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RATES OF FOREST REGROWTH IN EASTERN AMAZÔNIA: A COMPARISON OF ALTAMIRA AND BRAGANTINA REGIONS, PARÁ STATE, BRAZIL

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Extensive areas of secondary vegetation cover the Amazonian landscape and are becoming a prominent feature surrounding rural communities in the Amazon. Due to the shrinking domain of mature forest in colonized areas, farmers today commonly cut secondary forest (fallowed land) rather than mature forest as part of the cycle of shifting cultivation. Secondary forests are an integral part of Amazonian agricultural strategies, not only providing nutrient rich ash when burned, but also facilitating the area's restoration following abandonment. As a fallow matures organic matter and nutrients accumulate, leaching and erosion are checked, and water and nutrients from lower soil depths are drawn upwards (Smith, 1982; Nepstad *et al.*, 1991). This paper examines rates of forest regrowth, or secondary succession, as a process which must be understood as a product of both land use and initial environmental endowments.

Variance in the speed of forest regrowth is evident across regions and along a soil fertility gradient. The rate of forest succession is determined by several factors. Original floristic composition, neighboring vegetation, and soil fertility and texture may affect regrowth. In addition, farmers' land use decisions, such as clearing size, clearing procedures, crops planted, frequency of use, and duration of use, influence tree establishment and direct the path of secondary succession. At the regional scale addressed in this paper, soil fertility and land use history emerge as the critical factors influencing the rate of forest regrowth. In this paper we compare and contrast two study sites, Altamira and Bragantina, and examine the relationship between land use intensity and soil fertility and the rate of succession. Differences in tree density, height, and basal area served to distinguish between the rate of succession in Altamira and Bragantina. On the relatively nutrient-rich Alfisols in Altamira, we found a rate of forest regrowth nearly twice as fast as that of the nutrient-poor Oxisols and Spodosols in Bragantina. The two distinct rates put to rest attempts to formulate a uniform scenario for succession in Amazonia, even when confined to the eastern Amazon. However, similarities in structural development during forest regrowth can be found and facilitate understanding of Amazon-wide successional processes.

In the literature, it is common to separate successional stages into age classes. Age categories are useful in comparing rates of succession. However, research in the region has

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shown that age alone cannot be used to predict stages of development of secondary succession, since land use history can strongly influence structural differences among sites within the same age class (Uhl *et al*, 1988; Brondizio, 1996). Original vegetation, neighboring vegetation, and soil characteristics may also impact fallow development. Physiognomy provides a more consistent way of comparing secondary vegetation across sites and regions. From the point of view of remote sensing and land use analysis, the definition of structural parameters for regrowth stages is especially important, since structural features are associated with spectral data from satellite images.

This paper pursues two main goals: 1) to highlight the differences in rates of regrowth between Altamira and Bragantina, and 2) to propose a classification of regrowth stages based on structural criteria that takes into account regional differences in soil fertility and local differences in land use. The paper begins with a characterization of the study areas and is followed by a Methods section. In the Results and Discussion section, we investigate the pattern of secondary growth over time, and explore the variation in the rate of secondary regrowth between Altamira and Bragantina. Next, we present a new cross-regional classification key which divides stages of secondary succession according to physiognomic parameters follows. A discussion of the implications of our findings concludes the paper.

Study Areas

The *Altamira* study area lies along the Transamazon highway near 3°12'S latitude and 52°13'W longitude in the Brazilian state of Pará (see Figure 1). Annual rainfall for Altamira is approximately 2000 mm with an average temperature of 26°C. According to Köppen's climate classification system (1936), Altamira exhibits Awi[1] climate (Dantas, 1989). The region presents patches of nutrient-rich Alfisols and less fertile Ultisols. All but four of the sampled sites in this paper represent nutrient-rich Alfisols. Alfisols are estimated to represent less than 8% of the soils in the Amazon Basin (Nicholaides *et al.*, 1983) and are the best soils found in the terra firme. Settlers began to colonize the area in 1971 through a government sponsored colonization program. The region has experienced high rates of deforestation and secondary succession associated with implementation of agropastoral projects (Moran *et al.* 1994b). The majority of small farmers remaining in Altamira today plant mixed annual crops for one to two years, and afterwards they convert the cropped land to pasture or perennial cash crops (Fearnside, 1986).

The second study area surrounds the town of Igarapé-Açu in the micro-political region known as Zona *Bragantina* within the state of Pará (See Figure 1). It sits between 0°45'S and 1°39'S latitude and 46°16'W and 48°15'W longitude. Rainfall in Bragantina ranges from 2200 to 2800 mm annually. The mean annual temperature of the region is 25°C. According to Köppen's climate classification system (1936), the Bragantina Region is predominantly type Ami[2] (Denich, 1991). Igarapé-Açu is dominated by nutrient-poor Oxisols and Spodosols. Oxisols are estimated to represent 46% and Spodosols 3% of the soils in the Amazon Basin (Nicholaides *et al.*, 1983). Between 1870 and 1910 the rubber-boom caused a population explosion in Belém which greatly increased urban food demand. The government responded with a colonization program to develop agriculture in the Bragantina region (Penteado, 1967). Igarapé-Açu was founded in 1897. Of the almost 1 million hectares of dense tropical forest that covered the Bragantina Region at the beginning of the century, less than 2% remained by 1960 (Penteado, 1967). Today the dominant land use is short-fallow swidden cultivation.

Methods

Nested Sampling Strategy

The present study employs a nested sampling strategy organized by region, site, plot, and sub-plot to collect field data and link it to TM Landsat satellite images. The *region* sits at the highest level and represents the greater study area which includes all sample sites. What is designated as a *site* corresponds to the vegetation stand (fallow or mature forest) selected for sampling. Several tiers of information are gathered at each site: land use history, location (with a GPS (Global Positioning System device), vegetation inventory, and soil samples. To characterize the vegetation, *plots* (10 x 15 m) are distributed at the site in a stratified random fashion, and *sub-plots* (5 x 2 m) are nested within them. In the majority of cases ten plots and ten sub-plots were inventoried at each site. Plots are designed to inventory trees, whereas sub-plots are used to inventory saplings, seedlings, and herbaceous species. For the purpose of image analysis, each site becomes a "training sample", that is, an area of known identity that is used during supervised classification to identify areas of unknown identity. This procedure is detailed elsewhere (Moran *et al.*, 1994a; Brondizio *et al.*, 1996; Moran *et al.*, 1996a).

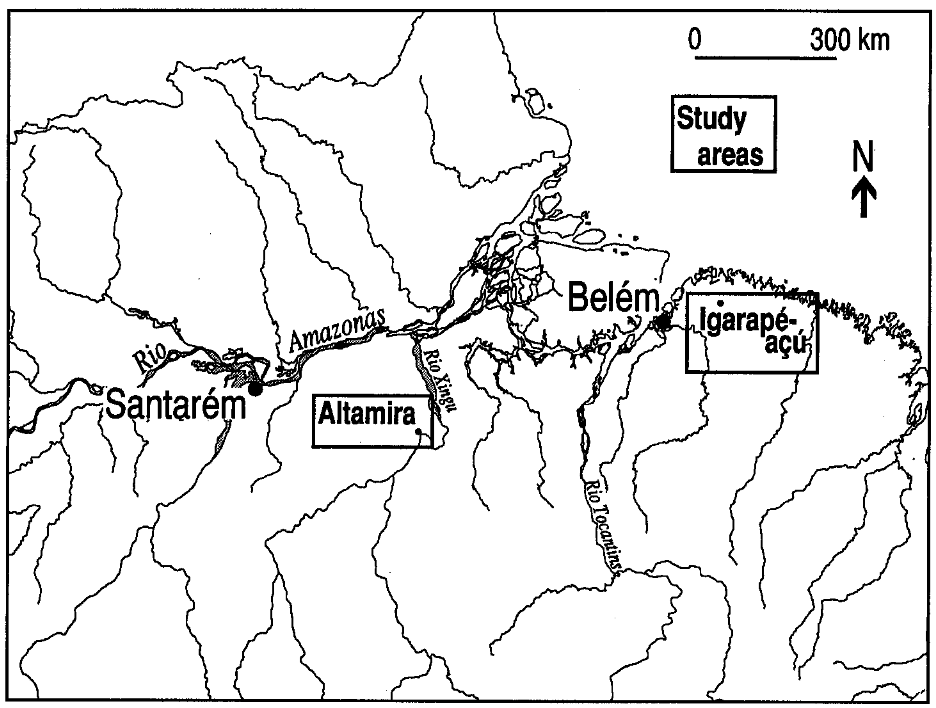

Fig. 1. Study Areas: Igarapé-Açu (Bragantina Region) and Altamira (Xingu Region)

Study Sites

To facilitate sampling, secondary vegetation sites were grouped according to time since abandonment: 0-5 years, 5-10 years, and 11+ years. An adequate number of representative samples were chosen from each age class of secondary succession to achieve a well-represented chronosequence of fallow ages. Landsat TM satellite images were used as a reference to encourage even spatial distribution of the sample sites throughout each region. The farmer's permission to conduct field research on his property was attained prior to any final site selection.

Altamira: Fifteen Altamira sites sampled in 1993 and 1992 are incorporated into the analyses, including two mature upland forest sites, one liana forest and one dense moist forest, representing the two types of mature forest present in the region. The successional sites encompass three sites from the 0-5 year age class, six from the 5-10 year age class, and four from the 11+ year age class. Most of the sites were cleared from primary forest during 1971 or 1972, and a few have been recleared from secondary vegetation. Two advanced succession sites serve as control sites. They were cleared from primary forest and then allowed to recover without further human interference as part of a regrowth experiment conducted by EMBRAPA (Empresa Brasileira de Pesquisa Agropecuaría) (Dantas, 1989). The most commonly encountered crop mixture consists of rice, beans, and corn, and land owners often plant both crop and pasture (see Table I for site summaries).

Bragantina Sample Sites: Sixteen sites from Igarapé-Açu sampled during 1994 and 1995 are examined in this paper. Only one mature forest site was sampled due to the scarcity of primary forest in the region. Of the fallowed sites, five belong to the 0-5 year age class, four to the 6-10 year age class, and six to the 11+ year age class. All fallowed sites have been cleared more than once. Most of the sites were planted for only 1-2 years, and all but two successional sites were previously cultivated with a combination of manioc, beans, and corn or rice. Only one abandoned pasture area was sampled (3 year old fallow) (see Table I for site summaries).

Farm-Level Interviews

In-depth land use interviews with the land owner, or tenant, were conducted at each sample site. Questions were asked to ascertain when the forest or secondary growth was last cut, clearing procedures, when it was burned, the length of prior fallow periods, cultivation and management techniques (such as fertilizer use), types of crops/pasture grown, yields, the time since the land was abandoned, and other pertinent land use history information. Because of the long history of settlement and cultivation, land use histories from Igarapé-Açu farms are limited to the last two or three cultivation cycles.

Vegetation Inventory

Plant individuals with diameter-at-breast-height, or DBH > 10 cm are referred to as *trees*, those with DBH < 10 cm but > 2 cm DBH or 2 m height as *saplings*, and any plants under 2 cm DBH are grouped as other (includes seedlings, vines and herbaceous plants). In fallows with trees, ten 10 x 15 meter plots were randomly located along a randomly-oriented transect within the forest stand. Inside each plot, all trees were identified and measured for diameter, stem height (height to the first major branch), and total height. Species identification was done in the field by an experienced field botanist. Plant samples were collected, in the case of uncertainty, and later identified by an herbarium technician using the EMBRAPA herbarium or the Museu Paraense Emílio Goeldi Herbarium both in Belém, Pará, Brazil. Height was estimated upon consensus of two or three observers using a five meter rod as a reference. Inside the plot, a sub-plot of 5 x 2 meters was randomly placed in which all species < 10 cm DBH were counted and identified, and saplings were measured for diameter and total height. In 1993, sub-plots (5 x 2 meters) were placed in half of the plots (5 sub-plots per site), while 10 sub-plots were sampled per site in 1994 and 1995 (one per 10 x 15 meter plot). In the sub-plots, if the number of individuals were uncountable (such as in the case of grasses), percent coverage was estimated.

In young fallows with few if any trees, five 10 x 2 meter plots were distributed similarly as above, each of which was divided into five 2 x 2 meter sub-plots. In each sub-plot the same procedures were carried out as in the 5 x 2 meter sub-plots mentioned above. For the year 1995 data gathered in Bragantina followed slightly modified procedures for young succession. Rather than sampling younger sites in a pattern of five contiguous 10 x 2 meter plots, we set ten 5 x 2 meter plots along a randomly-oriented transect at random distances from one another, thereby imitating sub-plots in the older fallows. In the majority of cases, the total area sampled remains constant (100 m^2), but the new method facilitates easier plot by plot comparison between younger and older sites.

Plot sizes for all sites are summarized in Table I. Differing sizes exist in some cases due to the ongoing refinement and modifications during the first four years of the project. Data from all the sites used in this paper can be compared for structural analyses.

Soil Samples

At each inventoried site, soil samples were collected with a soil auger at 20 cm intervals down to one meter depth. In Altamira, two subsamples were taken at each site and then combined whenever structure and color were consistent between the samples. In Bragantina, one complete sample was taken per site. Soil samples were delivered to the tropical soils laboratories at Centro de Pesquisa Agropecuária do Trópico Úmido da Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA/CPATU) in Belém, Pará, Brazil, where chemical and physical soil analyses were completed.

Results and Discussion

Successional Processes

Secondary succession associated with shifting agriculture in Amazonia follows a clear pattern of development. During crop or pasture use, burning and weeding delay succession, but after the field is abandoned, the forest begins to regenerate. Secondary vegetation establishes itself through four main processes: regeneration of remnant individuals, germination from the soil seed bank, sprouting from cut or crushed roots and stems, and seed dispersal and migration from other areas. During the first stage of succession, pioneer species such as light-demanding herbaceous vegetation, seedlings, and saplings occupy the area and compete for space and resources. Secondary species in tropical lowland forests are characterized by a short life cycle, high growth rate, high reproductive resource allocation, small seed size, and long seed viability[3] (Gómez-Pompa and Vasquez-Yanes, 1981). Few if any trees (individuals > 10 cm DBH) are present at this stage. A dramatic difference is evident in the second successional stage (generally after five years) which is characterized by a large presence of young trees but still dominated by saplings in terms of density.

Table I

SUMMARY OF LAND USE HISTORY AND SAMPLING PROCEDURES FOR STUDY SITES IN ALTAMIRA AND BRAGANTINA, PARÁ, BRAZIL.

Region	Site No.	Site Vegetation	Land Use Type	Land Use History	Sampling Methods			
					Large Plot	Area (m2)	Medium Plot	Area (m2)
Altamira	A009-93	SS(2yrs)	Swidden agriculture/pasture	1987-forest; 1989-pasture; 1991-fallow	5*(10x2m)	100	25*(2x2m)	100
Altamira	A010-93	SS(2yrs)	Swidden agriculture	1989-forest; 1990-crop; 1991-fallow	5*(10x2m)	100	25*(2x2m)	100
Altamira	A004-93	SS(3yrs)	Swidden agriculture/pasture	1987-forest; 1988-crop. 1989-pasture; 1990-fallow	5*(10x2m)	100	25*(2x2m)	100
Altamira	A006-93	SS(7yrs)	Swidden agriculture/pasture	1971-forest 1972-crop; 1973-fallow: 1984-crop; 1985-pasture; 1986-fallow	10*(10x15m)	1500	5*(5x2m)	50
Altamira	A014-93	SS(7yrs)	Swidden agriculture/agroforestry	1972-forest; 1973-crop; 1974-fallow: 1985-rice, beans, corn + cacao: 1986-fallow	10*(10x15m)	1500	5*(5x2m)	50
Altamira	A007-93	SS(8yrs)	Swidden agriculture/agroforestry	1972-forest 1978-crop; 1984-cacao;1985-fallow	10*(10x15m)	1500	5*(5x2m)	50
Altamira	A011-93	SS(9yrs)	Swidden agriculture/pasture	1971-forest 1972-pasture; 1977-fallow; 1980-crop; 1982-pasture; 1984-fallow	10*(10x15m)	1500	5*(5x2m)	50
Altamira	A005-93	SS(9yrs)	Swidden agriculture/pasture	1971-forest 1972-pasture: 1978-fallow; 1983-crop; 1984-fallow	10*(10x15m)	1500	5*(5x2m)	50
Altamira	A013-93	SS(10yrs)	Swidden agriculture	1982-rice, beans, corn; 1983-fallow	10*(10x15m)	1500	5*(5x2m)	50
Altamira	A002-93	SS(16yrs)	Swidden agriculture	1975-for; 1976-cl,crop; 1977-fallow	10*(10x15m)	1500	5*(5x2m)	50
Altamira	A001-93	SS(16yrs)	Swidden agriculture	1975-for; 1976-cl,crop: 1977-fallow	10*(10x15m)	1500	5*(5x2m)	50
Altamira	A005-92	SS(16yrs)	Experiment	1975-for; 1976-cl,burn	10*(10x20m)	2000	10*(5x2m)	100
Altamira	A001-92	SS(16yrs)	Experiment	1975-for; 1976-cl	15*(10x15m)	2250	2*(5x2m)	20
Altamira	A003-93	Liana Forest	Logging	selective logging	8*(25x10m)	2000	4*(10x2m)	80
Altamira	A008-93	Dense Forest	no use reported	no use reported	8*(25x10m)	2000	4*(10x2m)	80
Bragantina	B009-94	SS(2.5yrs)	Swidden agriculture	1984-corn, manioc. beans, rice: 1986-fallow: 1991-corn. manioc; 1992-fallow	none	-	5*(10x2m)	100
Bragantina	B005-94	SS(3yrs)	Swidden agriculture/pasture	1990-manioc. corn, rice; 1991-pasture; 1992-fallow	none	-	5*(10x2m)	100
Bragantina	B021-95	SS(3yrs)	Swidden agriculture	1991-crop; 1992-fallow	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B003-94	SS(4.5yrs)	Swidden agriculture	1989-beans. manioc, corn; 1990-fallow	none	-	5*(10x2m)	100
Bragantina	B026-95	SS(4.5yrs)	Swidden agriculture	1950?-crop; 1991-manioc	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B025-95	SS(6yrs)	Swidden agriculture	1988-manioc. beans; 1989-fallow	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B010-94	SS(6yrs)	Swidden agriculture	1985-beans, manioc, corn; 1988-fallow	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B027-95	SS(8yrs)	Swidden agriculture	1985?-crop; 1986-manioc	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B004-94	SS(10yrs)	Swidden agriculture	1983-corn,beans, manioc; 1985-fallow	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B001-94	SS(14yrs)	Swidden agriculture	1979-beans. manioc, corn: 1980-fallow	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B011-94	SS(15yrs)	Swidden agriculture	1976-rice. manioc, corn; 1980-fallow	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B006-94	SS(19yrs)	Swidden agriculture	1950s-manioc; 1960's-fallow; 1974-cotton: 1975-fallow	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B002-94	SS(20yrs)	Swidden agriculture	1974-manioc. corn; 1975-fallow	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B024-95	SS(20yrs)	Swidden agriculture	b/f 1973-agave for rope	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B020-95	SS(35yrs)	Swidden agriculture	1950 rice, manioc, corn, 1961-fallow	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B008-94	Dense Forest	Logging	1984-logged	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B023-95	Igapo Forest	Logging	occasional logging	10*(10x15m)	1500	10*(5x2m)	100
Bragantina	B022-95	Igapo Forest	Logging	occasional logging	10*(10x15m)	1500	10*(5x2m)	100

The trees attract animal seed dispersers thereby facilitating the introduction of new species. Animal dispersal plays a significant role in tree establishment. According to Howe and Smallwood (1982), at least 50% and often 75% or more of tropical forest tree species produce fleshy fruits consumed by birds or mammals. A closing canopy thins the shade-intolerant understory and alters the microclimate by reducing soil temperature and increasing soil moisture, thereby improving conditions for seed germination of mature forest species. Furthermore, gradual restoration of nutrient cycling and accumulation of organic matter facilitate the next stage of development. This third successional stage exhibits a clear shift in structural design. Pioneer tree species die off and are replaced by slow-growing, shade-tolerant mature forest species which favor increased shade and improved edaphic conditions. Trees now dominate the stand, while saplings play a secondary role. The understory consists of saplings and young trees, and fewer individuals are present during this stage. Figure 2 illustrates particular features characterizing the processes of secondary succession in tropical Amazon forests.

The advancement of successional growth is significantly impacted by trees which remain throughout the cultivation/pasture cycle. These trees accelerate successional processes through attracting dispersers, especially birds and bats who perch and defecate seeds. Increased seed rain occurs beneath the trees where microclimatic conditions are favorable for germination and growth of late successional and mature forest species. Discussion of the role of remnant trees in succession, often referred to as tree islands, can be found in Uhl *et al.* (1982), Uhl (1987), Nepstad *et al.* (1991), and Vieira *et al.* (1994). In the two regions discussed in this paper, remnant palms are frequently found in abandoned fields. Common remnant palms include *Orbignya phalerata* (*babaçu*) (generally associated with Altamira's Alfisols) and *Maximiliana maripa* (*inajá*) (associated with Oxisols in both regions). Both are well adapted to fire and disturbance initiated by slash-and-burn techniques.

Historical and physical conditions of the area are critically important to understanding rates of succession. As shown later in this paper, Altamira forests recover nearly twice as fast as Bragantina forests. In the case of Altamira and Bragantina, regional differences in soil fertility and settlement history are the major factors influencing tree establishment and fallow development. Altamira's rich Alfisols and recent land use history give this region a successional advantage over the nutrient-poor soils of Bragantina where settlers have exploited the area for 100 years. In Bragantina, mechanisms of colonization, like seed dispersal, seed migration from primary forest, and the seed bank, have broken down under pressure, and tree establishment occurs more slowly as a result.

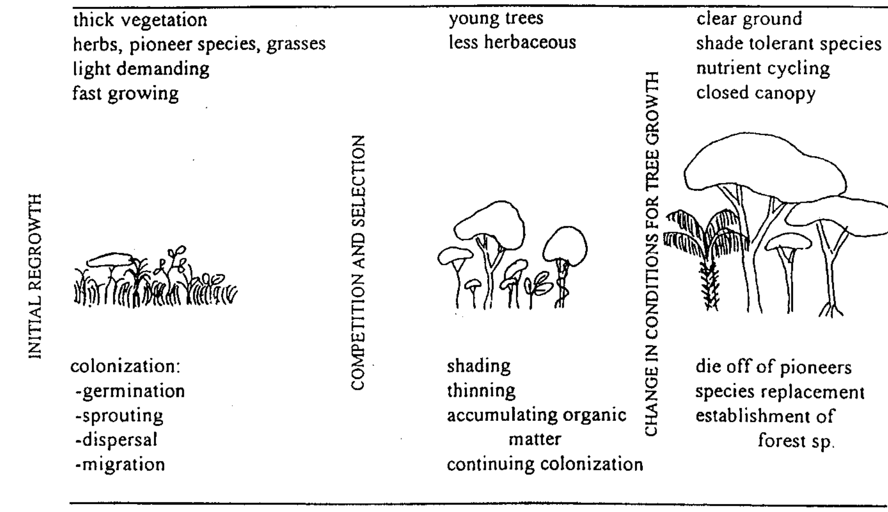

Figure 2. Diagram illustrating key features of secondary succession in Amazônia.

Two Distinct Rates of Secondary Succession: Altamira and Bragantina Regions

Density, height, and basal area clearly distinguish between the two rates of secondary forest development in Altamira and Bragantina.

1. Sapling and Tree Density

Change in sapling and tree density over time differs between Altamira and Bragantina (see Figure 3). During the age interval between six and 16 years, we found on average, more than 20 saplings per tree in Bragantina, but only half of that in Altamira. Forest regrowth in Altamira exhibits as many as 8600 saplings per hectare by the second year which gradually decline in number as the fallow ages and develops. Bragantina, on the other hand, has at most 6000 saplings per hectare by the third year, and the number of saplings continues to climb until about the tenth year when shade reduces sapling density. The absence of mature forest in Bragantina limits the seed source and may explain slower colonization of woody plants. Denich's (1991) study of young secondary succession in Bragantina found that only 30 of the seedlings which germinated from seeds within a 10 m^2 area were tree, shrub, or liana species. The remaining majority were herbaceous plants. Most secondary woody regrowth in this region result from sprouting. Denich (1991:88) found that all the individuals above 50 cm tall derived from sprouts. The longer time required for sapling establishment in Bragantina, slows the succession process. Despite these differences, a general trend of decline in sapling density over time with a concurrent increase in tree density is evident in both regions. In Altamira there is a remarkably high number of trees by the seventh year of fallow - as many as 773 trees/ha, compared to 407 trees/ha in an eight year old fallow in Bragantina. The larger number of young trees after seven years in Altamira reflects the larger sapling population during the first few years of succession.

2. Height

Throughout the process of succession, Altamira surpasses Bragantina in height (see Figures 4 and 5). Maximum total height represents the growth potential of a secondary forest. In Altamira, maximum height (10 m) during the first five years of succession is about six meters greater than in Bragantina (3.75 m), while average total height in Altamira (4.19 m) is double that in Bragantina (2.26 m). During the six to ten year period, maximum height is about ten meters higher in Altamira (22.5 m) than Bragantina (13 m). Average total height is the same for a ten year fallow in Altamira and a twenty year fallow in Bragantina (11 m). Thus, Altamira regrowth requires only half the time of Bragantina regrowth to reach the same height. Regional differences are still evident after 15 years of fallow. The average total height of 14-16 year fallows, each cropped for one year and then abandoned, is almost five meters taller in Altamira (13.5 m) than Bragantina (9 m). The maximum height for this age range found in Altamira was about 35 m but only 13 m in Bragantina. Between the two regions average total height is different for the 0-5 year age class ($p<0.05$), the 6-10 year age class ($p<0.001$), and the 11+ year age class ($p<0.001$).

3. Basal Area

Tree basal area provides a clear contrast between the rate of suc-

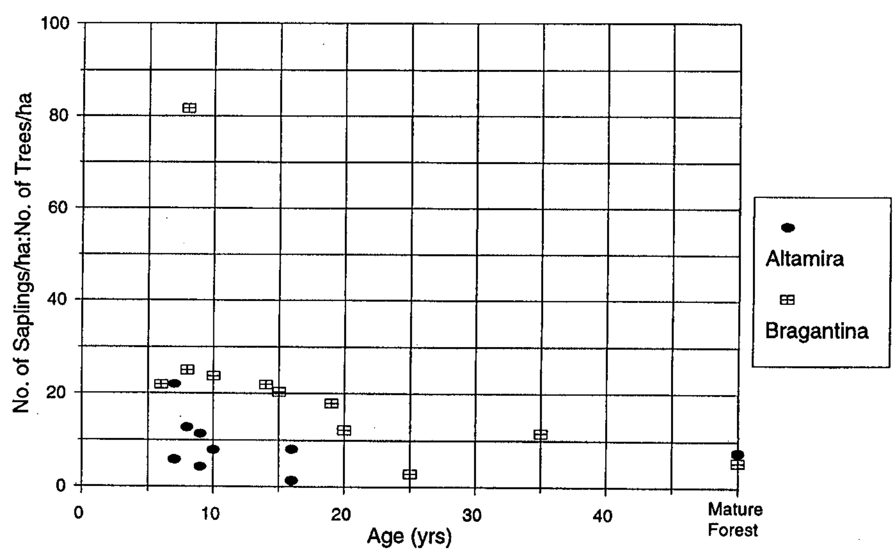

Figure 3. Ratio of the number of individuals per hectare of saplings to trees in secondary and mature forest in the Altamira and Bragantina regions.

cession in Altamira and Bragantina (see Figure 6). Total basal area, on the other hand, is a poor indicator of successional development especially between seven and twenty years of fallow. The balance between tree and sapling basal area can hide the level of maturation, because a fallow with few trees and dominated by saplings may exhibit the same total basal area as a fallow dominated by trees and sparsely populated by saplings. The latter is clearly more advanced, but this is not evident from total basal area. This does not pose an interpretation problem within early (0-5 year) succession, however, since few if any trees are present.

A four year old Bragantina site has total basal area of 2.7 m^2/ha – merely one third the total basal area the average for 0-5 year sites in Altamira (7 m^2/ha). This relationship parallels the difference in sapling density between the two regions. During 6-10 years of succession Bragantina exhibits an average tree basal area of 3.83 m^2/ha, merely one-fifth of the tree basal area in Altamira (15.07 m^2/ha). Demonstrating the continuing discrepancy as age increases, tree basal area of a 20 year old Bragantina fallow (9.71m^2/ha) is less than that of a seven year Altamira fallow (11.36 m^2/ha). Between the two regions mean total basal area/plot is different for the 0-5 year age class ($p<0.01$), the 6-10 year age class ($p<0.001$), and the 11+ year age class ($p<0.001$).

Clearly a major disparity in basal area arises in the contribution of saplings and trees to total basal area. In Bragantina, saplings contribute to the majority of total basal area until after twenty years of fallow, but in Altamira trees begin to contribute more than saplings as early as seven years (see Figures 7 and 8). This turning point is an important indicator to illustrate the different rates of regrowth and is easily determined from simple stand inventory data.

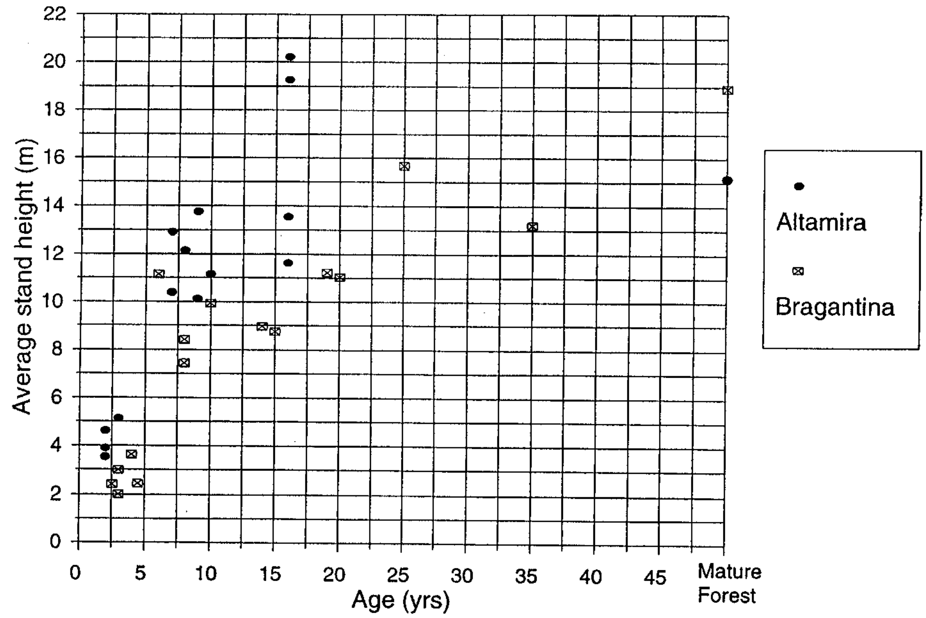

Figure 4. Comparison of average stand height of secondary and mature forest in the Altamira and Bragantina regions.

4. Effects of Soil Fertility and Texture on Succession

Significant differences in soil fertility and texture exist between Altamira and Bragantina. Table II presents chemical and physical analyses of representative sample sites in Altamira and Bragantina. Of the 15 sites sampled in Altamira, all but four exhibited Alfisol attributes. According to Brady (1974) and Falesi (1974), Alfisols include some of the world's best agricultural soils. Bragantina soils (Oxisols and Spodosols), however, are among the poorest. High soil acidity in Bragantina, in combination with significant amounts of aluminum, restricts plant root nutrient absorption in areas where nutrients are already scarce, thereby stifling plant growth.

The impact of soil fertility on secondary growth was tested with a soil fertility index (Moran *et al.*, 1996b)[4]. The results of an ANOVA including 74 study sites from five regions of Amazonia indicate that soil fertility impacts height accumulation in secondary succession and accounts for the significant difference in forest structure between Altamira and Bragantina. For each unit increase of the index, tree height increased 0.16 meters.

In addition to the contrast in soil fertility, soil texture also varies between Altamira and Bragantina. Altamira soils are dominated by clay, and Bragantina soils contain mostly sand (Table II). Sandy soils exhibit low water-holding capacity and tend to lose nutrients and minerals quickly (Brady, 1974). In Bragantina, low fertility and sandy texture

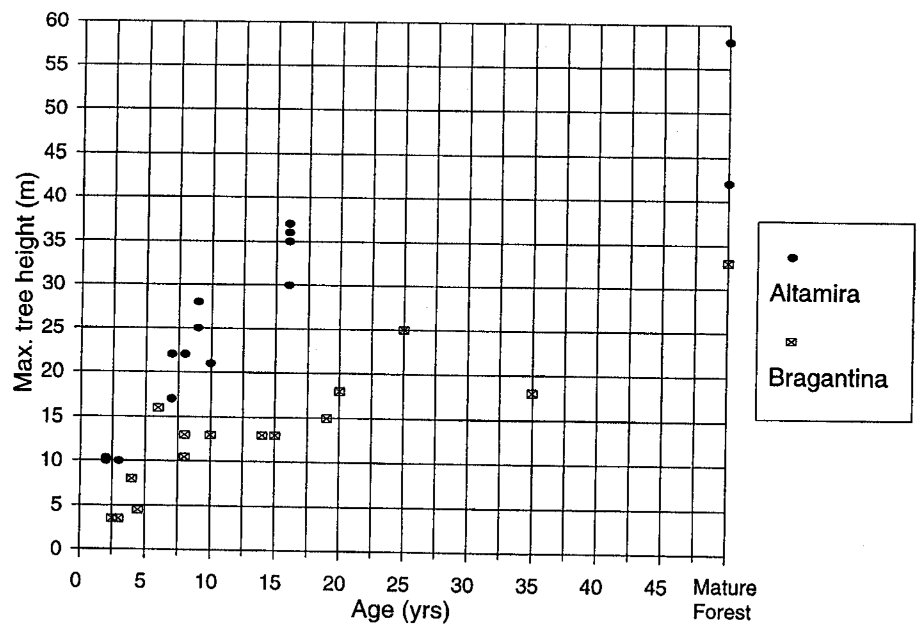

Figure 5. Comparison of maximun tree height of secondary and mature forest in the Altamira and Bragantina regions.

Table II

CHEMICAL AND PHYSICAL SOIL ANALYSES OF TWO REPRESENTATIVE SITES IN ALTAMIRA (Alfisols) AND BRAGANTINA (Oxisols), PARÁ, BRAZIL.

						meq/100g						Organic	%			Coarse	Fine		
Region	Soil Type	Site No.	Age	Depth (cm)	pH	Al	Ca+Mg	Ca	Mg	K	P (ppm)	Matter (%)	N	C	C/N	sand (%)	sand (%)	silt(%)	clay(%)
Altamira	Alfisol	A005-93	9	0-20	6	0	4.20	3.30	0.90	0.09	2	1.73	0.14	1.01	7.21	19	12	17	52
Altamira	Alfisol	A005-93	9	20-40	5.3	0.1	1.80	1.60	0.20	0.02	1	1.05	0.08	0.61	7.63	16	11	13	60
Altamira	Alfisol	A005-93	9	40-60	5.3	0.1	0.90	0.50	0.40	0.02	1	0.99	0.06	0.58	9.67	14	10	10	66
Altamira	Alfisol	A005-93	9	60-80	5.3	0	1.00	0.60	0.40	0.02	1	0.87	0.05	0.5	10.00	12	8	12	68
Altamira	Alfisol	A005-93	9	80-1.00	5.6	0	0.90	0.50	0.40	0.01	1	0.56	0.03	0.32	10.67	12	8	12	68
Bragantina	Oxisol	B002-94	20	0-20	4.3	0.8	0.6	0.4	0.2	0.01	2	0.96	0.05	0.56	11.20	55	26	11	8
Bragantina	Oxisol	B002-94	20	20-40	4.7	0.9	0.4	0.2	0.2	0.01	1	0.96	0.04	0.56	14.00	49	26	8	17
Bragantina	Oxisol	B002-94	20	40-60	4.6	1	0.4	0.2	0.2	0.01	1	0.98	0.04	0.57	14.25	47	23	9	21
Bragantina	Oxisol	B002-94	20	60-80	4.6	1	0.4	0.2	0.2	0.01	1	0.62	0.04	0.36	9.00	44	26	16	14
Bragantina	Oxisol	B002-94	20	80-100	4.6	0.9	0.4	0.2	0.2	0.01	1	1.07	0.04	0.62	15.50	41	28	9	22

retard regrowth. On the other hand, clayey soils in Altamira hold nutrients and minerals long enough for nutrient uptake to occur, and they retain water after drainage, thereby lessening the risk of plant wilt from drought (Jordan, 1985). Furthermore, clay is more resistant to compaction than sandy soils (Cochrane *et al.*, 1982). Altamira succession has a clear advantage over Bragantina in terms of soil fertility and texture.

Care must be taken when relating soil fertility to succession (Buschbacher *et al.*, 1988). The correlation needs to take into account changes in soil nutrient content due to the restoration of nutrient cycling as regrowth proceeds. This is especially true in Oxisols. Soil fertility measured at older sites tends to be lower given the cumulative nutrient uptake by the vegetation. Immediately following disturbance, soils are likely to present higher nutrient levels compared to older fallowed areas. More research is needed on this topic. Much is known about the effect of soil fertility and soil physical properties on agricultural crops in Amazonia, but in terms of soil fertility's and texture's[5] impact on mature or secondary successional forest, very little is known.

5. Effects of Settlement History on Succession

Settlement history exhibits a strong relationship with successional rate. The retarded rate of regrowth in Bragantina is at least partly due to prolonged history of land use. In parts of Igarapé-Açu colonist agriculture has been practiced for over 100 years (Denich, 1991). With increasing population pressure, primary upland forest has all but disappeared, and available land has decreased, resulting in shortened fallow cycles (usually no more than 5-6 years). Mechanisms of colonization and tree establishment face many obstacles due to the impacts of repeated land clearing and burning over the past century. Repeated burning depletes the seed bank and favors a limited number of fire resistant species. The clearing of virtually all primary forest in Bragantina restricts seed availability, and dispersal agents decline as the forest habitat disappears. Consequently, succession is slowed.

Not only is succession in Bragantina relatively slow, but studies denote impoverished species composition (Denich, 1991; Vieira *et al.*, 1996). Ac-

Table III

RANGE OF STRUCTURAL CHARACTERISTICS FOR THREE STAGES OF SECONDARY SUCCESSION COMBINING ALTAMIRA AND BRAGANTINA REGIONS*

	Initial Succession (SS1)	Intermediate Succession (SS2)	Advanced Succession (SS3)
Basal Area Dominance (tree/sapling)	Sapling	Sapling	Tree
Tree Basal Area (m2/ha)	0	1.76-11.36**	11.93-21.54
[Percent Tree Contribution to Total Basal Area]	[0%]	[14-49%]	[50-93%]
Average Total Height (m)	2.4-5.13	7.43-11.22	11.14-15.69
Mode Total Height (m)	2-5	9-11	14-16
Average DBH (cm)	2.04-4.3	10.46-14.72	14.44-19.75
Total Height - standard deviation (m)	0.38-1.99	1.27-2.87	2.4-5.44

*All values for SS2 and SS3 refer to tree individuals $\geq$ 10 cm DBH

**Excludes outlier with tree basal area of 13.3 m2/ha cording to Denich (1991), young succession which predominates in Bragantina may no longer function as a stage in the regeneration of primary forest. Compounding the effects of limited availability of mature forest species seeds, short fallow cycles prohibit fallows from developing past the early stages of succession thereby selecting for early successional species. Other species common to primary forests which favor conditions found in later successional stages are eliminated (Denich, 1991; Vieira *et al.*, 1996).

In contrast, the Altamira study area was settled only 25 years ago, and much land in the region remains forested (Moran, 1981; Moran *et al.*, 1994b). Fallows which have only undergone one or two cropping and/or pasture sequence(s) are common in Altamira. As a result, the viability of the seed bank is higher, still retaining seeds from the recent primary forest, and animal habitat still abounds for seed dispersers. Furthermore, cultivated land in Altamira is often surrounded by mature forest, unlike Bragantina, so wind dispersal and migration of primary forest species occur readily. Since Altamira has been settled only briefly compared to Bragantina, the mechanisms of colonization are still firmly in place.

Soil quality and settlement history do not exhaust the explanations for divergent successional rates, but in Altamira and Bragantina they embody two of the more important factors which account for the vast difference in the rate of regrowth. Size of clearing and surrounding vegetation have not yet been effectively evaluated but may also impact colonization and establishment of trees species during initial succession. Along with retarded rates of succession, agricultural yields in Bragantina fall well below those in Altamira. The identification of areas with quicker succession processes through the use of satellite imagery and remote sensing (Mausel *et al.*, 1993) can help identify beneficial land use practices and pinpoint areas within Amazonia which rebound quickly from disturbance, as well as those where succession is slow and extensive agriculture and/or pasture should be discouraged.

Table IV
AGE RANGE OF THREE STRUCTURAL STAGES OF SUCCESSION FOR BRAGANTINA, ALTAMIRA, AND BOTH REGIONS COMBINED

	Age Range (years)		
	Initial Succession (SS1)	Intermediate Succession (SS2)	Advanced Succession (SS3)*
Altamira	1 - 3	4 - 7	7 - 16
Bragantina	1 - 5	6 - 20	21 - 35
Combined	1 - 5	4 - 20	7 - 35

*the upper age limits for SS3 are constrained by the oldest sample site ages.

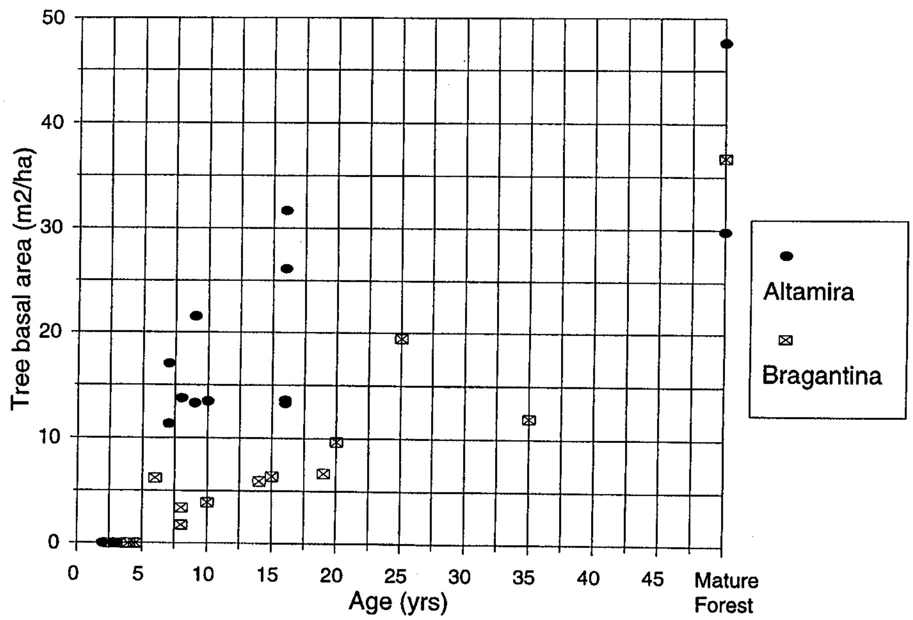

Figure 6. Comparison of tree basal area in secondary and mature forest in the Altamira and Bragantina regions.

A Region-Wide Key to Successional Stages Based on Structure

Literature related to forest succession in Amazonia commonly differentiates stages of secondary succession on the basis of age (Uhl *et al.*, 1988; Saldarriaga *et al.*, 1988; Dantas, 1989; Denich, 1991; Salomão, 1994). Although age is highly correlated with the development of secondary forests, factors like land use history (Uhl *et al.*, 1988; Brondizio, 1996), soil fertility (Moran *et al.*, 1996b), original vegetation, neighboring vegetation, and clearing size potentially cause significant variation within age categories, both within and across regions. To facilitate a standard system of classification which can be applied across different regions in Amazonia and aid remote sensing analysis, stages of secondary succession must be classified structurally, independent of age. This structural classification method is intended to provide a baseline for classifying stages of succession throughout the Eastern Amazon. Altamira and Bragantina encompass a significant range of soil and land use types, thereby providing a reasonable comparison to most upland areas of the Amazon Region.

A classification system based on physiognomic characteristics was developed from the combined Altamira and Bragantina field data. The primary structural features which uniquely identify each stage include: 1. the contribution of trees and saplings to total basal area, 2. average total height, 3. mode total height, 4. average DBH, 5. tree basal area, and 6. standard deviation of total height which indicates the degree of structural diversity among individual plants. These indicators are presented in Table III in which categories are split into initial (SS1), intermediate (SS2), and advanced (SS3) stages of succession and defined in terms of structural parameters. Because of limited data on older fallow sites, no stage was assigned beyond advanced, however, further research may demand another class. Table IV assigns age ranges to these structural stages, and illustrates the different time intervals required to pass through the three structural stages of secondary succession in Altamira and Bragantina. The differences in regrowth rates between the two regions illustrates the difficulty of using age classes as the main indicator of regrowth stages.

The central discriminating factor between stages of succession is the contribution of saplings and trees to the fallow's total basal area. In SS1, there are few if any trees, and herbs, seedlings, and saplings dominate the vegetation. During SS2 saplings constitute the greater amount of basal area, but young trees are also present. In SS3, trees contribute to the majority of the basal area, herbaceous vegetation has all but disappeared, and saplings play a subordinate role. The understory during SS3 is composed of both saplings and young trees, and fewer individuals overall are present during this stage. Using the balance between sapling and tree basal area as a key indicator of successional stage, the other parameters (tree basal area, average DBH, average total height, average mode height, and total height standard deviation) express themselves uniquely in each stage with virtually no overlap. Therefore, sapling/tree basal area relationships can help predict other structural features and effectively divide successional stages. The contribution of saplings and trees to above ground biomass, although not discussed here, may likewise be a focal point in distinguishing stages of secondary succession. We suggest these six criteria as determinants for successional stages which are delimited by structure. Regrowth stages based on structural criteria rather than age will help facilitate the aggregation of cross-regional data sets, help to understand the pace of regrowth in relation to management strategies, and furthermore, aid the development of a basin-wide classification system of remotely sensed images for secondary succession.

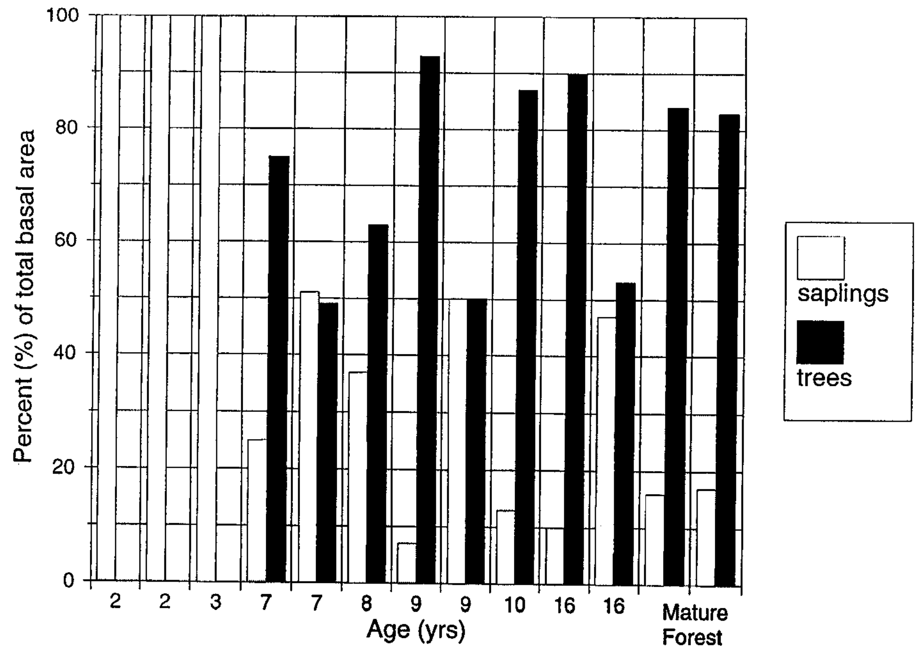

Figure 7. Relative contribution of trees and saplings to total basal area in Altamira's secondary and mature forest.

Conclusions

The investigation of regional variations in the rates of regrowth in the Amazon, as are evident in the Altamira and Bragantina regions, is important in the analysis and monitoring of land use and land cover change in Amazonia. Regrowth stages based upon structural criteria which can be identified independent of age will help facilitate the aggregation of cross-regional data sets, help to understand the pace of regrowth in relation to management strategies, and furthermore aid the development of a basin-wide classification system of regrowth stages based on remotely sensed images. Such knowledge can help make estimates of carbon release and sequestration more precise, since structural stages can be easily related to biomass (i.e. carbon stocks).

The findings in this paper also inform reforestation initiatives and regional agricultural evaluation and planning. The identification of two factors which influence regional differences in the rate of secondary succession, soil fertility and land use history, can inform future settlement schemes and remind planners of the implications of land use decisions in areas of low soil fertility. For instance, in a region where forest regrowth occurs rapidly, like Altamira, the fallow cycle can be shorter than in Bragantina. In reality, the exact opposite is taking place, partly due to population pressure and land tenure in the Bragantina Region which has led to a shortage of cultivatable land. Since less

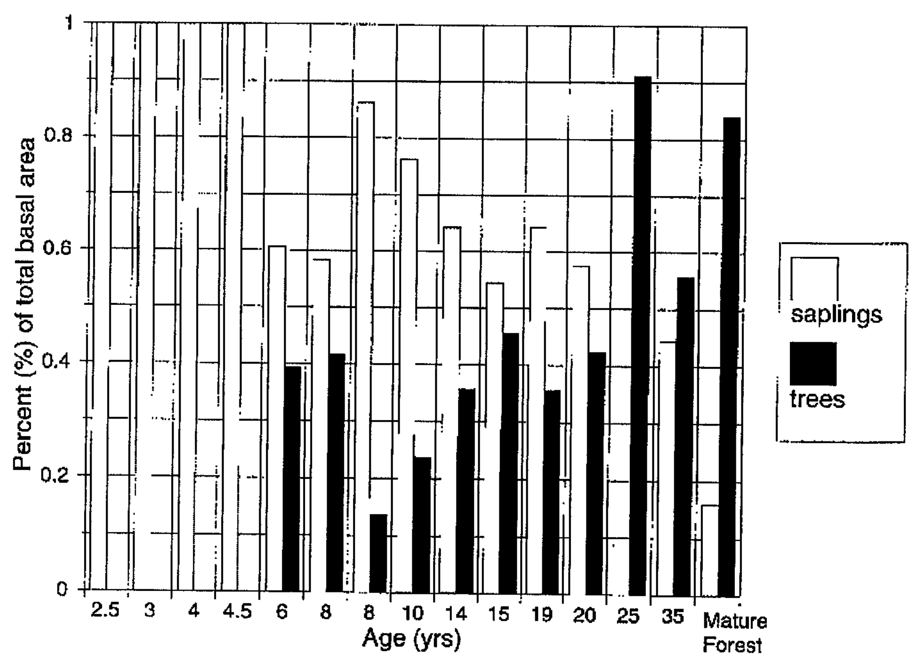

Figure 8. Relative contribution of trees and saplings to total basal area in Bragantina's secondary and mature forest.

land is available per family, the land must be cultivated more frequently. The expansion of large-scale pastures in Bragantina has also reduced land availability. As pasture areas continue to grow in Altamira, farmers could see reduced fallow periods and may no longer be able to sustain themselves through the practice of tree-fallow shifting agriculture. More research is needed to increase frequency and intensity of cropping without sacrificing land viability. A better understanding of secondary succession can assist local farmers in judging the benefits of clearing secondary forests of various stages of development without irreversibly damaging their long-term agricultural prospects.

Many factors which farmers can control, at little or no expense, may significantly influence the rate of succession in abandoned fields. For instance, clearing size and shape influences plant colonization and tree establishment after use, the proximity of the plot to mature forest determines which species colonize the area. Weeding techniques, such as preserving woody species during cropping and planting tree islands, speeds regrowth, and green manuring increases crop production and facilitates tree establishment. Faster rates of succession allow farmers to use the same land again sooner than otherwise. Projeto SHIFT, a German-Brazilian cooperation project based at EMBRAPA/CPATU and taking place in the Bragantina Region, is studying fallow enrichment with legumes as a strategy to intensify agriculture (personal communication). Fallow enrichment with hardwoods, another alternative, increases land value and diversifies income. Increased knowledge of the processes of secondary succession and familiarity with local land use strategies can help identify which land management practices retard or accelerate forest regrowth, and farmers may begin to apply methods which will shorten the fallow cycle, thereby decreasing land pressure and/or increasing net production. The role of land use strategies and initial soil fertility are important components of the system of natural forest regeneration.

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NOTES

1. Awi climate is characterized by high precipitation during the wet season and a well-defined dry period of about four months.
2. Ami refers to a climate characterized by high precipitation and a short dry period, including at least one month with rainfall below 66 mm.
3. There is a paper on seed longevity of C. *obusifolia* that indicated mean seed longevity of 8 months. A typical pioneer, then, can have a longevity comparable to a tolerant species' delayed germination. There may be danger in assuming 'long seed viability' as a paradigm until more studies have been done on this subject.
4. The index aggregates phosphorus, potassium, calcium, magnesium, aluminum (inverse value), pH, and organic matter. The index was prepared for each soil depth at 20 cm intervals to one meter, and an average index was prepared across depths.
5. The clay content of the soils differs dramatically, and presumably affects water retention. An alternative hypothesis is that the water stress induced by varying clay contents affects succession, particularly in its initial stages.

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