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Tropical Deforestation and Habitat Fragmentation in the Amazon: Satellite Data from 1978 to 1988

[David Skole and Compton Tucker](#)

Landsat satellite imagery covering the entire forested portion of the Brazilian Amazon Basin was used to measure, for 1978 and 1988, deforestation, fragmented forest, defined as areas less than 100 square kilometers surrounded by deforestation, and edge effects of 1 kilometer into forest from adjacent areas of deforestation. Tropical deforestation increased from 78,000 square kilometers in 1978 to 230,000 square kilometers in 1988 while tropical forest habitat, severely affected with respect to biological diversity, increased from 208,000 to 588,000 square kilometers. Although this rate of deforestation is lower than previous estimates, the effect on biological diversity is greater.

Deforestation has been occurring in temperate and tropical regions throughout history ([1](#)). In recent years, much attention has focused on tropical forests, where as much as 50% of the original extent may have been lost to deforestation in the last two decades, primarily as a result of agricultural expansion ([2](#)). Global estimates of tropical deforestation range from 69,000 km² year⁻¹ in 1980 ([3](#)) to 100,000 to 165,000 km² year⁻¹ in the late 1980s; 50 to 70% of the more recent estimates have been attributed to deforestation in the Brazilian Amazon, the largest continuous region of tropical forest in the world ([2](#), [4](#), [5](#)).

The area and rate of deforestation in Amazonia are not well known, nor are there quantitative measurements of the effect of deforestation on habitat degradation. We used 1:500,000 scale photographic imagery from Landsat Thematic Mapper data and a geographic information system (GIS) to create a computerized map of deforestation and evaluate its influence on forest fragmentation and habitat degradation. Areas of deforestation were digitized into the GIS and the forest fragments and edge effects that result from the spatial pattern of forest conversion were determined.

Background

Tropical deforestation is a major component of the carbon cycle and has profound implications for biological diversity. Deforestation increases atmospheric CO₂ and other trace gases, possibly

affecting climate (6, 7). Conversion of forests to cropland and pasture results in a net flux of carbon to the atmosphere because the concentration of carbon in forests is higher than that in the agricultural areas that replace them. The paucity of data on tropical deforestation limits our understanding of the carbon cycle and possible climate change (8). Furthermore, while occupying less than 7% of the terrestrial surface, tropical forests are the home to half or more of all plant and animal species (9). The primary adverse effect of tropical deforestation is massive extinction of species including, for the first time, large numbers of vascular plant species (10).

Deforestation affects biological diversity in three ways: destruction of habitat, isolation of fragments of formerly contiguous habitat, and edge effects within a boundary zone between forest and deforested areas. This boundary zone extends some distance into the remaining forest. In this zone there are greater exposure to winds; dramatic micrometeorological differences over short distances; easier access for livestock, other nonforest animals, and hunters; and a range of other biological and physical effects. The result is a net loss of plant and animal species in the edge areas (11).

There is a wide range in current estimates of the area and rate of deforestation in Amazonia. Scientists at the Instituto Nacional de Pesquisas Espaciais (12-15) estimated a total deforested area of 280,000 km² as of 1988 and an average annual rate of 21,000 km² year⁻¹ from 1978 to 1988. Other studies (2, 4, 5) have reported rates that range from 50,000 to 80,000 km² year⁻¹ (Table 1). Additional deforestation estimates have been made for geographically limited study areas in the southern Amazon Basin of Brazil with Landsat and meteorological satellite data (16-20).

The Amazon Basin of Brazil has been defined by law to include the states of Acre, Amapá, Amazonas, Pará, Roraima, and Roraima plus part of Mato Grosso do Sul, Maranhão, and Tocantins and is referred to as the Legal Amazon (21). It covers an area of ~5,000,000 km², of which ~4,090,000 km² is forested, ~850,000 km² is cerrado or tropical savanna, and ~90,000 km² is water (Table 2). Confusion has arisen among researchers regarding the stratification of the Brazilian Amazon into forest, cerrado, and water strata. A Food and Agriculture Organization (FAO)-United Nations Environmental Program (UNEP) study (3) found 3,562,800 km² of forest, whereas Fearnside and co-workers claim there is 4,195,660 km² of forest, 793,279 km² of cerrado (17), and 4,906,784 km² total (13). Meanwhile, an IBGE study (22) found 20,972 km² of water, 3,793,664 km² of forest, and 1,149,943 km² of cerrado for a total of 4,964,920 km². These differences prevent comparison of different deforestation studies.

The use of satellite data and the GIS make it possible to explicitly stratify Amazonia on the basis of cover types (22), thereby providing a means of comparison with other studies. This approach is also necessary for spatial analysis of habitat fragmentation and edge effects of deforestation. Finally, GIS provides a data management tool with which we could manage large amounts of spatial data and precisely merge and geocode information from the more than 200 satellite images used in this study.

Remote Sensing

The large area of the Brazilian Amazon necessitates a straightforward and accurate method of measurement. Landsat Thematic Mapper photo products are inexpensive and of sufficient spatial and spectral resolution for the determination of deforestation. Analysis with visual interpretation techniques produces quantitative results similar to digital processing of full-resolution, multispectral data from the Thematic Mapper and SPOT (23).

We acquired 210 black and white photographic images of the entire Brazilian Amazon. They were obtained with channel five of the Landsat Thematic Mapper (1.5; to 1.75 μm) at 1:500,000 scale and were primarily from 1988 (24). We digitized the deforested areas with visual deforestation interpretation and standard vector GIS techniques (Fig. 1). The digitized scenes were projected into equal-area geographic coordinates (latitude, longitude), edge matched, and merged in the computer to form a single, seamless dataset for the entire Brazilian Amazon.

Spatial analysis of the geometry of deforestation is critical to the estimation of forest fragmentation and the edge effect. If 100 km^2 of tropical deforestation occurs as a 10 km by 10 km square and we assume that the edge effect is 1 km, the total area affected is $\sim 143 \text{ km}^2$. In contrast, if the 100 km^2 of deforestation is distributed as ten strips, each 10 km by 1 km, the affected area is $\sim 350 \text{ km}^2$.

We extracted forest fragments $< 100 \text{ km}^2$ that were isolated by deforestation and computed edge effects for a zone of 1 km along the boundaries. All areas of closed-canopy tropical forest deforested by 1988 were delineated, including areas of secondary growth on abandoned fields and pasture where visible (Fig. 1). Areas of long-term forest degradation along river margins in central Amazonia were also included, as; were scattered small clearings associated with rubber tappers, mining operations, airfields, and other small disturbances. All visible roads, power line right of ways, pipelines, and similar human-made features were also digitized into the GIS and treated as deforestation. We used 50 digital Landsat Multispectral Scanner (MSS) scenes from 1986 and 15 digital Thematic Mapper images from 1988 for detailed examination of Acre, Amazonas, Mato Grosso, Para, and Rondonia.

To determine the extent of deforestation in 1978, we used the GIS to digitize maps of scale 1:500,000 from single-channel Landsat MSS data, produced jointly by the Instituto Brasileiro de Desenvolvimento Florestal (IBDF) and the Instituto de Pesquisas Espaciais (INPE) in the early 1980s (12, 23). These maps did not differentiate between forest and cerrado clearing. We compiled forest, cerrado, and water data by combining a vegetation map with analysis of Landsat images and meteorological satellite data (25). Our deforestation and affected habitat analyses for 1978 and 1988 were restricted to closed-canopy forest of the Brazilian Amazon.

Deforestation and Forest Fragmentation

Distribution of deforestation and affected habitat in the Brazilian Amazon for 1978 and 1988 (Figs. 2 and 3) was concentrated in a crescent along the southern and eastern fringe of the Amazon [a spatial pattern similar to the distribution of fires observed from thermal anomalies in data from Landsat's Advanced Very-High Resolution Radiometer (AVHRR) (20)] and along major transportation corridors in the interior of the Amazon. Deforestation increased between 1978 and 1988 (78,000 to 230,000 km^2), while the total affected habitat increased (208,000 to

588,000 km²) ([Table 3](#)). The total area deforested increased by a factor of two to three or more in every state except Amapá; but it is likely that the deforested area in Amapá is higher than our assessment because excessive cloud cover in this region prevented complete analysis ([Table 2](#)). We found that 6% of closed-canopy forest had been cleared as of 1988 and ~15% of the forested Amazon was affected by deforestation-caused habitat destruction, habitat isolation, and edge effects ([Fig. 2](#) and [Table 3](#)).

Our analysis of the spatial pattern of deforestation found a strong tendency toward spatial concentration; areas of undisturbed tropical forest tended to be sizable ([Table 4](#)). This is more pronounced than [Table 4](#) indicates because many of the large areas of undisturbed tropical forest are contiguous among states.

For the entire Brazilian Amazon, our deforestation estimate is close to, but lower than, the estimates of Fearnside et al. ([13](#)) and the INPE ([15](#)) of ~280,000 km² as of 1988. The difference is a result of three factors: (i) different stratification of forest, cerrado, and water; (ii) slightly different estimates of secondary growth, which is spectrally similar to intact forest in channel five; and (iii) positional accuracy, interpretation, and boundary generalization. We estimate that ~30,000 km² of the difference is from a different evaluation of the forest-cerrado boundaries in Mato Grosso and Tocantins. By comparison, our analysis suggests that deforestation estimates based on coarse-resolution meteorological satellite data in the southern Amazon of Brazil have overestimated deforestation by ~50% ([18](#), [23](#)).

The average deforestation rate in the closed-canopy forests from 1978 to 1988 (~15,000 km² year⁻¹) ([Table 3](#)) is higher than the rate from 1975 to 1978 ([3](#)) but considerably lower than recent estimates ([2](#), [4](#), [5](#), [20](#)). Our estimates can be used in assessments of net flux of carbon from land clearing and biomass burning in the Brazilian Amazon. Current estimates of these fluxes have largely been based on model calculations with deforestation values much higher than we report. In addition, many deforested areas are in stages of regrowth following abandonment ([26](#)). If regrowth is widespread, estimates of the net flux of carbon should be further reduced because carbon accumulates in regrowing biomass.

The preponderance of affected habitat results from proximity to areas of deforestation (~341,000 km² for a 1-km edge effect) and not from isolation of forest (~15,000 km²) or deforestation per se (~230,000 km²). While the rate of deforestation averaged ~15,000 km² year⁻¹ in the Brazilian Amazonia from 1978 to 1988, the rate of habitat fragmentation and degradation was ~38,000 km² year⁻¹. Implications for biological diversity are not encouraging and provide added impetus for the minimization of tropical deforestation.

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24. Images: 7 from 1989, 175 from 1988, 8 from 1987, and 20 from 1986. All data from the Brazilian Landsat receiving station. The exact boundary between intact forest and deforested land was digitized in the Universal Transverse Mercator projection and then edited and error-checked with use of clear velum plots of the line-work overlaid on each photographic image. Each Landsat scene contained coordinate control points in decimal degree units, such that each scene could be geographically registered within precise tolerances and mosaicked together. For digitization, vertices were placed approximately every 50 m of ground position. Tests of positional accuracy in digitizing followed those of R. Dunn, R. Harrison, and J. C. White [Int. J. Geograph. Inf. Syst. 4, 385 (1990)] and indicated encoding; hence, area-estimation errors were less than 3% (23). The variance associated with interpretation and delineation of boundaries between intact forest and deforested areas was less than 10% overall. Further accuracy assessment was made in test sites established in Rondonia, where fragmentation was very high. An explicit spatial comparison between our estimate of deforestation and the same derived from high-resolution (20-m resolution) SPOT satellite imagery was highly correlated ($r^2 = 0.98$; $y = 1.11x - 57.358$). Additional ground checking and verification was done in eastern Para state (north of Manaus) and along the Rio Negro, both in Amazonas.

25. Fundamental to our analysis was a specified representation for water, cerrado or savanna, and forest for the Brazilian Amazon. We used a vegetation map (23) that was augmented by Landsat Thematic Mapper and meteorological satellite imagery for more accurate depiction of cerrado and water. This GIS representation is available upon request.

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