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Nonfrontier Deforestation in the Eastern Amazon

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ABSTRACT: While interest in Amazonian deforestation mostly focuses on frontier areas, the amount of forest cover in areas already dominated by human settlement is also changing. Secondary forests play an increasingly important role for maintaining genetic diversity, hydrological functioning, and greenhouse gas emissions of altered landscapes, but secondary forests are also being converted to more intensive agricultural uses. Five dates of Landsat imagery from 1984 to 2002 were analyzed, covering 8000 km^2 of the Zona Bragantina of the eastern part of the Brazilian state of Pará, which underwent its most intensive wave of deforestation several decades ago. However, even in this area of relatively long-term human occupation, ongoing decreases of forest cover were

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found, both in the small remaining areas of mature forest and in the more widespread areas of secondary forests, as human population increased and land use intensified. Although there was an initial increase in the area of secondary forest from 1984 to 1994, there has been a steady decline since then, from 75% secondary forest cover in 1994 to 54% in 2002. The amount of pasture was relatively stable from 1984 to 1994 but more recently has shown a steady increase, reaching 37% cover in 2002. The average rate of carbon loss over the 18-yr study period was 0.9 Mg C ha^{-1} yr^{-1} for the 8000 km^2 study area. Forests in this long-settled region of eastern Amazonia continue to be degraded, resulting in the loss of ecosystem services and carbon stocks due to continued land-use change.

1. Introduction

Most of the attention on deforestation in the Amazon basin has focused on the deforestation frontier, which forms a broad arc along the eastern and southern boundaries of the Brazilian portion of the Amazon forest (Fearnside 2005). Although the arc of deforestation is the site of most rapid land-use change (INPE 2008), the fate of secondary forest cover and remnant mature forest cover in regions that were partially or largely deforested in previous decades should not be neglected. Secondary forests that form after agricultural abandonment provide important ecosystem services, including regulation of the hydrologic cycle, nutrient and carbon accumulation, reserves for resource extraction, seed sources, and as wildlife habitat (Brown and Lugo 1992; Moran et al. 1994; Vieira et al. 1996; Alves et al. 1997; Davidson et al. 2007; Chazdon 2008). Pioneer successional forest vegetation usually develops deep roots within a few years and thus quickly reestablishes rates of evapotranspiration that are similar to mature forests (Hölscher et al. 1997; Nepstad et al. 2001), which may, in turn, affect the regional climate (Malhi et al. 2008). Nutrient accumulation in the aboveground biomass of young forests is crucial for slash-and-burn agriculture, and these lands also serve as reserves for resource extraction and potential agricultural expansion or rotation. Carbon accumulation would be important if secondary forests were allowed to persist for many years or decades, but even rapid rates of forest regrowth have little consequence on the regional carbon budget if the forests are recleared within only a few years (Fearnside and Guimarães 1996; Salimon and Brown 2000). Although young secondary forests seldom have the same biodiversity of plants and animals as mature forests, they nevertheless provide important buffer habitat and seed sources in landscapes that are a mosaic of native vegetation and cleared land (Vieira et al. 1996). Secondary regeneration provides the mechanisms by which ecological and hydrological functions, biomass (carbon and nutrients), and biodiversity are restored in forest lands.

The future of tropical forests depends heavily on the potential for secondary forests to develop following human and natural disturbances (Lamb et al. 2005). Despite the increasing importance of secondary forest regeneration throughout the tropics, research on the ecology and dynamics of second-growth forest has lagged behind studies conducted in mature forests. The lack of adequate information has spawned a strong debate in the scientific literature regarding the potential for secondary forest regrowth to recover levels of biodiversity and ecosystem services of lost old-growth tropical forests (Brook et al. 2006; Laurance 2007).

In the Brazilian Amazon basin, about 14%–16% of the original forest area (approximately 4 million km^2) has been cleared (Carreiras et al. 2006; INPE 2008), but basin-scale estimates of secondary forest cover are more difficult to obtain because of frequent confusion in satellite imagery among young secondary forests and other land-cover types (Powell et al. 2004). As much as 30%–50% of cleared land in Amazonia has been estimated to be in some stage of secondary forest succession following agricultural abandonment (Hirsch et al. 2004). Carreiras et al. (Carreiras et al. 2006) provided four estimates of the area of secondary forest, based on different methodologies, ranging from 140 000 to 233 000 km^2. Almeida (Almeida 2008) estimated 132 000 km^2 of secondary forest cover in the legal Amazon in 2006. Neeff et al. (Neeff et al. 2006) estimated that there was an increase in the area of secondary forests in the Amazon basin from approximately 30 000 km^2 in 1978 to 160 000 km^2 in 2002, the latter figure representing about 20% of deforested land and about 4% of the natural forest area. The mean age of Amazonian secondary forests is estimated to be 4–5 years (Almeida 2008; Neeff et al. 2006).

In an earlier study focused on the São Francisco do Pará municipality in the Bragantina region of the eastern Amazon, we were able to identify three successional stages of secondary forest using 1999 *Landsat 7* Enhanced Thematic Mapper (ETM) imagery (Vieira et al. 2003). Forests of 16 training sites were grouped into young (3–6 yr), intermediate (10–20 yr), and advanced (40–70 yr) successional stages, and mature old-growth forests. Each of these classes had distinct species composition, height distributions, and spectral signatures that distinguished it from the other classes (Vieira et al. 2003). Here, we expand the area examined to include neighboring municipalities, and we analyze Landsat scenes from five dates from 1984 to 2002 to develop a time series of land-cover change and a transition matrix of land covers. The objective of this study is to estimate temporal transitions among classes and the recent fate of secondary forests and remnant mature forest stands in the Bragantina region of the eastern Amazon, where the first waves of deforestation had occurred in previous decades. We also calculate the carbon storage consequences of continued land-cover change in this region.

2. Methods

2.1. Study area

The 8000 km^2 study area is within the Zona Bragantina, within the Brazilian state of Pará, east of the state capital city of Belém (Figure 1). This area is one of the older areas of colonization in Amazonia. Much of the original deforestation happened many decades to a century earlier, although there were also additional waves of colonization in the midtwentieth century (Vieira et al. 2003). The combined population of the 14 municipalities within this region was about 437 000 in 2000, with an annual growth rate of 3.9% from 1996 to 2000 (additional information is available online at http://www1.ibge.gov.br/home/estatistica/populacao/default_censo_2000.shtm). Population density is about 55 persons per square kilometer. The dominant vegetation of the region was moist lowland tropical forest but is now mostly secondary forests and small agricultural fields of corn, rice, beans, and manioc as well as pastures and tree crops such as oil palm, coconut,

Figure 1. Study area (trapezoid) overlaid onto a map of eastern Pará state of Brazil.

Brazil nut, orange, mango, and remnant rubber plantations (Costa and Carvalho 2009). Remnant stands of mature riparian (igapó) forests and mature upland (terra firme) forests are also present. Slash-and-burn agriculture is the dominant economic activity, with many young secondary forests as temporary fallow phases within the agricultural cycle. The demands of an increasing human population are causing the fallow period to be shortened (Vieira et al. 1996). Although there is diversity in soil properties across this large region, most soils are generally acidic with medium texture and were formed on tertiary deposits of the Barreiras formation (Vieira et al. 2003). Mean annual precipitation in this region is about 2200 mm, with a distinct dry season from June to November (Vieira et al. 2003). Mean annual temperature is 26°C with very little seasonal variation.

2.2. Landsat data

All Landsat satellite data utilized were from World Reference System (WRS) Path/Row 223/61. This Landsat scene is centered at 1°30′S latitude and 48°W longitude. This work focuses on an 8000 km^2 subset of the region that includes the two municipalities of São Francisco do Pará to the north and Capitão Poço to the south, where members of our group have previously conducted field work. All satellite imagery was from the dry season when clouds are less common and pasture grasses are largely senescent. The scenes used in this study were Landsat Thematic Mapper (TM), 27 July 1984; Landsat TM, 21 June 1994; Landsat ETM, 13 July 1999; Landsat ETM, 3 August 2001; Landsat ETM, 7 September 2002. A subset of an 8000 km^2 study area was created for each of these dates of Landsat imagery. Ideally, we would like to have had yearly satellite data to examine the land-cover transitions at higher temporal resolution, but mostly cloud-free scenes were not available for intervening years. Therefore, while the transitions that we describe are valid, they cover multiyear intervals, and unobserved transitions certainly occurred between the years that were analyzed.

We used Earth Resources Data Analysis System (ERDAS) Imagine Software V 8.5, 9.0 and 9.1 (Leica Geosystems Geospatial Imaging LLC, Norcross, GA) to analyze the satellite imagery. A modified version of the cosine approximation model (COST) of Chavez (Chavez 1996) was used to convert the digital satellite data to reflectances and to accommodate atmospheric attenuation and scattering. Geometric correction of the imagery was aided by handheld GPS [Garmin Model GPS-12; Datum, SAD-69, Universal Transverse Mercator (UTM) projection] data collected in the field.

To classify the data we used a minimum distance classifier, also known as a minimum distance to means classifier (Lillesand and Kiefer 1999). Minimum distance is simple and fast in assigning pixels to classes. Land covers were determined by supervised classification of the satellite imagery from the years 1994, 1999, 2001, and 2002, using the same classification system as described in detail by Vieira et al. (Vieira et al. 2003) for the 1999 imagery. In that study, each secondary forest training site ranged from 0.5 to 25 ha, depending on the local conditions, reflecting the sizes of previous slash-and-burn rotations. Training sites from 4 to 64 ha in size were similarly located at mature forest sites. There were also four training sites for croplands with sizes from 7 to 41 ha, three training sites for pasture with sizes from 7 to 106 ha, and four training sites for tree crops or perennial culture with sizes from 12 to 40 ha. Training sites for water, clouds, and shadows were identified based on visual inspection of the imagery. All pasture sites had signs of active grazing, although some also showed significant presence of invading shrubs and treelets, which were classified as "dirty pasture." The classification error matrix of the 1999 image showed good agreement in most cases, with an overall accuracy of 81% (Vieira et al. 2003). The kappa statistic value for the matrix presented in was 0.768, indicating that the classification avoided 76.8% of the errors that a completely random classification would have generated.

For the earlier 1984 imagery data, a different classification approach was necessary, as we did not have field data from that era, nor are we aware of any other possible ground reference data. An ISODATA classifier was used, which is a type of unsupervised classification (Campbell 1987). The ISODATA algorithm uses minimum spectral distance to create several arbitrary pixel clusters and then aggregates them through an iterative process. Each reclustering shifts the cluster means and the process is repeated until a minimum percentage of unchanged pixels remains between the classes. Ten iterations of the algorithm were sufficient to produce 10 classes with a change threshold of less than 5%. For subsequent work described below on transitions, the cloud and shadow classes were merged into a class called "other." To test the comparability of classifications using an ISODATA classifier and a minimum distance to means classifier, both were applied to the 2001 Landsat image, which was the most cloud-free of the recent images.

A transition matrix was constructed to estimate the temporal dynamics of the identified land classes. To create the matrix, we used all 9.8 million classified pixels and examined their change over the five dates by creating a numerical sequence such that all nine possible classes for the first date (1984) were assigned a 5-digit value (10 000, 20 000, 30 000, . . . , 90 000), all nine possible classes for 1994 were assigned a 4-digit value (1000, 2000, 3000, . . . , 9000), all nine possible classes for 1999 were assigned a 3-digit value (100, 200, 300, . . . , 900), all nine possible classes for 2001 were assigned a 2-digit value (10, 20, 30, . . . , 90), and all nine possible classes for 2002 were assigned a 1-digit value (1, 2, 3, . . . , 9). Summing all five classifications then yields a 5-digit numerical label for each pixel. For example, if mature forest has a value of 1 and remains as mature forest for all dates, then its 5-digit value would be 11 111. Or, if mature forest (value 1) was converted to clean pasture (value 6) in the third date (year 1999) and remained clean pasture, then its 5-digit value would be 11 666. After all classified pixels were assigned 5-digit values, the values were exported to a spreadsheet where each unique value was counted (e.g., all 11111s, all 12222s, all 13333s, etc.) to determine how many pixels changed from one class to another or remained the same for each transition from one image to the next.

3. Results

3.1. Spectral properties of land-cover classes

The classification process uses information from all spectral bands simultaneously, but for the purpose of visualizing how spectral properties varied among the land-cover classes a two-dimensional plot of normalized difference vegetation index (NDVI) and band 5 reflectance is shown in Figure 2. Variation among scenes, likely due to differing amounts of rainfall in months preceding the image acquisition, causes some overlap among the clusters of classes, especially for the forest-cover classes. Within a single scene, however, the younger forests consistently have lower NDVI and higher band 5 reflectance values than do the older forests. A decrease in band 5 reflectance with forest age has been attributed to increases in vegetation moisture and increased trapping of midinfrared radiation as the structural complexity of the canopy develops with forest age (Lucas et al. 2002; Vieira et al. 2003). Bare soil, dirty pastures (pastures with significant invasion of weeds and woody shrubs), and clean pastures (those with little or no woody vegetation) have progressively higher band 5 reflectances and lower NDVI values.

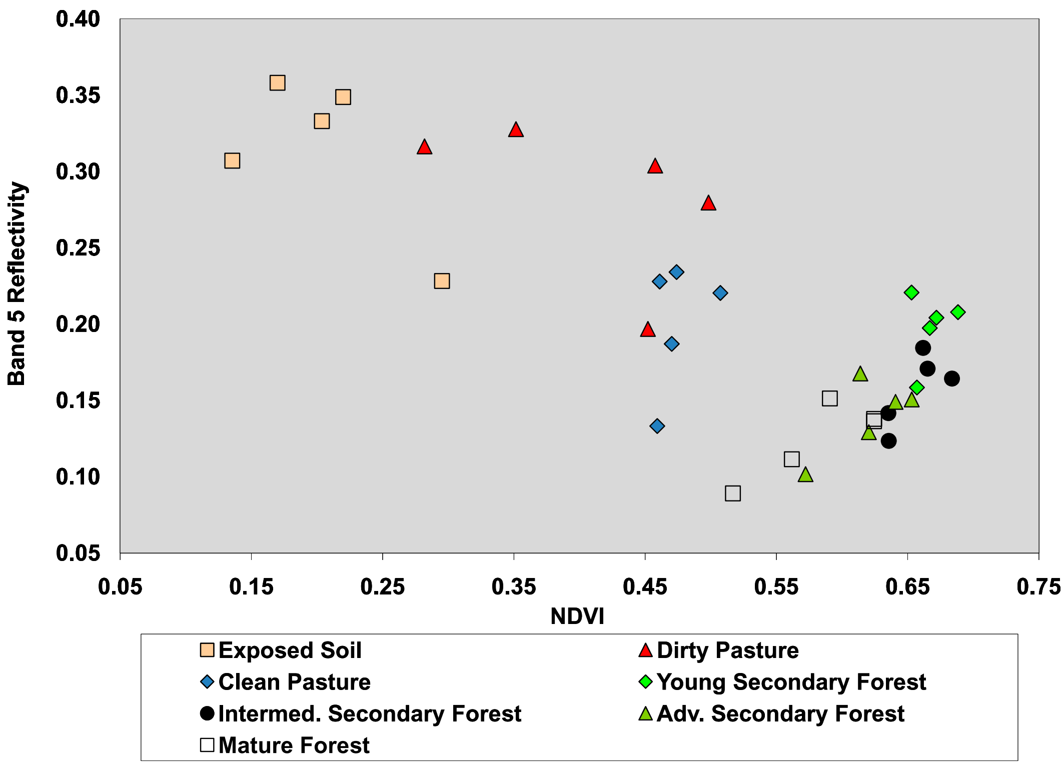

Figure 2. The separation of land-cover classes plotted on a 2D space of NDVI and band 5 reflectivity, both calculated from Landsat imagery. Each point represents the mean values for a land-cover class for one of the five years of images analyzed.

3.2. Temporal trends

Land-cover maps for four of the dates are shown in Figure 3. Large patches of mature forest remained in the southern part of the image in 1984 but were mostly cleared by 1994. By 1999, there were only two small patches of mature forest—one in the southeast corner and a smaller one in the northwest corner. The remaining areas classified as mature forest mostly occur in margins of streams and rivers, which are locally known as igapó forests. Between 1999 and 2002, a significant expansion of clean pasture (yellow in Figure 3) is apparent.

The area of mature forest declined from 21% of the region in 1984 to about 5%–8% at the end of the study (Figure 4). The slight increase in mature forest cover from 2001 to 2002 is probably within the margin of error of classification, indicating some confusion between advanced secondary forest and mature forest classes. The large decrease in mature forest cover from 1984 to 1994 appears to have resulted in a commensurate increase in secondary forest cover. However, secondary forest cover then decreased after 1994, with a proportionate increase in pasture cover.

The increase in secondary forest cover from 1984 to 1994 was primarily in the intermediate-aged secondary forest class (Figure 5), which we previously identified

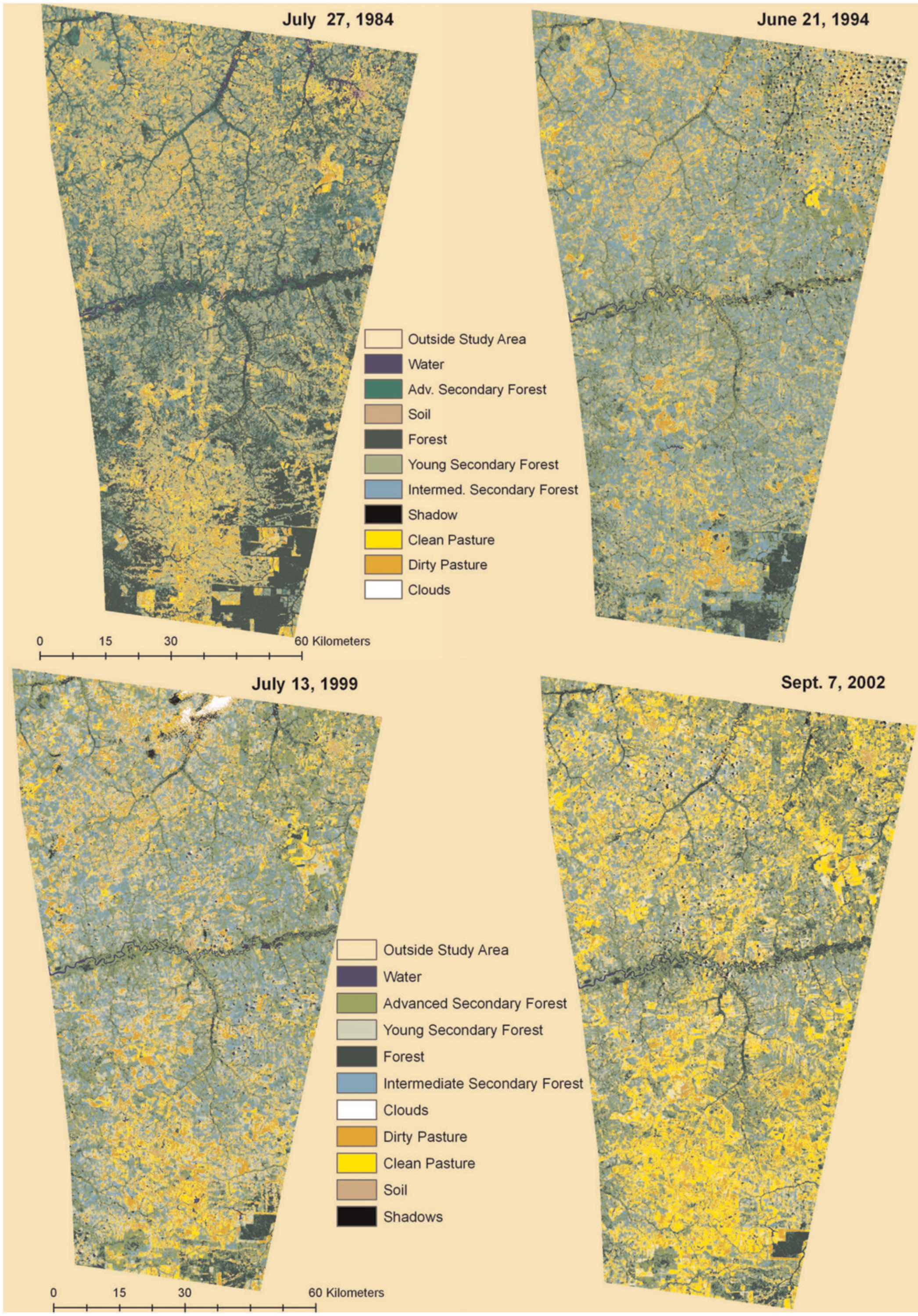

Figure 3. False color images showing classifications of cover types for four of the five years. Not shown is the 2001 image, because it is similar to the 2002 image.

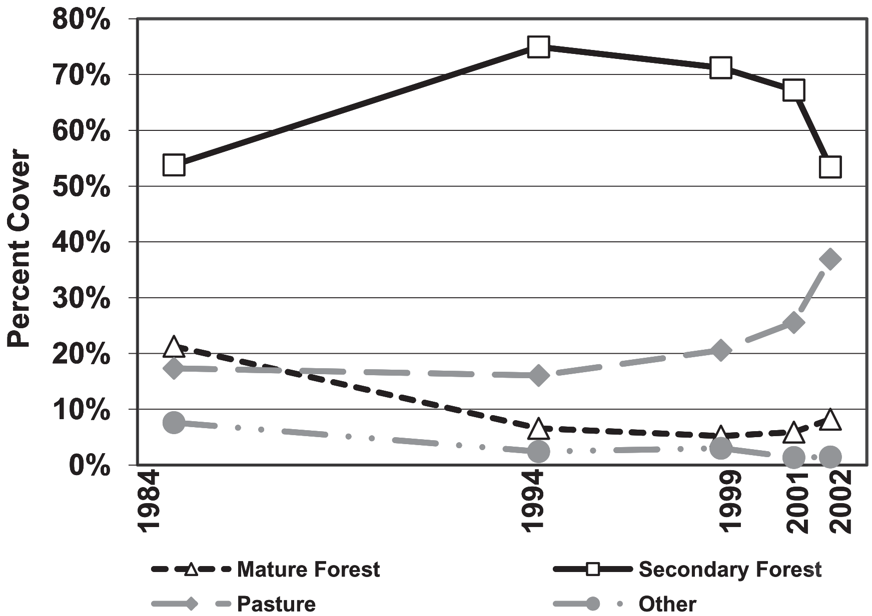

Figure 4. Temporal change in the percent cover of four land-cover classes, aggregated from the data presented in Table 1.

as 10–20-yr-old forest stands (Vieira et al. 2003). Forest clearing in the late 1970s and early 1980s may have resulted in the relatively large area classified as young forest in 1984, which then grew into the intermediate-aged forest class by 1994. Because it was necessary to use the ISODATA classifier method on the 1984 image, differences in classification methodology applied to this and the later images (where the minimum distance to means classifier was used) could account for some of the reported differences between 1984 and 1994. When these two methods were both applied to the 2001 image, the ISODATA classifier underestimated secondary forest cover by 14% and overestimated pasture cover by 11%, partly because of confusion between “dirty pasture” and secondary forest. If the same was true for the 1984 ISODATA classification, then some of the 17% of the 1984 image classified as pasture might have been in secondary forest.

The transition matrix shows that 1385 km^2 classified as young secondary forest in 1984 were classified as intermediate secondary forests in 1994 (Table 2). Apparently, the demand for agricultural land was not so high during this period to require that fallow fields be recleared before the secondary vegetation grew to an age class that we recognize as intermediate according to observed spectral properties in the 1994 image. After 1994, however, the intermediate-aged secondary forests declined as the area of pasture increased (Figures 4 and 5). Total pasture cover increased from 17% to about 37% of the study area, with clean pasture being 6 times more common than dirty pasture in the 2002 scene. The area of dirty pasture declined from 1999 onward (Table 1). One of the more significant changes evident from the transition matrix (Table 2) is the loss of secondary forest to clean pasture in the last two time periods (1999–2001 and 2001–02), when 820 and 1241 km^2 of the area of secondary forests were converted to clean pasture, respectively.

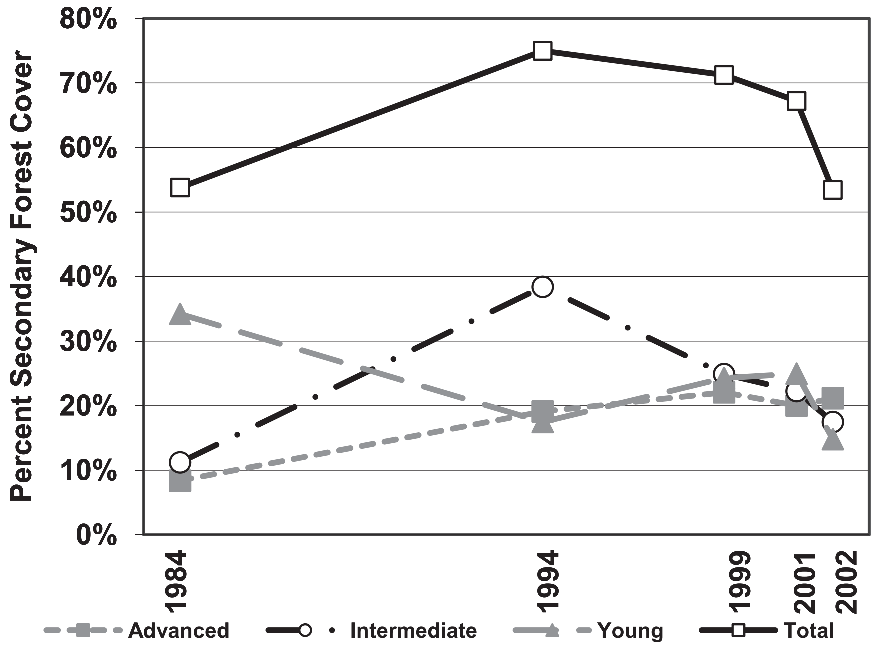

Figure 5. The percent cover of secondary forest, disaggregated into three successional stage classes from 1984 to 2002.

The "other" class shown in Figures 4 and 5 includes a wide range of cover types, such as pepper and other row crops, bare soil, some tree crops (oil palm, mangos, oranges, passion fruit, pupunha palm, papaya, and rubber), water, and clouds. Bare soil, water, and clouds are given as separate classes in Table 1. The small water class suffers from confusion with cloud shadows and fluctuates year to year because of highly variable water levels in riverine (igapó) forests. The small bare soil class is about the same as the size of the cloud and shadow classes. Depending on the time of year, the type of crop and cultivation intensity, the cultivated class could contain some bare soil leading to confusion with the bare soil class. The tree crops may also be confused with secondary forests.

Table 1. Percent area of the 8000 km^2 study region by land-cover class for five dates of Landsat data.

Class	1984	1994	1999	2001	2002
Mature forest	21.3	6.6	5.2	5.9	8.2
Advanced secondary forest	8.4	19.1	22.1	20.0	21.1
Intermediate secondary forest	11.2	38.4	24.9	22.3	17.5
Young secondary forest	34.2	17.5	24.3	25.0	14.8
Dirty pasture	9.2	8.7	10.6	5.3	7.1
Clean pasture	8.1	7.3	10.0	20.3	29.8
Soil	2.8	1.2	1.5	0.9	0.6
Water	2.1	0.2	0.5	0.4	0.2
Cloud	2.7	0.4	0.5	0.0	0.2
Shadow	0.0	0.6	0.5	0.0	0.5

Table 2. Transition matrix for area of land-cover classes (km^2) for four time periods examined (1984–94, 1994–99, 1999–2001, and 2001–02). To determine the transition, read down in the leftmost column for the land cover at the beginning of the period and then to the right in the same row to see the area found at the end of the time period in the land cover identified by the column headings. For example, there were 346 km^2 classified as mature forest in 1984 that remained classified as mature forest in 1994, and 223 km^2 classified as mature forest in 1984 and that were classified as young secondary forest in 1994.

1984–94	Mature forest	Advanced secondary forest	Intermediate secondary forest	Young secondary forest	Dirty pasture	Clean pasture	Soil	Water	Other	Sum
Mature forest	346	573	532	223	83	89	9	4	19	1877
Advanced secondary forest	80	263	217	86	39	40	5	1	9	739
Intermediate secondary forest	39	242	410	175	65	40	9	0	9	989
Young secondary forest	56	381	1385	669	291	173	40	1	21	3018
Dirty pasture	10	65	338	163	123	94	18	0	6	816
Clean pasture	21	87	261	103	84	136	9	1	11	713
Soil	5	19	97	49	38	25	12	1	4	250
Water	20	36	47	17	15	32	2	9	7	185
Other	3	18	101	57	32	19	5	0	1	236
Sum	580	1684	3388	1541	770	647	108	17	87	8822

1994–99	Mature forest	Advanced secondary forest	Intermediate secondary forest	Young secondary forest	Dirty pasture	Clean pasture	Soil	Water	Other	Sum
Mature forest	196	203	45	52	25	36	4	6	13	580
Advanced secondary forest	150	801	317	207	82	93	9	4	20	1684
Intermediate secondary forest	41	623	1187	873	315	276	40	5	28	3388
Young secondary forest	8	92	448	634	219	99	28	2	9	1541
Dirty pasture	10	61	103	228	192	142	26	3	5	770
Clean pasture	41	135	70	104	69	212	8	3	5	647
Soil	1	6	12	29	26	14	18	0	1	108
Water	1	1	0	0	0	1	0	13	1	17
Other	9	24	14	13	7	9	2	6	4	87
Sum	458	1946	2196	2142	934	881	135	44	86	8822

1999–2001	Mature forest	Advanced secondary forest	Intermediate secondary forest	Young secondary forest	Dirty pasture	Clean pasture	Soil	Water	Other	Sum
Mature forest	226	128	24	25	3	50	0	3	0	458
Advanced secondary forest	200	994	352	182	22	193	4	1	0	1946
Intermediate secondary forest	18	381	1089	498	48	152	10	1	0	2196
Young secondary forest	9	121	383	1000	136	475	17	1	0	2142
Dirty pasture	6	30	50	312	168	351	17	1	0	934
Clean pasture	37	85	44	134	45	527	7	2	0	881
Soil	1	2	4	39	37	28	24	0	0	135
Water	6	2	2	3	1	6	0	23	0	44
Other	18	23	16	10	3	9	3	5	0	86
Sum	520	1765	1963	2201	464	1790	83	36	0	8822

2001–02	Mature forest	Advanced secondary forest	Intermediate secondary forest	Young secondary forest	Dirty pasture	Clean pasture	Soil	Water	Other	Sum
Mature forest	202	160	39	23	7	80	0	2	6	520
Advanced secondary forest	277	724	306	148	36	258	3	1	12	1765
Intermediate secondary forest	106	572	659	308	53	251	5	0	9	1963
Young secondary forest	53	249	412	550	182	732	13	0	11	2201
Dirty pasture	8	23	28	80	114	196	12	0	3	464
Clean pasture	68	131	93	182	213	1082	11	1	10	1790
Soil	1	3	4	14	22	24	12	0	1	83
Water	9	4	1	1	1	7	0	9	0	36
Other	0	0	0	0	0	0	0	0	0	0
Sum	724	1866	1541	1306	627	2630	57	14	51	8822

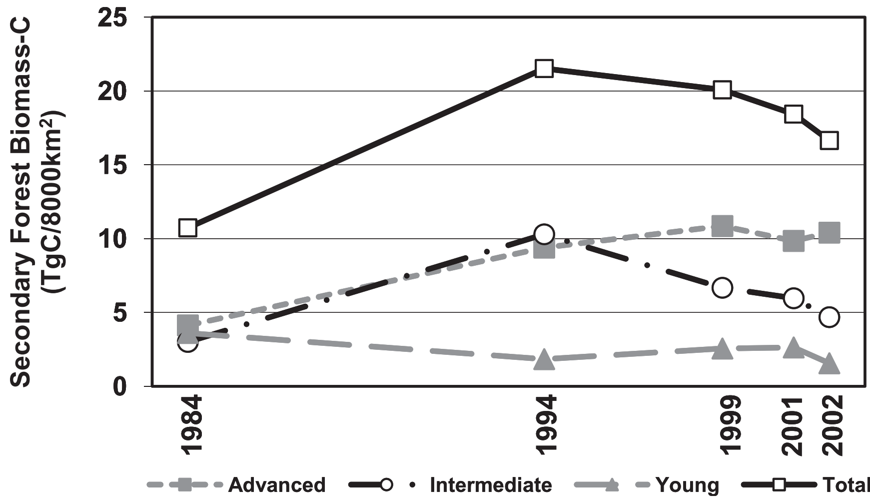

Figure 6. Estimated secondary forest biomass from 1984 to 2002 by successional stage class for the entire 8000 km^2 study area.

3.3. Carbon implications

Three studies from the Bragantina region have estimated the aboveground biomass of secondary and mature forests specific to this region (Johnson et al. 2001; Leal 2002; Vieira et al. 2003). The mean (1σ) for young, intermediate, and advanced secondary forests are 26 ($\pm$22), 67 ($\pm$19), and 123 ($\pm$4) Mg biomass per hectare, respectively. Assuming 50% carbon content and using the areal coverages for each age class shown in Figure 5, we calculated secondary forest biomass in the 8000 km^2 study area for each date (Figure 6). The secondary forest biomass increased from 1984 to 1994 as the area increased and as secondary forests aged. However, this pattern was reversed after 1994, as secondary forest biomass declined, mostly because of the loss of intermediate-aged secondary forests. The 8000 km^2 area was losing about 1.0 Tg C yr^{-1} from 1999 to 2002 because of the loss of secondary forest biomass, which is equivalent to about 1.3 Mg C ha^{-1} averaged over the entire 8000 km^2 area. The secondary forest biomass in 2002 was about equal to that present in 1984 (Figure 6), but mature forest cover also decreased from about 21% to about 8% during this period (Figure 4). Assuming an average mature forest biomass of 251 ($\pm$72) Mg ha^{-1} for this region (Johnson et al. 2001; Leal 2002; Vieira et al. 2003), the net loss of aboveground forest biomass was about 13 Tg C for the 8000 km^2 area, which is equivalent to an average loss of 0.9 Mg C ha^{-1} yr^{-1}. Whereas the average loss estimate of 1.3 Mg C ha^{-1} yr^{-1} between 1999 and 2002 due to the loss of secondary forest biomass would be subject to uncertainties of misclassifications among successional stages of forest, the average net rate of carbon loss 0.9 Mg C ha^{-1} yr^{-1} since 1984 integrates the transitions among all forest classes over the 18-yr study period.

4. Discussion

This region of eastern Amazonia, although not part of the current frontier of deforestation, nevertheless continues to lose forest cover and forest biomass. Total forest cover declined from 75% in 1984 and 62% in 2002. The net change primarily reflected a decrease in mature forest cover from 21% to 8%. Since 1999, the few remaining large patches of mature forests are private forest reserves. Although there was no net change in secondary forest cover from 1984 to 2002 (54% for both dates), secondary forest cover first increased to 75% in 1994 and then declined to 54% in 2002. Moreover, the secondary forest areas were dynamic, transitioning among young, intermediate, and mature successional stages. As noted in our earlier study of only the 1999 Landsat image (Vieira et al. 2003), occasional misclassifications occur, including confusion among the various stages of forest succession; the overall accuracy was 81% for the study of the 1999 image. Although some confusion among secondary forest classes no doubt also occurred in the multitemporal analysis of the current study, the more important point is that the sum of all types of secondary forest cover has declined substantially since 1994 (Figure 4).

The loss in total forest area was commensurate with an increase in pasture, particularly clean pasture. Brazilian federal agricultural statistics for the state of Pará (available online at http://www1.ibge.gov.br/home/estatistica/economia/agropecuaria/censoagro/2006/tabela1_3_5.pdf) show a doubling of the cattle herd within the previous 9 years, which suggests that the trend of increasing pasture area observed in our study area probably applies to much of the state. The number of cattle per hectare, a measure of land-use intensity, also more than doubled from 0.4 ha^{-1} in 1970 to 1.0 ha^{-1} in 2006. The total area of farms increased 150% since 1970 with average farm size increasing from 76 ha in 1970 to 122 ha in 2006. These trends point to recent increasing intensification in the uses of the land and perhaps some form of farm consolidation as farm size increases. Hence, land-use change remained an important process even after most of the mature forest was removed.

The average rate of carbon loss over the 18-yr study period was 0.9 Mg C ha^{-1} yr^{-1} for the 8000 km^2 study area. This rate of carbon loss is of the same order as many estimates of carbon sequestration rates in mature Amazonian forests (Hirsch et al. 2004; Malhi et al. 2004). Secondary forests are often considered potential carbon sinks, which would be the case if they were left alone to regrow. At least for this study region in eastern Amazonia, however, it appears that forests, and most recently secondary forests, are continuing to be cleared or degraded, resulting in loss of ecosystem services and carbon stocks due to continued land-use change. Policy instruments, such as Reduced Emissions from Deforestation and Degradation (REDD), and other forest conservation incentives need to consider conservation of secondary forests in regions where most of the original deforestation occurred in previous decades. This study demonstrates that this area of historic deforestation, which no longer receives the same attention as the deforestation frontier, is still losing substantial amounts of forest biomass carbon to the atmosphere as a result of continued clearing and degradation of remaining mature and secondary forests.

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References

Almeida, C. A. de, 2008: Estimativa da área e do tempo de permanência da vegetação secundária na Amazônia legal brasileira utilizando imagens Landsat/TM. Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, 129 pp.

Alves, D. S., J. V. Soares, S. Amaral, E. M. Mello, S. A. O. Almeida, O. F. Da Silva, and A. M. Silveira, 1997: Biomass of primary and secondary vegetation in Rondônia, western Brazilian Amazon. *Global Change Biol.,* **3,** 451–461.

Brook, B. W., C. J. A. Bradshaw, L. P. Koh, and N. S. Sodhi, 2006: Momentum drives the crash: Mass extinction in the tropics. *Biotropica,* **38,** 302–305.

Brown, S., and A. E. Lugo, 1992: Aboveground biomass estimates for tropical moist forests of the Brazilian Amazon. *Interciencia,* **17,** 8–27.

Campbell, J., 1987: *Introduction to Remote Sensing*. The Guilford Press, 551 pp.

Carreiras, J. M. B., J. M. C. Pereira, M. L. Campagnolo, and Y. E. Shimabukuro, 2006: Assessing the extent of agriculture/pasture and secondary succession forest in the Brazilian Legal Amazon using SPOT VEGETATION data. *Remote Sens. Environ.,* **101,** 283–298.

Chavez, P. S., Jr., 1996: Image-based atmospheric corrections—Revisited and revised. *Photogramm. Eng. Remote Sens.,* **62,** 1025–1036.

Chazdon, R., 2008: Beyond deforestation: Restoring forests and ecosystem services on degraded lands. *Science,* **320,** 1458–1460.

Costa, F. de A., and D. F. Carvalho, 2009: *Agricultura familiar em transformação no nordeste paraense: O caso de Capitão Poço*. Universidade Federal do Pará, Núcleo de Altos Estudos Amazônicos, Belém, 260 pp.

Davidson, E. A., and Coauthors, 2007: Recuperation of nitrogen cycling in Amazonian forests following agricultural abandonment. *Nature,* **447,** 995–998.

Fearnside, P. M., 2005: Deforestation in Brazilian Amazonia: History, rates, and consequences. *Conserv. Biol.,* **19,** 680–688.

——, and W. M. Guimarães, 1996: Carbon uptake by secondary forests in Brazilian Amazonia. *For. Ecol. Manage.,* **80,** 35–46.

Hirsch, A. I., W. S. Little, R. A. Houghton, N. A. Scott, and J. D. White, 2004: The net carbon flux due to deforestation and forest re-growth in the Brazilian Amazon: Analysis using a process-based model. *Global Change Biol.,* **10,** 908–924.

Hölscher, D., T. D. de A. Sá, T. X. Bastos, M. Denich, and H. Fölster, 1997: Evaporation from young secondary vegetation in eastern Amazonia. *J. Hydrol.,* **193,** 293–305.

INPE, 2008: Monitoramento da cobertura florestal da Amazônia por satélites: Sistemas prodes, deter, degrad e queimadas 2007–2008. INPE, 47 pp. [Available online at http://www.obt.inpe.br/prodes/Relatorio_Prodes2008.pdf.]

Johnson, C. M., I. C. G. Vieira, D. J. Zarin, J. Frizano, and A. H. Johnson, 2001: Carbon and nutrient storage in primary and secondary forests in eastern Amazonia. *For. Ecol. Manage.,* **147,** 245–252.

Lamb, D., P. D. Erskine, and J. Parrotta, 2005: Restoration of degraded tropical forest landscapes. *Science,* **310,** 1628–1632.

Laurance, W. F., 2007: Have we overstated the tropical biodiversity crisis? *Trends Ecol. Evol.,* **22,** 65–70.

Leal, E. C., 2002: Potencial de regeneração da capoeira após preparo de área com queima e sem queima na região Bragantina. Dissertação de Mestrado em Agricultura Familiar Pesquisa Formação e Desenvolvimento, Universidade Federal do Pará, Belém, Brasil, 121 pp.

Lillesand, T., and R. Kiefer, 1999: *Remote Sensing and Image Interpretation*. 4th ed. John Wiley and Sons, 724 pp.

Lucas, R. M., X. Xiao, S. Hagen, and S. Frolking, 2002: Evaluating TERRA-1 MODIS data for discrimination of tropical forest secondary regeneration stages in the Brazilian Legal Amazon. *Geophys. Res. Lett.,* **29,** 1200, doi:10.1029/2001GL013375.

Malhi, Y., and Coauthors, 2004: The above-ground coarse wood productivity of 104 neotropical forest plots. *Global Change Biol.,* **10,** 563–591.

——, R. Timmons, R. Betts, T. Killeen, W. Li, and C. Nobre, 2008: Climate change, deforestation and the fate of the Amazon. *Science,* **319,** 169–172.

Moran, E. F., E. S. Brondizio, P. Mausel, and Y. Wu, 1994: Integrating Amazonian vegetation, land-use, and satellite data. *Bioscience,* **44,** 329–338.

Neeff, T., R. M. Lucas, J. R. dos Santos, E. S. Brondizio, and C. C. Freitas, 2006: Area and age of secondary forests in Brazilian Amazonia 1978–2002: An empirical estimate. *Ecosystems,* **9,** 609–623.

Nepstad, D. C., P. R. S. Moutinho, and D. Markewitz, 2001: The recovery of biomass, nutrient stocks, and deep-soil functions in secondary forests. *Biogeochemistry of the Amazon Basin and its Role in a Changing World,* M. E. McClain et al., Eds., Oxford University Press, 139–155.

Powell, R. L., N. Matzke, C. de Souza, Jr., M. Clark, I. Numata, L. L. Hess, and D. A. Roberts, 2004: Sources of error in accuracy assessment of thematic land-cover maps in the Brazilian Amazon. *Remote Sens. Environ.,* **90,** 221–234.

Salimon, C. I., and I. F. Brown, 2000: Secondary forests in western Amazonia: Significant sinks for carbon released from deforestation? *Interciencia,* **25,** 198–202.

Vieira, I. C. G., R. de Paiva Salomão, N. de Araujo Rosa, D. C. Nepstad, and J. Roma, 1996: O renascimento da floresta no rastro da agricultura (The rebirth of the forest in the wake of agriculture). *Ciência Hoje,* **20,** 38–45.

——, A. S. de Almeida, E. A. Davidson, T. A. Stone, C. J. R. de Carvalho, and J. B. Guerrero, 2003: Classifying successional forests using Landsat spectral properties and ecological characteristics in eastern Amazonia. *Remote Sens. Environ.,* **87,** 470–481.