsible for a dynamic spectral behavior in large portions of the Amazon Basin. Disturbances and disturbance indicators not easily detected include blowdown sites $> 30$ yrs old, blowdowns $< 30$ hectares in size, liana forests and babassu palm forests.

INTRODUCTION

Much attention has been focussed recently on human-induced changes in the vegetation cover of the Amazon and their consequences. The latter include contribution of greenhouse gases (Fearnside, 1990; Houghton, 1991); nutrient leaching (Jordan, 1985); soil compaction and erosion (Nepstad et al., 1991); and increased frequency and penetration of fires into forests near pastures (Uhl and Buschbacher, 1988). Modelled and postulated effects of deforestation on climate and the hydrologic cycle include increased surface and soil temperatures (Shukla, Nobre and Sellers, 1990); increased rainy season and decreased dry season runoffs resulting in decreased soil moisture (Salati and Nobre, 1991); and possibly longer dry seasons due to reduced water vapor recycling (Salati and Nobre, 1991; Gash and Shuttleworth, 1991).

Since 50-60% of rainfall in the Amazon Basin is derived from water vapor recycled to the atmosphere by forests (Salati and Nobre, 1991), intact forests may suffer a reduction in rainfall after large scale conversion of neighboring or distant upwind forests to pasture. Remote sensing can play a key role in verifying such
postulated changes by revealing signs of water stress in the intact forests: degree of deciduousness, synchronous seasonal leaf drop and releafing, forests killed by fires and post-fire secondary forests. Natural disturbances (e.g. fires, blowdowns, vine forests) and synchronized phenology (leaf drop, releafing, or monocarpic bamboo life cycles) cause spectral variability, making it difficult to detect and monitor a possible signal of human-induced changes in the spectral properties of intact Amazon forests. Natural and indigenous disturbance mechanisms may also help explain the spatial distribution of plant species, of vegetation types and of floristic diversity patterns in the Amazon Basin (Whitmore and Prance, 1987; Posey and Balée, 1989).

MATERIALS AND METHODS

Brazil’s National Institute for Space Research (INPE) measures deforestation on an annual basis using geometrically corrected false color photographic prints at a scale of 1:250,000, derived from Landsat Thematic Mapper (TM) bands 3, 4, and 5. These cover the entire five million km$^2$ of the Brazilian Amazon, of which 3.9 million km$^2$ were originally forested and 426,000 km$^2$ deforested by 1991 (INPE, 1992; Alves et al., 1992). Designed for accurate assessment of human impacts, this complete coverage of the Brazilian Amazon also constitutes a unique resource for study of natural vegetation at high spatial resolution on a broad scale. These images were examined for evidence of recent natural changes in the forest (last $10^1$ to $10^2$ yrs). Relict floodplains, ghost drainage patterns and other extensive geomorphological indicators of change can also be detected in Landsat images, but these features of greater age ($10^3$ to $10^5$ yrs) are not considered here.

Naturally changing forests are recognized in the TM images as areas with spectral signatures suggestive of leafless trees (mortality, leaf drop) or of secondary forests (recovery after mortality caused by fire, blowdowns or monocarpic bamboo life cycle). In the case of blowdowns and bamboo mortality, change is also directly evident in a time series of images in the INPE files. Recent aeolian activity is deduced from the presence of well-defined dune features and thin vegetation cover.

Over the period 1989–1993, ground truthing was undertaken at five blowdown sites (near Manaus and the Urucu River), at the site of former forest fires (Morro dos Seis Lagos and along the Curuaú do Sul River), at the site of “terra firme” flooding mortality (near Manaus), at parabolic dune fields (along the Aracá and Catrimani Rivers) and at two periodically burned table mountains (Surucucu and Aracá). Floodplains with seasonal synchronous leaf drop (lower Purus and Cuieiras Rivers) were checked in overflight. Verification of bamboo forest and bamboo mortality is based on prior reports (John, 1989; Cardoso da Silva et al., 1990) and field visits by colleagues in the state of Acre and in Peru (V. F. G. Pereira, pers. comm. 1992; H. Tuomisto, pers. comm., 1993; R. Foster, pers. comm. 1993). Additional verification of vegetation types is derived from the author’s botanical field trips across the Brazilian Amazon since 1977.
After field verification, the natural change features were quantified across the entire forested Brazilian Amazon using the images on file at INPE. Areal extent of blowdowns was measured on the original 1:250,000 scale prints by summing, for each Landsat scene, length \( \times \) width-at-midpoint of all fan-shaped blowdown features with longest axis > 1.25 km. Areas of bamboo forests, fire scars and recently active dune fields were calculated by copying the relevant TM scenes to 35 mm slides then projecting onto a cartographic base at 1:1,000,000 or 1:2,500,000. For closer examination and digital enhancements—linear contrast stretch, NDVI (Tucker, 1979), and end-member mixing model (Adams et al., 1990)—the following TM scenes were examined using WISP image processing software at the University of Washington Geological Remote Sensing Lab.: WRS 001/058, 001/062, 001/063, 227/062, 230/062 and 231/062.

RESULTS AND DISCUSSION

Six types of natural change were detected: fires, large blowdowns, synchronous mortality of bamboo forests, synchronous leaf drop in flooded forests, mortality from anomalous flooding of terra firme forests, and recently active parabolic dune fields. Landslides are also important on steep forested slopes in western Roraima but have not yet been examined. Floodplain forest mortality associated with rapid tectonic subsidence and/or sedimentation has been documented in the Peruvian Amazon by other workers (Kalliola et al., 1991; Dumont and Garcia, 1991). Each of the natural change types is described and discussed below (see Figure 1 for sites).

Fires

High water content of dense forest biomass will usually stop the penetration of fires but, in the dry season of the 1983 El Niño, fires spread into dense primary forest on clay soil plateaus, causing crown death totaling > 500 km\(^2\). These fires occurred in the area delimited by 54–57º W longitude and 2–3º S latitude, which is within a dry belt where average annual rainfall is 1500–2000 mm/yr (Figueroa and Nobre, 1990). The largest plateau fire was east of Juruti Lake and covered 210 km\(^2\), while three separate plateau fires near the upper Curuá do Sul River totaled 240 km\(^2\) (Figure 2). Crown death and/or defoliation are visible in 1984 images as high TM band 5 and low TM band 4 reflectance. Areas with crown death can be distinguished from deleafed trees in TM images five years after the burn since the former are occupied by secondary forest. An area of about 1000 km\(^2\)—mainly drier forest on sandy soil slopes—was affected mostly by defoliation in 1983. By 1988 these crowns relaefed rather than being replaced by secondary forest. Understory fires in 1983 probably covered a much larger area than the total 1,500 km\(^2\) with visible canopy effects.

The large size and the rounded limits of the fire scars indicate that they penetrated beyond any mechanized logging activities in the area. Logging and nearby agricultural fires were nonetheless important for catalyzing the burns. Because of
FIGURE 2 Landsat Thematic Mapper band 4 image of the upper Curuá do Sul River. Three areas of high reflectance on plateaus are secondary forests occupying total of 240 km² after 1983 fires which penetrated dense forest. Note rounded limit of fire scars and increasing intensity of fires as they progressed westward. Image WRS 227/62 of August 3, 1988. White arrow is true north; white scale bar = 6 km.

the low stocking density of commercial tree species, skidders used in mechanized logging operations damage and kill many non-commercial species which then dry out under the highly broken canopy. These disturbed forests with dry combustible material are susceptible to fire penetration (Uhl and Buschbacher, 1988). After the more normal dry season of 1987 this kind of fire—with very irregular limits defined by the penetration of selective logging activity—was detected east of the lower Curuá River in a Landsat TM image.

Large rounded fire scars covering hundreds of km² are also found in primary forest near cattle ranches in Maranhão in the lower left of TM scene 222/061. These were occupied by secondary forest mixed with primary forest survivors in 1988. They probably therefore also occurred in 1983.
Because the 1983 fires spread into primary forest it is certainly conceivable that, in even more extreme dry seasons, large forest fires could occur in dense forest far from human activity, set by lightning. Pre-Columbian slash-and-burn may have increased the frequency of such fires. There are, in fact, historical accounts of very large fires in native forests of the Negro River basin (Sternberg, 1987) in 1912 and 1926, two years with extremely low river gauge records at Manaus, probably attributable to extreme El Niño phenomena (Richey et al., 1989). Low rainfall and periodic fires may play synergistic roles in reducing local plant diversity. In the Curuá plateau forest just six common species comprise more than half of the woody plants > 5 cm diameter (S = 188, N = 4956; Barros, 1986). Large patches of recent secondary forest suggestive of fires have not, however, yet been detected in Landsat images of terra firme forests on clay soils outside of the dryer parts of Amazonia, that is, where annual rainfall exceeds 2,000 mm/yr.

Circular anomalies of the upper Xingu
Circular “phyto-physionomic anomalies” of 2–13 km diameter occur in the upper Xingu River basin. They were first described from aerial photos by Braun (1969) and later studied and mapped using Landsat images, color-IR aerial photos and a short ground check by Trindade (1988). Within some of the larger circular features concentric bands of forest alternate with a defoliated or dead vegetation; in others the intervening bands appear to have a spectral signature and canopy structure similar to secondary forest. The anomalies occur in transition forest near the limit with “cerrado” vegetation (scrub savanna). Counting just the 55 features with major axis > 2.5 km, the anomalies cover 1,068 km² within the rectangle 51°–54°W, 11°–13°30′S.

The cause of the anomalies has never been established. Three different explanations have been offered by Braun, Trindade and INPE researchers: insect damage, flooding of interfluve depressions, or fires. None of these adequately explain the distinct banding, though in some anomalies the bands appear to follow contour intervals, which would support the flooding hypothesis. Comparison of Landsat MSS and TM scenes from 1975 to 1992, on file at INPE, shows the concentric bands of a large 1992 anomaly cutting across the orientation of bands in a previously present anomaly. This is inconsistent with flooding, more suggestive of fire. Similar banding is found in the 210 km² post-burn secondary forest near Juruti Lake in the state of Amazonas. Another argument in favor of fire is the fact that the large anomalies are concentrated along the natural limit between forest and cerrado. Of the 55 large anomalies mentioned above, 31, with 79% of total area, occur less than 40 km from the forest/cerrado boundary.

Liana forest: A fire sub-climax?
A possible indication of extensive natural burns prior to 1983 may be the liana forest common between Santarém and Marabá in the state of Pará (2°–6°S, 49°–56°W), covering about 100,000 km² (Pires, 1973). Liana forest is a mixture of abundant heavy lianas and tall widely spaced trees (Figure 3) with a tangled
undergrowth which includes some sun-loving pioneer species. Liana forests occur in large areas of hundreds of hectares or isolated patches of just a few hectares (Heinsdijk, 1957).

The origin of these areas has puzzled botanists and foresters for some time. Heinsdijk (1957) speculated that the smaller gaps are caused by winds and that the more extensive areas are possibly related to soil type. Pires (1973) later rejected the soil hypothesis. Veloso et al. (1974) attributed the broken forest canopy to weight of the lianas themselves, increasing the number and frequency of tree-fall gaps, which in turn favor growth of more lianas. Liana forests would in this case be another example of natural disturbance. More recently, Balée and Campbell (1990) showed that two liana forest plots along the Xingu River include a few tree species resistant to fires as well as many post-disturbance late successional species. They suggested that this vegetation type could be a result of disturbance by indigenous swidden fires.

Field checking of the Curuá do Sul burn sites nine years after the 1983 El Niño fire showed that woody lianas themselves comprise a major component of the post-burn secondary forest. Large patches of older, "natural" liana forest were observed in over-flight away from the burn limits. These patches have a spectral signature similar to very old secondary forest (> 25 yrs age) on a 1988 Landsat TM 3, 4, 5 false color composite. The Curuá liana forests may therefore be sites of fires associated with earlier El Niño events. Both the liana forests and the burn sites have scattered tall trees with crown architecture indicating that they recently grew close together, so the hypothesis can be tested by comparing species composition of the burn survivors with that of tall trees in liana forest. According to local loggers, commercial species with thick bark, such as Bertholletia excelsa and Hymenaea courbaril, were preferential survivors of the 1983 fires.

**Fire sub-climax fern savanna**

Fern savanna covering 600 km² in the Serra Parima, on the Brazil/Venezuela border (2°20'-2°55'N, 63°55'-64°15'W), is the result of burning by Yanoama Indians over many decades or centuries. This has transformed primary montane forest into a fire sub-climax dominated by the braken fern, Pteridium aquilinum.
var. *arachnoideum* (Huber et al. 1984). Susceptibility to fire is related to the very shallow soil which forms on the Surucucu Granite. A rain shadow effect may also be important since the savannas are concentrated on the western flank of the Serra Parima. Rainfall on the Venezuelan flank of the Serra Parima is typical of transition forest areas: 1750 mm/yr with 3–4 months < 100 mm/month. The most extensive patch of savanna is traversed by Yanomama trails. Standing dead witness trees and freshly burned areas observed in overflight are proof that the savannas have expanded into forest. Discontinuous savanna on adjacent hilly terrain suggests that the forest can recover ground if fires are not set continuously. Motives for the burning were not determined. Possibly the fires are used to flush game, but recreational pyromania should not be discounted (Shoumatoff, 1986).

Fern savanna has also developed as a result of indigenous burning east of Serra Parima at the Surucucu table mountain (2°50'N, 63°40'W) on shallow soil of fine quartz sand. The western half of the plateau near the air strip and FUNAI post is most heavily affected by these fires, which were observed being set deliberately for no apparent management purpose. The eastern half is partially protected by natural fire barriers (streams) while a small, uninhabited outlying segment of the table mountain to the northwest serves as a control. That site is covered with a *Clusia*-dominated forest. The fern savanna, partially burned table mountain and *Clusia* forest are all easily distinguished in TM 3, 4, 5 composites.

**Small fires on other shallow soil sites**

Fires occur on other substrates with very shallow soils in the forested portion of the Brazilian Amazon. Pilot G. F. Almeida of Santarém has reported burned hilltops in the Brazilian shield south of Itaituba, probably set by lightning. The uninhabited Aracá table mountain (1°00'N, 63°20'W) has fire-resistant bromeliads which record at least one recent fire event in their thick, insulating, reflexed, dead leaf bases. This table mountain of quartzite with extensive pegmatitic intrusions has very shallow sandy and rocky soil. A small circular canga hill of about 300 meters altitude and five km diameter known as Morro dos Seis Lagos is located at 0°30'N, 66°50'W in the high rainfall zone near São Gabriel da Cachoeira. Most of the surface has no soil but is nonetheless covered with a forest with thick root mat. Forest species composition is similar to the Amazon white-sand forest of the surrounding plains. A recent fire restricted to the north end burned about 15% of the hill. The burned area is now dominated by *Vismia* sp. and can be detected in the visible wavelengths due to the reddish leaves of this species. According to a CPRM geologist, the fire was caused by a rock boring crew working on the hill in the very dry summer of 1983.

**Dune Fields**

Fossilized parabolic dunes can be detected in Landsat images of the extensive waterlogged sands on both sides of the lower Branco River, extending from the Anauá River west to the Aracá River and north shore of the Negro (1°30'N–1°00'S, 60°30'–64°00'W). The dune fields are traversed by modern drainage,
so are thousands of years old. J. O. S. Santos of the Brazilian mineral exploration company CPRM has observed that modern trade winds at this latitude are constant and strong enough to create wind ripple marks on the few bare surfaces now exposed. The dunes could therefore remobilize if present vegetation cover were removed and local water table lowered. This could occur in a severe drought year with fire. Reactivation has occurred at different times in the isolated patches rather than across the entire dune province. The most recently active dune fields—which with sharply defined parabolic dune fronts and thin vegetation cover—are roughly circular in shape, another indication that localized fire is the reactivation agent. High in TM band 5 reflectance (dry savanna and/or bare sandy soil), these recently active fields measure 15–30 km diameter and occur near the Catrimani River at 1º10'N, 62º00'W and south of the Aracá table mountain at 0º30'N, 63º15'W.

The Catrimani dune field was examined in stereo vertical photographs and in TM band 5 photographic products of INPE (1:100,000). The site was also observed in overflight and visited on foot with J.O.S. Santos of CPRM. Judging from the degree of erosion of the limbs of these parabolic dunes and the dense woody "campina" vegetation covering the apical portions, the dunes have been stable for several decades, if not centuries. The interior acolian excavation channels immediately behind the parabolics' apices were occupied by marshes and small lakes during the 1992/93 dry season. The external sandy flats between parabolic dunes are seasonally flooding savannas with a few charred branches and sedge rhizomes, burned within the last few years. No sign of recent fire was found in campina vegetation along a traverse of the limbs and apices of two large dunes.

**Bamboo Forests**

Forests dominated by two tall bamboo species—*Guadua weberbaueri* Pilger and *Guadua sarcocarpa* Londoño and Peterson (X. Londoño, pers. comm., 1992)—cover 121,000 km² in 15 contiguous Landsat TM images between 7º–11ºS latitude and 66º–74ºW longitude (Figure 4). This includes most of central and eastern Acre state, as well as a small part of southwestern Amazonas state, southeastern Peru and northern Bolivia. Additional extensive bamboo forests occur south of 11ºS latitude in southeastern Peru outside the Landsat coverage examined. In the Brazilian portion of the 15 Landsat scenes bamboo forest covers 92,000 km², about equal to the estimates of Prance (1987, Figure 2.4) and the RADAMBRASIL Project (cited in Lopes, 1975).

This is one of the rare cases where canopy species of an Amazonian forest are recognizable in Landsat images. Two types of natural change are visible:

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1 Different names are found in the literature for the arborescent bamboos of Acre. Corrêa (1926–1978) refers to the giant bamboo of the upper Purus as *Guadua superba* Hub. In their report to the RADAM project (Brasil, 1976) bamboo specialists T. Soderstrom and C. Calderon cite two genera: *Guadua* and *Merostachys*. 
FIGURE 4 Distribution of bamboo-dominated forest within 15 Landsat TM scenes in the southwest Amazon.
1. The boundaries of bamboo-dominated forests are often circular or amoeboid in shape, suggesting that they have recently spread into and replaced the surrounding mixed-species terra firme forest. In some cases, especially in the Peruvian Amazon, the geometry suggests that bamboo forest has first penetrated up the drainage thalwegs of dissected terrain, then coalesced over the interfluvies.

2. Like many of the world’s bamboos, these oligarchic stands flower gregariously at long but regular intervals then die off completely (McClure, 1966). Massive, infrequent flowering and fruiting may be a strategy to keep populations of seed and seedling predators low most years, then easily satiated during reproductive years (Janzen, 1976). Die-back of the dense, rhizomatously expanded clumps guarantees sunlight for vigorous growth of the new cohort of young plants (Soderstrom et al., 1987). In a three year time series of the WRS 003/066 Landsat TM scene, about 70% of the scene underwent dieback, leaving brown, leafless expanses covering thousands of $\text{km}^2$ (Figure 5). In an image prior to dieback different bamboo densities (or the growth stages of different cohorts) can be recognized as large amoeboid or circular areas, each being spectrally homogeneous internally, but spectrally distinct from one another.

Pre-dieback bamboo forests have spectral signatures similar to those of secondary forests when 15–25 yrs old. Two reports from former rubber tappers (M. Queiroz and D. S. da Silva, pers. comm., 1993) date previous synchronous flowering, fruiting and mortality episodes at about 1930–1933 close to Sena Madureira and at 1959–1960 on the upper Jurupari River. B. A Krukoff collection No. 5235 from the upper Jupari River is a flowering specimen of *Guadua sarcocarpa* subsp. *sarcocarpa* collected in 1933 (Londoño and Peterson, 1991). These sites are on the eastern and western extremities, respectively, of the WRS 003/066 Landsat scene. Jacques Huber published a diagnostic description of a spiny giant bamboo which he found flowering in 1904 at Boca do Acre, 160 km ENE of Sena Madureira (Huber, 1906). This would suggest flowering (and mortality) at 26–29 year intervals (1904, 1933, 1959, 1987–1990), an interval corroborated by biologist Eduardo Martins (pers. comm., 1993), who witnessed the bamboo mortality near Sena Madureira in 1988, and was informed by numerous local residents of a previous episode about 30 years earlier.

No report of a flowering, fruiting and mortality episode prior to 1904 has yet been found. The dense spiny bamboo forest of the upper Purus River basin was first described by Chandless (1866). Figueiredo (1940), who spent four years in Acre and travelled overland between the rivers, also remarked on the dense stands of spiny bamboo which “take many years to flower [and] die soon after blooming” but he did not provide dates.

Mortality is locally synchronous but progresses as a slow wave across the range of bamboo forest. Thus, some mortality can be found in progress in Landsat TM images dating 1985–1991 across central and eastern Acre. The type specimen of *G. sarcocarpa* was found flowering in 1982, 650 km SW of Sena Madureira (Londoño and Peterson, 1991).

When a dry El Niño year coincides with a year of massive bamboo mortality, it is possible that extensive fires occur. This could explain the rounded limits of
large bamboo forest patches on the images. Widespread forest fires have been reported to occur after synchronous bamboo dieback in India and to favor the bamboo regrowth (Gadgil and Prasad, 1984).

**Synchronous Leaf Drop in Floodplain Forests**

Comparison of August and January images of muddy water ("varzea") floodplain forests of the lower Purus River shows an apparent seasonal difference in the near-infrared (NIR) reflectance, indicating the forest is more deciduous in January. To date, seasonal comparisons have been made using only 1:250,000 scale uncalibrated photographic products from INPE. The January image was examined digitally and encoded radiance (DN) values compared for the tall varzea forest and tall terra firme forests. TM band 5 is about six DN values higher in the tall floodplain forest. In dry season images of other TM scenes these two vegetation types are indistinguishable. It is therefore reasonable to infer accentuated leaf drop in January.

**Flood Mortality**

Mortality from anomalous flooding of terra firme forest has been documented in a study plot 90 km north of Manaus by Mori and Becker (1991). The first five months of 1989 were the wettest on record. Within a 100 ha plot, standing water accumulated in seven small depressions totalling 2.5 ha and caused tree mortality by the following dry season. At the height of the dry season (September, 1989) three of the seven mortality sites were visible in a TM image as groups of more than three contiguous pixels with high band 5 and low band 4 reflectance. These pixels total 2.0 ha. Small depressions with dead trees were restricted to a swath extending 100 km east/west at about 90 km north of Manaus. No mortality occurred closer to the city, for example, at the Ducke Forest Reserve. Only the two TM images near Manaus (WRS 230/062 and 231/062) have been examined with digital medium for the 1989 dry season. Because of the small size of the patches the mortality is not detectable in the standard 1:250,000 scale TM 3, 4, 5 false color prints on file at INPE. If the 2-2.5% flooding mortality were generalized across the entire forested Brazilian Amazon it would be a very large area (78,000-97,500 discontinuous km²).

Kalliola et al. (1991) reported patches of hundreds of km² with dying or dead trees in the flood basins of the Pastaza-Marahuon and Ucayali in the Peruvian Amazon, attributable to very rapid tectonic subsidence (Dumont and Garcia, 1991) with consequent increase in water depth and siltation. Kalliola et al. (in press) also report that 12% of the Peruvian Amazon lowlands are occupied by modern floodplain, a highly disturbed successional habitat completely turned over by erosion and deposition every 330 yrs. This extrapolation was based on a four year time window.
FIGURE 6 Landsat TM band 5 image of 2,700 hectare downburst fan about nine months after wind event, located at 2°11'S, 64°45'W, 100 km north of Tefé. Note radial destruction at north end of fan, inferred site of first impact by descending ring vortex. White arrow is true north. Paired white and black spots are clouds and their shadows. Image WRS 001/062 of June 28, 1986.

Large Blowdowns

Examination of 136 Landsat TM scenes dominated by primary forest revealed 330 features larger than 30 hectares with geometries and spectral signatures suggestive of downburst type destructive winds (Fujita, 1985). Downburst blowdowns are fan shaped, being caused by a downward and forward moving convective air column which may develop a ring vortex, much like a smoke ring. After contact with the ground the ring vortex breaks up into pieces. These rotor microbursts leave narrow linear swaths of destruction which can extend several kilometers from the distal end of the downburst fan (Figure 6).

Four blowdowns were verified by checking on foot. One of these, near Manaus, was discovered in a time series of TM images examined by J. Adams and S. Willis of the University of Washington. A fifth blowdown, near the Tefé River, was shown by Petrobrás geologists Braun and Siegl (1990) to also appear suddenly
in a time series of TM images. That site was overflown by helicopter in 1990 when it was a sea of early successional tree species covering 840 hectares. In a time series of false color composites of TM bands 3, 4 and 5, recent blowdowns are recognized as fan shaped areas with high DN values for TM bands 3 and 5 (fallen or standing leafless trees) and low TM band 4 values. Within two years secondary successional growth covers the dead fallen trees so that TM band 4 (and NDVI) become much higher than in the surrounding primary forest. TM bands 4 and 5 remain anomalously high for years but gradually drop to the level of the surrounding forest. Blowdowns become indistinguishable after about 25–30 years. This varies greatly depending on the number of scattered primary forest survivors contributing to canopy roughness, i.e. pixel shade content, within the blowdown.

Most of the Landsat scenes east of Manaus are free of large blowdowns. They are concentrated in a north/south zone between southern Venezuela and northern Rondônia, with the largest and most numerous between 63°–67° W and 0°–6° S (Figure 7). The largest single blowdown is in this zone and occupies 2,700 continuous hectares (Figure 6). If the large blowdowns (> 30 ha) occupied by secondary forest are distinguishable from primary forest for 27 years (based on the spectral evolution of an 80 ha blowdown of known age near Manaus) turnover of the entire forest occurs after 9,000 years, this in the Landsat scene where they are largest and most numerous. On this time scale natural climate change, neotectonic tilting and subsidence, and sea level effects on Amazon floodplain height are probably important disturbance mechanisms (Schubert, 1988; Absy et al., 1989; Kronberg et al., 1991; Dumont and Garcia, 1991; Räsänen, 1991; Klammer, 1984). One cannot, however, discount the possibility that more intense wind disturbance—at intervals longer than the TM observation window—might be an ecologically important phenomenon, as has been postulated for some Far Eastern forests (T. C. Whitmore, pers. comm., 1992). Areas routinely affected by wind disturbance within every 100–200 years should have a higher number of species requiring gaps for maturation than areas with lower probability of such disturbances.

Importance of downbursts in the Brazilian Amazon

If one considers just eight years of TM observations (1984–1991) to be representative, downburst blowdowns, together with much rarer tornado blowdowns, are of minor ecological importance even in that part of the Amazon Basin where they are most severe and frequent. The detectability of downbursts over such a large area is, however, of considerable interest. The Amazon forest has acted as an enormous chalk slate, recording the location, size, storm direction and three dimensional wind geometry of large downbursts. This record lasts at least 20 years. No comparable opportunity exists for the study of these features on a continental scale. Inferring severe downburst behavior, mechanisms and causes from their imprints on the Amazon forest is of practical value as well. Wind shear contributed to over 600 aviation fatalities between 1964 and 1986 and two out of three wind shear events were related to convective storms (The Boeing Com-
FIGURE 7  Total area of large downburst fans per Landsat TM scene mapped as isolines with 5 km$^2$ intervals. Minimum is 5 km$^2$ and maximum is 85 km$^2$ in 28,000 km$^2$ cell, which is the overlap-corrected size of a scene. Dots indicate center points of scenes for which measurements are made. Only features with longest axis $> 1.25$ km and area $> 0.3$ km$^2$ were counted; these have a visibility lifetime of about 20-30 yrs.
TABLE 1

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<td>blowdowns</td>
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<tr>
<td>18-20 Sep, 1993</td>
<td>Minor damage</td>
<td>Manaus</td>
<td>Informant</td>
</tr>
</tbody>
</table>

pany, 1986). Larger downbursts cause considerable loss of property and lives in both the USA (Fujita, 1985) and Brazil (Folha de São Paulo, May 19, 1992). The concentration of large downburst activity in the west-central Amazon and their rareness in the state of Pará are so far unexplained. They may be related to large-scale organized convective systems rather than isolated cumulo-nimbus convection, since the latter occurs throughout the Amazon. Squall lines propagating across the Amazon basin from east to west at the rate of 10º/day cross eastern Pará during the night, when convective activity is subdued, but few of them remain intact for more than 2,000 km (Cohen, 1989), which is the distance to Manaus from the coast. Damage from convective wind events is most commonly reported in the months of August to October (Table 1) when cloud cover is lowest and convective heating therefore greatest.

CONCLUSIONS

The spectrally dynamic and naturally disturbed vegetation types quantified in this paper are listed in Table 2. Liana forests were estimated by Pires (1973) to cover at least 100,000 km², based on their commonness as viewed in overflights and on field trips. Synchronous leaf drop of floodplain forests is not included as it’s extent has not been quantified.

It is interesting to note that the disturbed and dynamic vegetation types in this table are equivalent to 46% of the cumulative deforestation attributable to modern man as of 1991. Natural disturbances which have not yet been measured in the Brazilian Amazon include landslides, flooding mortality on terra firme, drowning and silting of floodplain forests, and floodplain turnover by shifting river channels. Not all disturbances can be quantified with TM images. For example, liana forests and blowdowns smaller than 30 hectares are not easily distinguished. Weak blowdowns which leave many standing trees have a high shade
content after the surviving trees releaf. Within one or two years their pixels take on spectral characteristics similar to the rough canopy of primary forest. Understory fires are also undetectable after releafing of the upper canopy. Though encompassing two extremes of rainfall (1983 and 1989), the TM time window is very brief. Furthermore, TM discriminates fire scars and blowdown scars for less time than required for complete biomass and floristic recovery of these sites.

The large areas of natural disturbance do not vindicate tropical deforestation as environmentally benign. Soil compaction and leaching of nutrients are certainly higher when forest is converted to pasture or subjected to short fallow cycles in swidden agriculture (Buschbacher et al., 1988; Jordan, 1985). Among the natural and indigenous disturbances quantified in this paper, savanization of the Serra Parima is the most ecologically damaging, since repeated burning prevents reestablishment of forest. These savannas total just 0.14% of the deforestation attributable to modern man. Perhaps the least intense disturbance agent is the downburst in the western Amazon, with a site-repeat cycle on the order of thousands of years. Though not an important turnover mechanism, large blowdowns may have provided crucial habitat for those pioneer tree species requiring very large gaps prior to the arrival of indigenous swidden agriculture.

The concentration of certain forms of natural disturbance in different regions—bamboo mortality in the southwest, fires in the seasonal transition forests and large blowdowns in the Têfê region—will be reflected as regional variations in plant diversity and species distributions. Transition forests dominated by babassu palms (*Orbignya phalerata*), as well as liana forests, may themselves be products of periodic fires associated with the long series of late Holocene El Niño events now well documented for western South America (Ortlieb and Macharé, 1992).

Late Holocene natural fires or indigenous swidden burns have left their mark even in the dense forests of the central Amazon. In situ carbonized roots have been found in soil pits under primary forest 90 km north of Manaus (Fearnside, 1990; T. Dunne, pers. comm., 1991). Fire-adapted babassu is the most common large palm in the terra firme forest 50-150 km east of Manaus, but is entirely absent in primary forest on the same soil type closer to the city. Other primary forest species such as *Vouacapoua americana* and *Bertholletia excelsa* have sharply defined range limits, are absent from large areas within their range and occur in dense colonies (Heinsdijk, 1957), suggesting that localized populations derived from founder trees subsequent to large patch disturbance.

### TABLE 2
Natural Disturbances in the Brazilian Amazon

| Area dominated by liana forest (Pires, 1973) | 100,000 km² |
| Area with bamboo dominance in Brazil | 92,000 km² |
| Aracá and Catrimani dune fields | 1,500 km² |
| Area affected by blowdowns (each > 30 ha.) over 20-30 years | 900 km² |
| Yanomama form savannas (including Venezuela) | 600 km² |
| El Niño fires causing crown death near Jurutí Lake and Curuá do Sul River | > 500 km² |
| Terra firme flooding mortality in 1989/1990 | 2-2.5% of area where documented |
The dynamic spectral behavior of Amazon forests must be borne in mind when monitoring or assessing potential human impacts on intact forests. Coarse resolution monitoring of vegetation indices (e.g. NDVI from NOAA-AVHRR GAC data set) must take into account the wave of mortality periodically crossing more than 122,000 km² of bamboo forest in the southwest Amazon. Bamboo growth and mortality cycles may also affect carbon fluxes over a vast area. Seasonal leaf-drop in floodplains and the anomalous flood mortality covering 2–2.5% of terra firme forests in the region north of Manaus will also contribute to a temporary lowering of vegetation index.

It is perhaps most useful to conclude with some questions raised by this study:

1. Can understory and crown fires be detected directly in 1983 MSS or AVHRR images?
2. Can large fires be detected far from human habitation in 1983 images?
3. Why do regenerating fire scars show concentric rings in the TM images?
4. What tree species survived in the documented fire scars? Are these the same species found in vine forests? Are previous fires or very dry years recorded as tree rings?
5. Does the extent or structure of a vine forest patch change in a historical series of air photos?
6. Can periods of dune field activity be carbon-dated?
7. What is the effect of cyclic bamboo mortality and regrowth on carbon flux in the southwest Amazon?
8. What is the nature of the bamboo/mixed-forest boundary?

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