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Agricultural land-use change in Brazilian Amazônia between 1980 and 1995: Evidence from integrated satellite and census data

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Abstract

As cropland and pasture have replaced forest and cerrado in Brazilian Amazônia, concern has mounted over the effects of changing the biogeochemical and hydrological properties of one of the world's great storehouses of biomass and biodiversity. Although much recent effort has focused on the location, effects, and causes of deforestation and cerrado conversion, much less is known about the basin-wide spatial distribution and density of the land use following conversion for crops or pasture.

In this paper, we use census and satellite records to develop maps of the distribution and abundance of major agricultural land uses across 4.5×10^8 ha of Brazilian Amazônia in 1980 and 1995. Results indicate an overall expansion of 7.0×10^6 ha in total agricultural area in Brazilian Amazônia between 1980 and 1995. The net change during this period is estimated for three different land-use types: croplands (an increase of 0.8×10^6 ha), natural pastures (a decrease of 8.4×10^6 ha), and planted pastures (an increase of 14.7×10^6 ha). These estimates, the first spatially explicit quantifications of agricultural land-use activities in 1980 and 1995 across Brazilian Amazônia, are shown to be consistent with the results of applying a land use change and secondary regrowth model to published deforestation rates for the period.

The resulting time slices, presented for each land-use category at 5-min (~ 9 km) spatial resolution, allow for the quantification of land-use changes in this region for biogeochemical, demographic and economic models. Several foci of agricultural change existed within Brazilian Amazônia during this period: in the state of Pará, cropland was lost and planted pasture increased markedly; in Mato Grosso, both cropland and planted pasture increased; in Rondônia, planted pasture replacing forest was the primary route to agricultural expansion.

Keywords: Brazil; Amazon; Tocantins; Land use; Land cover; Agriculture; Census; Deforestation; Crop; Pasture

1. Introduction

Understanding change in land use and land cover has been identified as a key research theme of the Large-scale Biosphere–Atmosphere Experiment in Amazônia (LBA), because changes in the land surface can affect energy, water, carbon, and trace gas and nutrient cycles in the region (Nobre et al., 1997). Through its focus on the key question of the effects of human activity upon the region, the LBA project has provided the scientific community with an excellent opportunity to begin to uncover the causes and consequences of land-use change, as well as the corresponding patterns of human activity in Brazilian Amazônia.

Beginning with the interpretation of Landsat data for the Legal Amazon in Brazil (Instituto Nacional de Pesquisas Espaciais, 2000; Skole & Tucker, 1993) and the rest of the Amazon Basin (Global Land Cover Facility, 1998) for the 1980s, researchers first quantified the location and amount of deforestation, which is a precursor of agricultural activity in many areas. In recent years, a new set of satellite-based land-cover products (Belward & Loveland, 1996; Hansen, Defries, Townshend, & Sohlberg, 2000; Saatchi, Nelson, Podest, & Holt, 2000) has further augmented our understanding of the earth's surface in Amazônia. Efforts to understand the effects of land-cover conversion have indicated significant changes: in addition to large changes in biomass (e.g., Guild, Kauffman, Ellingson, Cummings, & Castro, 1998), conversion can affect hydrological (Williams & Melack, 1997) and biogeochemical processes (Brown & Lugo, 1990; Holscher, Ludwig, Moller, & Folster, 1997).

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While the rates of forest clearing have been carefully examined across Amazônia, less is known about the fate of land that has been converted to human use. Most of our understanding of agricultural land use in Brazilian Amazônia comes from comprehensive, site-specific studies (e.g., Dale, O'Neill, Pedlowski, & Southworth, 1993; Moran & Brondizio, 1998; Moran, Brondizio, Mausel, & Wu, 1994; Moran, Packer, Brondizio, & Tucker, 1996; Walker, Moran, & Anselin, 2000), and there have also been useful estimates of whole-basin activities and trends (Fearnside, 1996; Houghton, 1990; Houghton et al., 2000). An additional little-used source of land-use information is census data, which has recently been explored for its relationship to remotely sensed imagery (Imhoff et al., 1997; Lo & Faber, 1997; Radeloff, Hagen, Voss, Field, & Mladenoff, 2000; Wright & Boag, 1994). With the notable exception of a study of the correlation between deforestation rates and socioeconomic and demographic variables (Wood & Skole, 1998), most applications of census data cover much less area than that of Brazilian Amazônia.

The distribution, abundance, and types of land use, as distinct from land cover, are also important to understand in Brazilian Amazônia. In a comprehensive review of Amazônian soils, the pH, total C, and total N in soils growing annual crops differed from soils supporting pasture (McGrath, Smith, Gholz, & Oliveira, 2001), perhaps because pastures are typically not cultivated (Houghton, 1991).

Perhaps the most compelling reason to monitor land-use change as well as land cover is the strong effect of land-use history on the state and fate of converted areas: lands covered with natural pasture, planted pasture, or crops can mask strikingly different histories of intensity and duration of use. In planted pastures, the aboveground biomass and nutrient pools change over time as residual products from initial fires are reburned while the pasture is in use (Kauffman, Cummings, & Ward, 1998); in natural pastures, these long-lasting woody products are not present and thus do not influence biogeochemical cycles. On agricultural land that is later abandoned, regrowth rates on former croplands differ from rates on former pasture (Moran et al., 2000). Among abandoned pastures, differences in fire frequency, management treatment, and land-use duration strongly affect the rate of regrowth (Buschbacher, Uhl, & Serrao, 1988; Nepstad, Uhl, Pereira, & daSilva, 1996; Nepstad, Uhl, & Serrao, 1991; Tucker, Brondizio, & Moran, 1998; Uhl, Buschbacher, & Serrao, 1988). Regrowth rates also vary strongly by soil fertility (Moran et al., 2000), and thus broad-scale estimates of carbon uptake from regrowth would benefit from a spatially explicit partition of agricultural land-use area into land used for cropland and that used for natural and planted pasture.

These effects illustrate the imperative for a spatially explicit time series of agricultural land use—including representations of deforestation, farming practices, shifting cultivation patterns, and abandonment—across the entirety of Brazilian Amazônia. Such a time series would provide modelers with a baseline from which to make more educated assumptions about likely land-use histories and conditions in an area, while facilitating stronger projections of biomass recuperation, hydrological patterns, and future likely land-use scenarios.

Unfortunately, it does not appear possible to create such a land-use data set using only satellite data. Because they sense reflectance values, satellite products in the tropics are best suited to include only categories of land cover (e.g., Saatchi et al., 2000; Skole & Tucker, 1993) or of land cover with, perhaps, tropical cropland included (e.g., Belward & Loveland, 1996; Hansen et al., 2000). The challenge of correctly identifying land use from satellites, however, is well known and some products have acknowledged understandable difficulty in separating crops from natural phenologies (Hansen et al., 2000).

In this study, we examine changes in broad-scale patterns of major agricultural land-use practices in Brazilian Amazônia between 1980 and 1995. Building on previous work integrating census and satellite data to create a new statistically fused data set for 1995, we use census-derived information to estimate agricultural activities 15 years earlier. We present the density of cropland, natural pasture, and planted pasture at 5-min (~ 9 km) spatial resolution, explain the relationship between these snapshots of land use and deforestation rates, and investigate several areas witnessing dramatic change during the period.

2. Study area

Our work in Amazônia focuses on the area within the hydrological borders of the Amazon and Tocantins river drainage basins, as derived and presented in Costa et al. (in press). Because the area is defined hydrologically we are able to use it to address, for example, questions of river discharge amount and timing that cross national political borders. Since land-use processes and actors are more tied to individual nations than are ecological processes (e.g., migrants can pass more easily within a country than between countries), and since agricultural processes have been more thoroughly studied in Brazil than in neighboring countries, we selected the subset of that region within the political borders of Brazil for this study (Fig. 1). This includes more than 80% of the Brazilian Legal Amazon, which has been studied closely during this period (e.g., Skole & Tucker, 1993). The study area is comprised of the entirety of the states of Acre, Amazonas, Rondônia, Roraima, and Tocantins; in addition to these states, those parts of Goiás, Pará, and Mato Grosso within the hydrological borders are included, as are small portions of Amapá and Maranhão. The study basin covers 4.5×10^8 ha.

Although land conversion for agriculture in this region has garnered world attention since the 1980s, there is a long history of cattle ranching in Brazilian Amazônia. Cattle

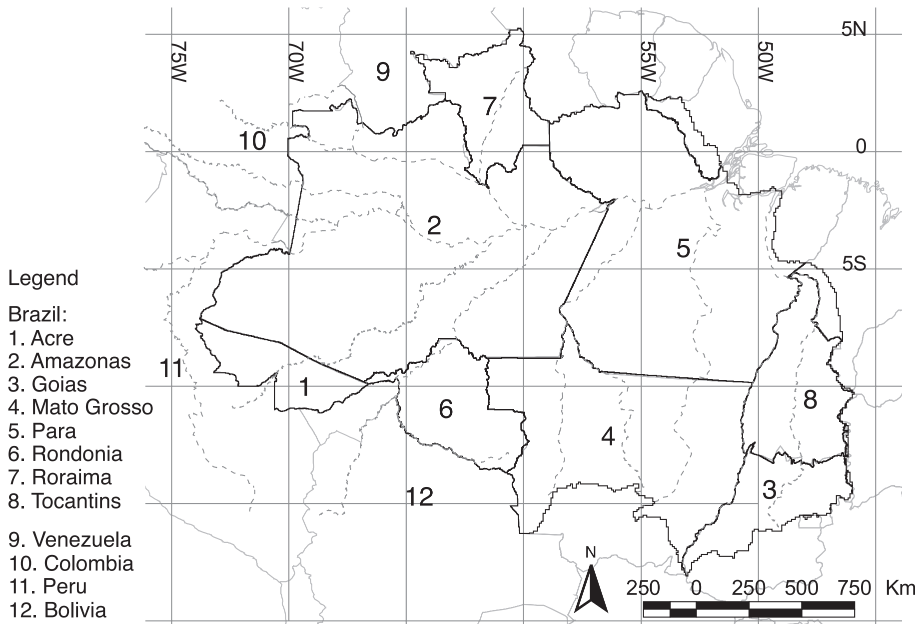

Fig. 1. Major administrative boundaries in the Amazon and Tocantins river drainage basins.

were in Belém in the 1600s (Smith, 1999), and the eastern portion of Brazilian Amazônia, along the Tocantins and Araguaia Rivers, was already known by 1950 as the cattle center of the region (International Association of Agricultural Economists, 1969). At that time, more than 13 million hectares of grazing land were estimated (Fundação Instituto Brasileiro de Geografia e Estatística, 1956) within the old state of Goiás, which also encompassed the state now known as Tocantins until 1988. Even greater land conversion for agriculture began with the building of the Belém-Brasilia highway in 1958; pasture replaced savannas, scrub forest, and tropical deciduous forests to such an extent that the number of cattle increased to 5 million by the 1980s (Mahar & World Bank, 1989; Moran et al., 1994). Deforestation for crops and pasture increased dramatically during the last decades of the 20th century: satellite records indicate that 90% of the deforested area in 1988 was created after 1970 (Skole, Chomentowski, Salas, & Nobre, 1994).

In central Amazônia, large-scale land conversion has been much more recent than in eastern Amazônia. Following the improvement of the unpaved road BR 364 in Rondônia in 1970, for example, incentives to colonization were established and a "continuous flow" of pioneer families began shortly thereafter (Martine, 1980). The net result was a seven-fold increase in agricultural area within the state between 1970 and 1980 (Fundação Instituto Brasileiro de Geografia e Estatística, 1974, 1983).

3. Methods

In (Cardille, Foley, & Costa, 2002), we presented the results of combining two different types of data for the entire Amazon and Tocantins river drainage basins: 1990s land-cover information from the Global Land Cover Facility at the University of Maryland (Hansen et al., 2000) and land-use information from near-contemporary agricultural census data. Here we summarize only the most important components of data fusion to provide background for the reader. For a more detailed discussion see Cardille et al. (2002).

Beginning with mid-1990s agricultural census data from both Peru and Brazil, we first created *municipio*-level maps of the three major categories of agricultural land-use activity: cropland, natural pasture, and planted pasture. For the cropland category, basic census variables (the planted area of annual and perennial crops, temporarily fallow area associated with cropland, and land harvested but not yet replanted) were summed in each *municipio*. We similarly extracted each administrative unit's amount of natural pasture, those areas "covered by pastures which have grown by natural means," (Instituto Nacional de Estadística e Informática, 1996), as well as planted pasture, those areas "dedicated for grazing and formed through planting" (Fundação Instituto Brasileiro de Geografia e Estatística, 1997). Although it is difficult to quantify the quality of census data over the vast area of Brazilian Amazônia, these particular variables are believed by census officials to be among the most reliable in agricultural censuses. In particular, the relatively strong funding of the 1995 Brazilian agricultural census increased the reliability of the reported values, since more agricultural units were directly sampled than in previous censuses (Fundação Instituto Brasileiro de Geografia e Estatística, 2001).

To understand the link between census-based land-use and satellite-derived land-cover information, we investigated global land-cover maps from the early 1990s in this region. Produced from monthly values of the Normalized Difference Vegetation Index and reflectance values from AVHRR channels for 1992–1993, the University of Maryland (UMD) land-cover classification used decision tree analysis to categorize the land cover of each 1-km pixel on the earth's surface. Although not rigorously validated (Hansen & Reed, 2000), the UMD classification and similar IGBP DISCover classification (Belward & Loveland, 1996) provided crucial new spatial and thematic information about the Amazon and Tocantins basins during this period of rapid land-use change.

Designed to identify land cover not land use, the UMD and IGBP DISCover land-cover classifications nevertheless appeared on visual inspection to be closely related to information derived from the nearly contemporary agricultural census data from Peru and Brazil (Cardille et al., 2002). The idea that there might be a systematic relationship between satellite-derived land-cover categories and important ground-censused agricultural land-use activities suggested a statistical blending that could distribute agricultural land-use activity into those areas likely being used for cropland and pasture.

After a series of tests indicated that the UMD product was more closely related to census data than was the IGBP DISCover classification (Cardille, 2002; Cardille et al., 2002), we generated a regression tree that statistically linked the census and UMD product. Unlike a simple renaming of, for example, the wooded grassland category to be planted pasture, the regression-tree-based technique determined the statistical relationship of agricultural density and the fraction of each of 12 categories within reporting polygon-based census units. The method produced a new statistically fused data set, at 5-min (~ 9 km) spatial resolution (Fig. 2, right), combining much of the spatial detail of the satellite information with the attribute detail collected only in ground-based agricultural censuses. Based on this analysis, fitted cropland positively correlates with UMD classes for wooded grassland (0.81), woodland (0.52), cropland (0.30) and grassland (0.26) and is negatively correlated with the presence of evergreen broadleaf forest (– 0.81, Table 1). Considering the physical attributes of these land-cover classes, these statistical relationships make sense.

Table 1
Correlation between fitted cropland-pasture data and the UMD classification

Land cover category	Correlation
Bare ground	0.05
Closed shrubland	0.05
Cropland	0.30
Deciduous broadleaf forest	0.01
Evergreen broadleaf forest	– 0.81
Evergreen needleleaf forest	0.06
Grassland	0.26
Mixed forest	0.00
Open shrubland	0.07
Water	– 0.12
Wooded grassland	0.81
Woodland	0.52

For each 5-min cell, the fraction of each classified land cover type was calculated and compared with the fused data (modified from Cardille et al., 2002).

By partitioning the merged data set using the relative proportions of cropland, natural pasture, and planted pasture reported in each administrative unit in the agricultural censuses, we produced maps showing, for the first time, the density of each of these major agricultural land uses across all of Amazônia for 1995. These results have been seen to be consistent with both the original census data and with satellite imagery collected on independent platforms (Cardille, 2002; Cardille et al., 2002).

For this analysis, we developed maps representing 1980 Amazônian agricultural density using a combination of the 1995 total agriculture map and the 1980 and 1995 Brazilian agricultural censuses (Fundação Instituto Brasileiro de Geografia e Estatística, 1983, 1997). For each state, we deter-

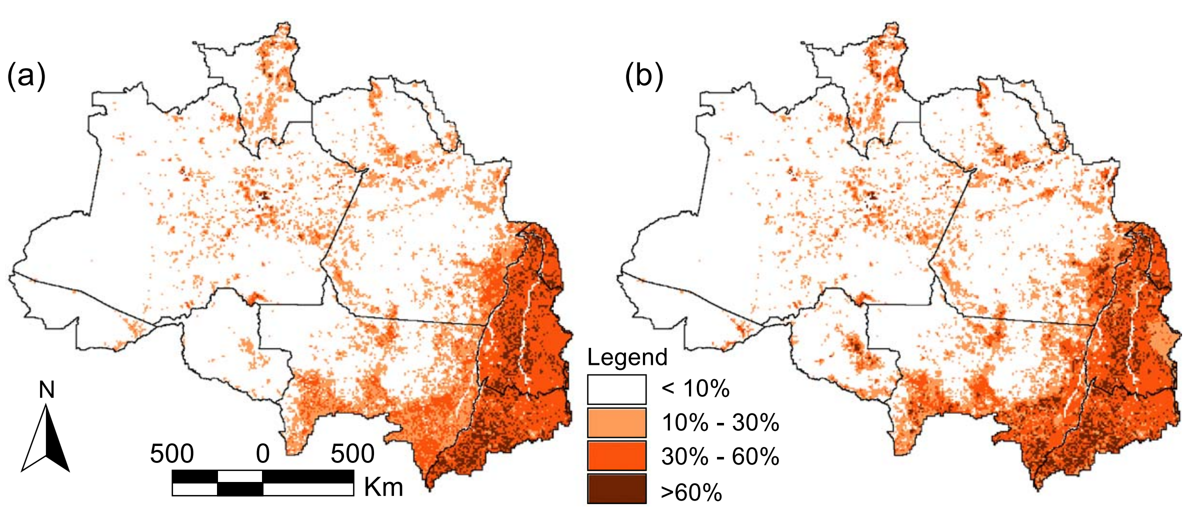

Fig. 2. Total agricultural land use in Brazilian Amazônia for (a) 1980 and (b) 1995, derived from fused satellite and agricultural census data.

mined the ratio between the total agricultural area (the sum of the area used for annual crops, perennial crops, fallow land, natural pasture, and planted pasture) from the 1995 census and the same quantity from the 1980 census. This formed a set of per-state multiplicative factors representing the estimated ratio of total agricultural area between 1980 and 1995. The value for 1995 agricultural density in each 5-min grid cell in Brazilian Amazônia was multiplied by its state's factor to create a map of the density of agriculture in 1980. The total agricultural area in each cell was then apportioned according to the relative amounts of cropland, of natural pasture, and of planted pasture in its state in the 1980 Brazilian agricultural census.

4. Spatial patterns of Brazilian agricultural land use in 1980 and 1995

Between 1980 and 1995, there was net increase of 7.0×10^6 ha in total agricultural land in Brazilian Amazônia (Fig. 2, Tables 2 and 3)—including all of the changes in cropland, natural pastures, and planted pastures. These results indicate a basin-wide annual net increase in total agricultural area during the period of about 1%. Results ranged from a 6% decrease of total agricultural area in Tocantins and Goiás to a near 300% increase in Rondônia.

Using the major land use categories described in the agricultural census data, we can break down these basin-wide net changes in agricultural land into their three components: changes in cropland, natural pasture, and planted pasture density between 1980 and 1995. Our results indicate that total cropland within the basin grew by 0.80×10^6 ha, though cropland was lost in some areas and gained in others (Fig. 3a, Table 3). The increase in total agriculture during the period was driven by a major expansion in the area of planted pasture, which rose, by a total of 14.6×10^6 ha, nearly everywhere in the basin during this period (Fig. 3c, Table 3). Much of this gain in planted pasture was offset by a decrease (8.4×10^6 ha) in natural pasture during the period (Fig. 3b, Table 3). Though the changes of natural and planted pasture relate in tandem to the amount of cattle-based activity in Brazilian Amazônia, it is important to distinguish the processes that form them: it is assumed here that most natural pastures are established from and abandoned to grasslands or savannas (cerrado), while most planted pastures are established in former forests. As a result, changes in the amount of natural pasture are probably not linked to the deforestation process, while changes in planted pasture are directly tied to patterns of forest clearing and secondary regrowth.

Table 2
Estimated area of cropland, natural pasture, and planted pasture for states within Brazilian Amazônia in 1980

	Cropland (ha)	Natural pasture (ha)	Planted pasture (ha)	Total agriculture (ha)
Brazilian Amazônia Total[a]	9,006,524	25,063,771	14,652,252	48,722,548
Acre	72,042	37,299	111,552	220,894
Amazonas	3,091,519	1,564,733	1,125,144	5,781,396
Goiás[b]	1,185,055	6,217,028	3,333,915	10,735,999
Mato Grosso[b]	1,047,464	5,708,206	2,655,829	9,411,499
Pará[b]	1,842,684	1,770,965	2,874,391	6,488,039
Rondônia	196,612	115,623	243,034	555,270
Roraima	74,555	1,798,499	98,020	1,971,074
Tocantins	1,496,593	7,851,419	4,210,366	13,558,378

As described in the text, fused satellite and census data for the mid-1990s was scaled backward in time based on the ratio of 1980 and 1995 Brazilian agricultural census data.

[a] Totals for Brazilian Amazônia do not include Maranhão, Piaui, or Amapá, which have a very small amount of area within the Tocantins basin.

[b] Totals for these states include only that area within the Amazon and/or Tocantins River drainage basins.

Table 3
Change between 1980 and 1995 in the area of cropland, natural pasture, and planted pasture for states within Brazilian Amazônia

	Cropland change (ha)	Natural pasture change (ha)	Planted pasture change (ha)	Total agriculture change (ha)	1995 Total Ag/1985 Total Ag
Brazilian Amazônia Total[a]	802,826	− 8,427,505	14,661,200	7,036,521	1.14
Acre	10,800	7,586	168,360	186,747	1.85
Amazonas	796,471	− 395,751	− 527,738	− 127,017	0.98
Goiás[b]	− 635,735	− 3,227,322	3,260,525	− 602,531	0.94
Mato Grosso[b]	1,413,592	− 2,769,445	6,028,897	4,673,043	1.50
Pará[b]	− 249,912	− 414,207	3,195,217	2,531,099	1.39
Rondônia	16,970	99,829	956,958	1,073,757	2.93
Roraima	209,151	− 846,980	700,272	62,443	1.03
Tocantins	− 758,510	− 881,217	878,709	− 761,019	0.94

[a] Totals for Brazilian Amazônia do not include Maranhão, Piaui, or Amapá, which have a very small amount of area within the Tocantins basin.

[b] Totals for these states include only that area within the Amazon and/or Tocantins River drainage basins.

5. Agricultural land-use and deforestation rates

Since deforestation precedes the establishment of much of the new agriculture in this region (especially for planted pastures and croplands), we investigated the relationship between observed deforestation rates and our estimates of land-use change in Brazilian Amazônia. Although these methods of understanding human activity do not measure exactly the same quantities—unlike satellite-based measurements of deforestation rates, our estimates of agricultural activity depict changes in land use, rather than changes in land cover—we expected that they should be closely related. Yet despite tens of millions of hectares of deforestation in the Legal Amazon between 1980 and 1995 (Houghton et al., 2000), we estimate a net increase during that time of only 7.04 M ha in active agriculture. Although at first glance

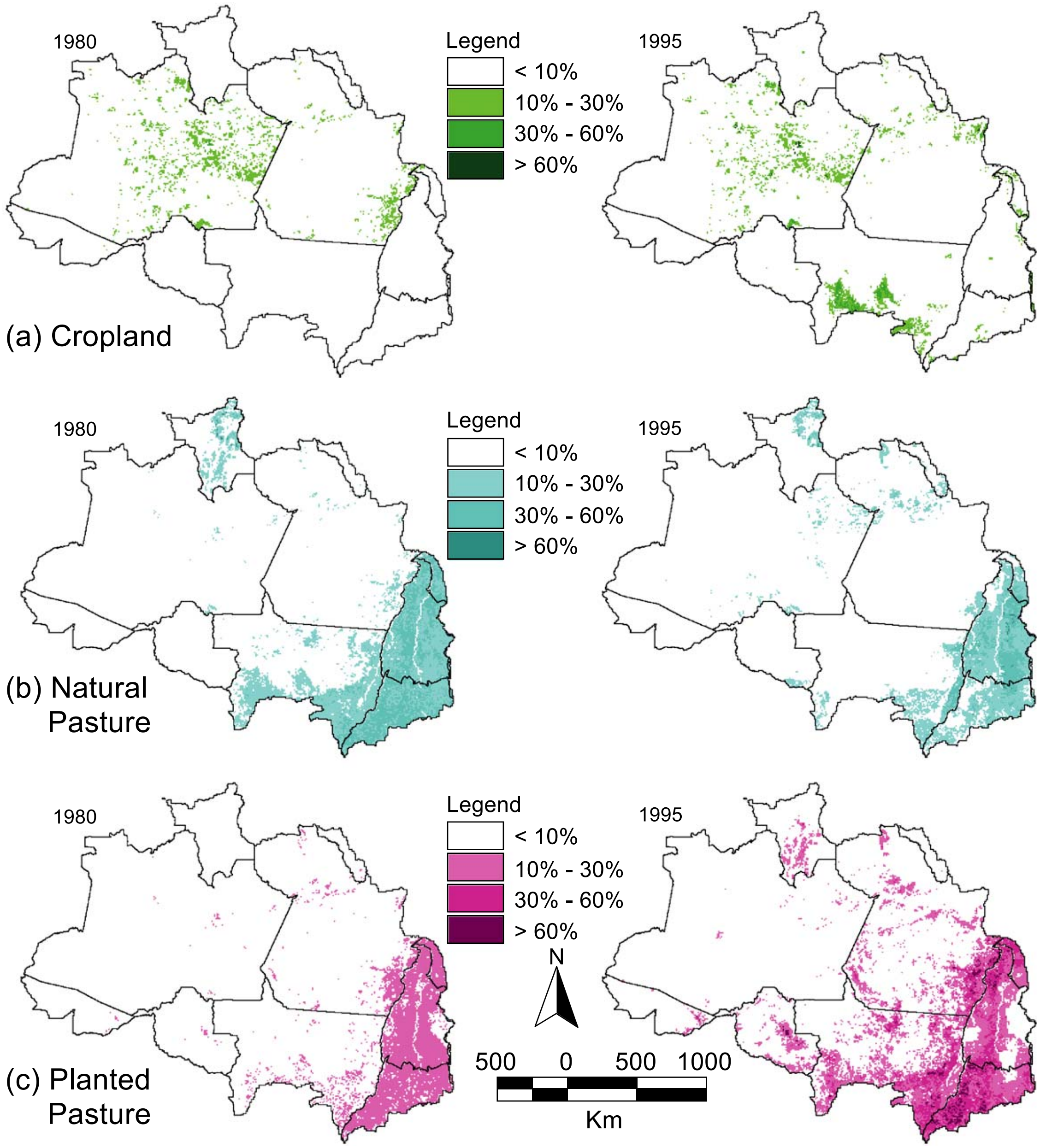

Fig. 3. Comparison of (a) cropland, (b) natural pasture, and (c) planted pasture for Brazilian Amazônia in 1980 (left) and 1995 (right).

this discrepancy appears large, a closer look reveals that these measures are actually quite compatible, and their relationship highlights important questions about the interactions among land use, land cover, and regrowth. Several factors account for the difference, including our study region, which includes areas outside of the legal Amazon where deforestation is typically estimated, natural pasture, which is reported as a large loss in agriculture (thus reducing the area of active pasture in 1995), and pasture abandonment to second growth. When these factors are taken into account, our estimates fall between the widely published values from INPE and the Tropical Rainforest Information Center (Houghton et al., 2000). To illustrate, a more detailed discussion is included in the remainder of this section.

5.1. Deforestation between 1980 and 1995 in the adjusted study area

To understand the relationship between published deforestation rates and estimated agricultural change, it is first necessary to determine the intersection of our study area (Fig. 1) with the borders of the Legal Amazon, for which deforestation rates are reported. The area of intersection encompasses the entire states of Acre, Amazonas, Rondônia, Roraima, and Tocantins, as well as 84% of Pará and 78% of Mato Grosso. (The portions of the states of Amapá and Maranhão within the Amazon and Tocantins basins, though part of the Legal Amazon, were small and therefore excluded from being considered part of the intersecting area.) Goiás, though part of our study region, is not part of the Legal Amazon and thus land-use change there was not comparable to published deforestation rates. The resulting intersecting analysis area covers 82% of the Legal Amazon, and can be compared to that part of Tables 2 and 3 with Goiás removed.

To estimate the amount of deforestation reported in this adjusted study area, we totaled the observed rates of deforestation in (Houghton et al., 2000) for the 15 years between 1980 and 1995. By summing the INPE estimates of the annual amount of deforestation reported in the intersecting study area (e.g., the full deforestation amount from Acre, 84% of the deforestation amount reported for Pará, etc.), we estimate that 25.32 M ha in this region were deforested between 1980 and 1995. Houghton et al. emphasize that deforestation rates are somewhat uncertain, noting that rates derived at the Tropical Rain Forest Information Center (TRFIC) were systematically 73% of those produced at INPE; an estimate based on TRFIC analysis within this region, then, is 18.49 M ha of deforestation.

5.2. Land-use change estimates

Our estimates of total agriculture change in Brazilian Amazônia between 1980 and 1995 include cropland increase, loss of natural pasture, and increase in planted pasture (Table 3). In order to relate these changes to land-use patterns suggested by observations of deforestation, we needed to understand the relationship of changes in each category to the recorded loss of forest area during this period.

Unlike the increase in planted pasture and cropland, losses in natural pasture were probably not closely related to deforestation activities. Defined in the Brazilian agricultural census as "areas dedicated to cattle grazing that were not planted, although they could have received some sort of agricultural treatment [such as fertilization]" (Fundação Instituto Brasileiro de Geografia e Estatística, 1997), the natural pasture category is most likely cerrado used to support the vast increase in cattle during the period. Though some natural pasture may have been converted to cropland (for example in Mato Grosso), we assumed that the loss of natural pasture estimated during this period (Table 3) was due to the abandonment of formerly used lands to degraded pasture. Given that abandoned natural pasture is extremely unlikely to support regrowing forest, it is inappropriate to include losses of this category in calculations of deforestation rates. Therefore, when estimating these rates, we focused strictly on the relationship between changes in cropland, planted pasture and deforestation.

To estimate the change in cropland and planted pasture within the adjusted study area, we extracted the change in these quantities for all states in Table 3 except Goiás, which was not part of the Legal Amazon. Our methods estimate that of the land deforested in this region between 1980 and 1995, 12.84 M ha were still actively used as either cropland or pasture in 1995.

5.3. Fate of land deforested between 1980 and 1995

To compare that estimated amount of deforestation with our net change in cropland and planted pasture, we needed to estimate the eventual fate of land after conversion. Land deforested in Brazilian Amazônia can later undergo a wide array of transitions among uses in which a typical parcel of land might be deforested for cropland, then converted to planted pasture, then reburned for planted pasture every few years, either purposely or accidentally (Cochrane et al., 1999; Fearnside, 1990; Guild et al., 1998; Nepstad et al., 1991). As a result of these land-use transitions over time, a complex mosaic has emerged of active cropland and pasture, as well as regrowing forest of various ages and land-use histories (Moran et al., 2000, 1996; Uhl et al., 1988). Developing methods to understand the locations and impact of regrowing forest has been a subject of increasing scrutiny in recent years (Alves et al., 1997; Coomes, Grimard, & Burt, 2000; de Carmargo et al., 1999; Houghton, 1995; Steininger, 2000a,b; Tucker et al., 1998; Zarin, Ducey, Tucker, & Salas, 2001). Understanding the connection between deforestation and agricultural land-use change between 1980 and 1995 can be aided by estimating the fate of deforested land as it was converted, regrown, and reconverted, transitioning among land uses and sometimes becoming regrowing forest during the intervening years.

To better understand the complex interactions in Amazônia among agricultural land-use types, Fearnside (1996) developed a Markov model of agricultural land use in Brazilian Amazônia for this period. Populated with transition rates derived from site studies in Eastern Pará and Rondônia, the model specified rates of major land-use changes over time in Amazônia in the 1980s and 1990s—for example, the rate of conversion of recently deforested land into cropland and pasture, the likelihood that cropland will be converted for pasture use, that pasture will become regrowing forest, and that regrowing forest will later be re-used for pasture.

We applied the Fearnside model to the annual study area-adjusted amounts of deforestation from (Houghton et al., 2000) in order to estimate the net change in cropland, pasture, and regrowing forest resulting from deforestation between 1980 and 1995. We tracked the area-adjusted amount of each year's deforested land as an annual cohort, allowing its area to move among various land uses and regrowing forest between the year of deforestation and 1995, following the specified annual transition rates. Because each year's estimate of deforested amount was tracked separately, the oldest cohorts were nearest to the equilibrium estimates by 1995, while young cohorts were still relatively similar to their conditions at the time of deforestation at the end of the study period. Following Fearnside, we assumed that land-use transition probabilities did not change across the study area between 1980 and 1995, an assumption that is undoubtedly too simple but can be used to estimate the approximate fraction of regrowing forest during the period.

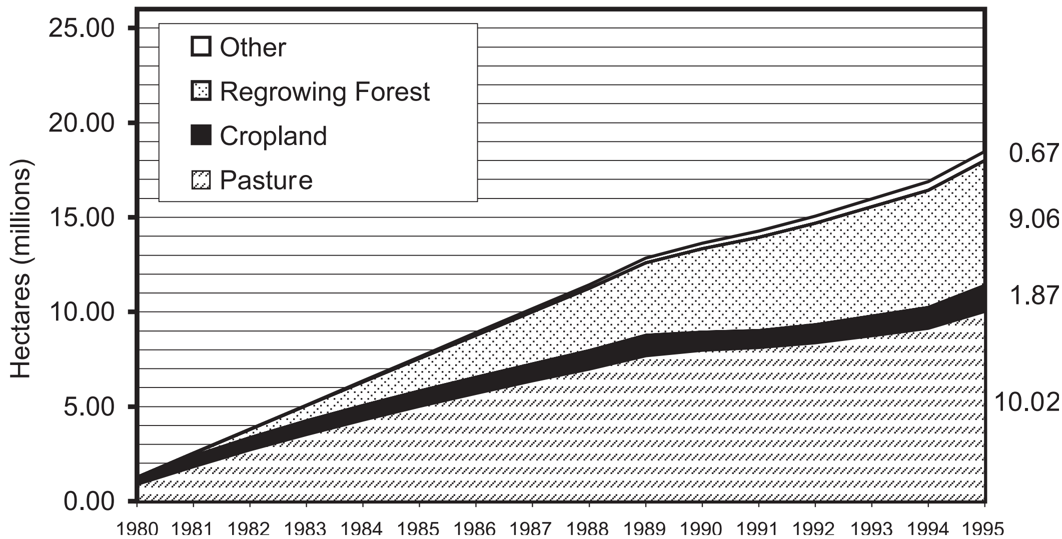

Fig. 4. Fate of deforested land in Brazilian Amazônia, 1980–1995 using the model of Fearnside (1996) and deforestation rates from Houghton et al. (2000). According to the model, 36% of the land deforested in this period was regrowing forest in 1995.

Using the Fearnside annual transition probabilities and the annual INPE estimates of deforestation within the adjusted study area, we estimate that of the 25.32 M ha deforested between 1980 and 1995, 7% (1.87×10^6 ha) was in cropland in 1995, 54% (13.73×10^6 ha) was active pasture, 36% (9.06×10^6 ha) was regrowing forest, and 0.67×10^6 ha was degraded land (Fig. 4). Using the TRFIC estimates of 18.49 M ha deforested in this adjusted study area, these amounts are 1.36×10^6 ha cropland, 10.02×10^6 ha active pasture, 6.61×10^6 ha regrowing forest, and 0.49×10^6 ha degraded land.

This ratio of secondary growth to initial clearing (0.36) is consistent with Lucas, Xiao, Hagen, and Frolking (2002), who estimated that between 31% and 37% of deforested land across the Legal Amazon had reverted to some stage of regrowth by the early 1990s. In its estimate that 25% of deforested area was regrowing forest in 1986, the model is also consistent with the 1986 Landsat-derived land-cover classification used by Houghton et al. (2000), who found that about 30% of the deforested area was regrowing at that time.

5.4. Comparison of deforestation and land-use change estimates

Within the adjusted study area, we can compare our changes in cropland and planted pasture to the amount of active cropland and pasture estimated independently by the published deforestation rates and subsequent land-use change. As calculated above, the estimated increase in cropland and pasture from our analyses of the census and satellite records is 12.84 M ha between 1980 and 1995. This

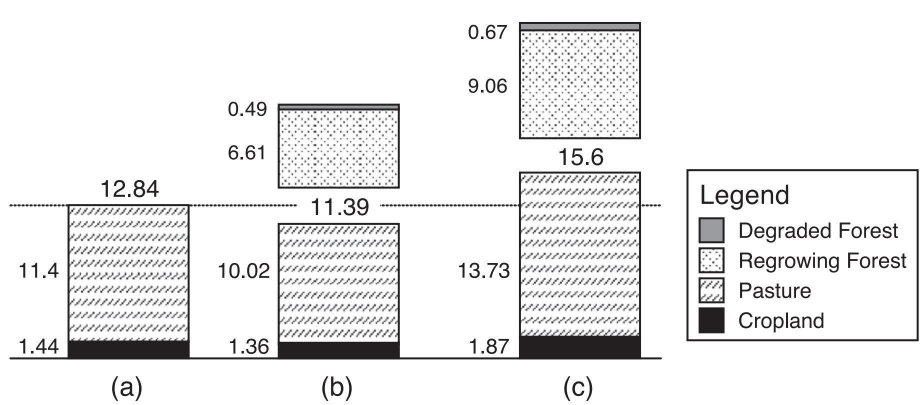

Fig. 5. Three estimates (in millions of hectares) of cropland and planted pasture increase between 1980 and 1995 in part of Brazilian Amazônia. Part (a) estimates a total agricultural increase on deforested land of 12.84×10^6 ha, estimated from a fusion of agricultural census and satellite data. Deforestation rates for the period from Houghton et al. (2000) were applied to the land use change model of Fearnside (1996) to estimate regrowing forest, degraded forest, and active cropland and planted pasture during the period. The amounts estimated through the fusion of census and satellite data agreed best with the rates developed at the Tropical Rain Forest Information Center (TRFIC); the amount of active agriculture in the two approaches (a,b) differed by less than 15%. The census-driven estimate was between the amount of cropland and pasture predicted using TRFIC (b) and INPE (c) deforestation rates.

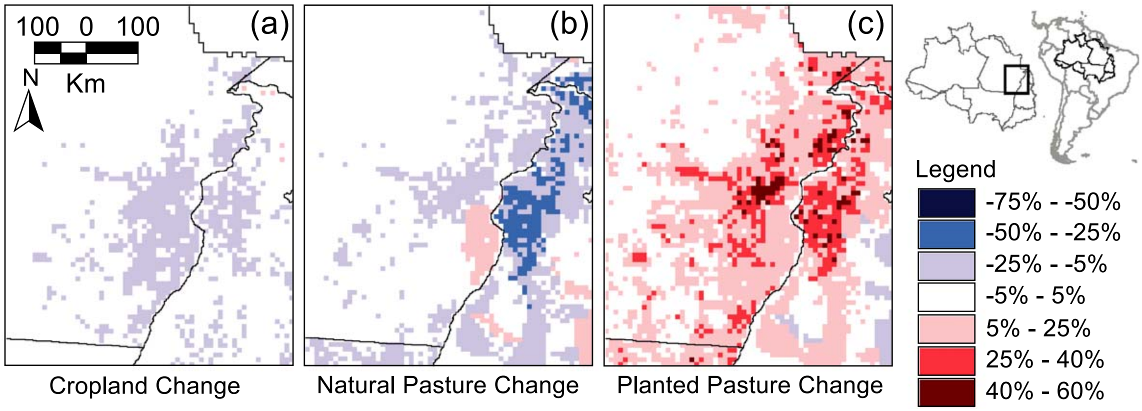

Fig. 6. Land use changes in Eastern Pará and Northern Tocantins between 1980 and 1995. This region saw a decrease in cropland (a), a larger decrease in natural pasture (b), and a very large increase in planted pasture (c) during the period. In this figure, loss/gain figures indicate a percent of each 5-min (~ 9 × 9 km) cell that changed. Thus, a change of +20% in a given grid cell represents about $0.20 \times 9 \times 9$ km = 16.2 km^2.

value is consistent with the values obtained by tracking annual INPE and TRFIC deforestation estimates through stages of cropland, planted pasture, regrowth, and re-establishment (Fig. 5). Our estimate is situated between 11.39 and 15.60 M ha, the modeled amounts of cropland and planted pasture in 1995 derived from, respectively, TRFIC and INPE deforestation rates. Additionally, the two methods agree on the portion of that increase that is due to cropland: in our method, 11% (1.44/12.84 M ha) was due to cropland expansion; in the land-use change model, 12% of the increase was due to the increase in cropland.

Though this model assumes probabilities of land-use change that were constant across space and fixed in time, it provides a key link in understanding the relationship between the static land-use maps presented here and published rates of deforestation measured annually during the study period. Although simple, this model does suggest that these maps are consistent with deforestation rates over this period in Brazilian Amazônia. More complex future analyses, perhaps with drivers varying over time and space, may help to refine our understanding of these relationships even further.

6. Eastern Pará

Though the maps indicate an increase in agricultural area, there are three distinct regions of major land-use change in Brazilian Amazônia between 1980 and 1995: Eastern Pará, Mato Grosso, and Rondônia. These regions revealed substantially different net land-use changes during this time period, and are highlighted in detail in following three sections.

Eastern Pará and Northern Tocantins experienced a dramatic increase in planted pasture between 1980 and 1995 (Table 3, Fig. 6), a continuation of the trend seen in the rest of Tocantins in earlier decades. Notably, the same regions of Eastern Pará and Northern Tocantins experiencing the increase in planted pasture saw a decrease in the amount of cropland and natural pasture (Fig. 6). The combined census and satellite products for this period indicate a significant increase in agricultural activity across much of Eastern Pará. These results are consistent with observations that the land-use dynamic during this time favored the conversion of cropland, after several growing seasons, to planted pasture (Fearnside, 1996). Land formerly

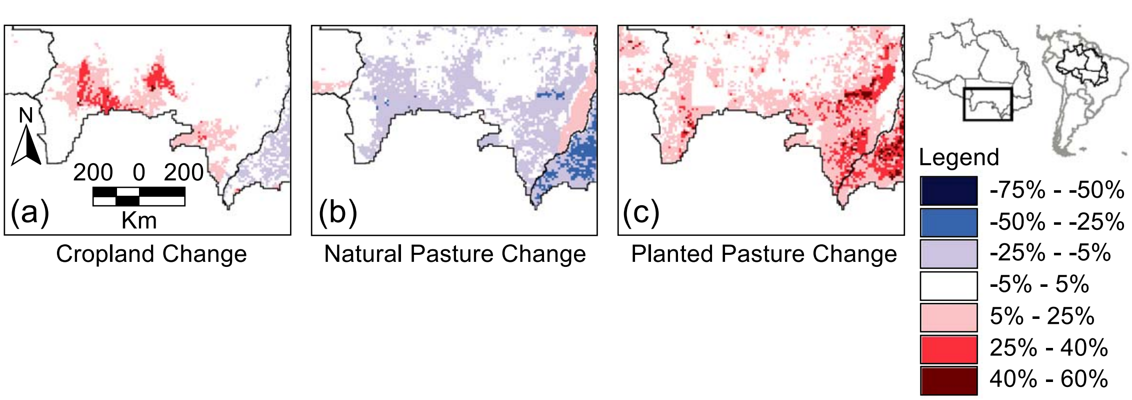

Fig. 7. Agricultural land use change in Mato Grosso between 1980 and 1995. This region saw a large increase in cropland (a), a decrease in natural pasture (b), and a very large increase in planted pasture (c) during the period. In this figure, loss/gain figures indicate a percent of each 5-min (~ 9 × 9 km) cell that changed. Thus, a change of +20% in a given grid cell represents about $0.20 \times 9 \times 9$ km = 16.2 km^2.

used for annual crops was typically sold or otherwise transferred to the control of large- or medium-size ranchers (Fearnside, 1993), who planted pasture grasses after cutting and burning in the area (Uhl et al., 1988).

7. Mato Grosso

Mato Grosso showed a 50% increase in total agricultural area (Table 3, Fig. 7) between 1980 and 1995. Unlike Eastern Pará, which experienced a loss of cropland, Mato Grosso more than doubled its cropland during this period; census records indicate that much of the increase was due to the planting of soybeans and sugar cane. Much of the 4.6×10^6 ha expansion of cropland and planted pasture (Table 3) appears to have come at the expense of natural pasture (Fig. 7, panel 2). This state experienced a decrease in this land use of 3 million ha, a loss of 51% of the natural pasture existent in Mato Grosso in 1980. In addition to the substantial increase in cropland, the tripling of planted pasture during this period made Mato Grosso one of the most rapidly changing states within Brazilian Amazônia.

8. Rondônia

Rondônia in the 1990s was one of the most notorious regions of deforestation, and census and satellite records agree that the expansion of agriculture for planted pasture in particular (Table 3, Fig. 8) was substantial in this state during this period. In this state, planted pasture increased nearly 500% from its 1980 levels during this time period. Most of this expansion was centered on the cities of Ji-Paraná and Ariquemes along Highway BR 364. Additional expansion was seen around Porto Velho, near Guajará-Mirim, and in the cerrado areas of the southern part of the state (Fig. 8). Cropland and natural pasture amounts remained generally low (Table 3, Fig. 8) relative to planted pasture during this period, indicating that the expansion of planted pasture was likely not due to the conversion of existing agricultural land (as seen in Pará), but was instead derived from deforestation or cerrado conversion.

9. Discussion and conclusion

Information from agricultural censuses can be integrated with satellite data to provide additional information that would otherwise not be available. This combination of satellite and census data allows analysis of the spatially explicit patterns of agricultural land uses within Brazilian Amazônia. Through an inspection of the relative changes in simple quantities between censuses, we have estimated changes in agricultural activities in a way that is consistent with satellite imagery and ground-based data sources. This integration of census and satellite information appears to hold promise for understanding the distribution and abundance of cropland and cattle pasture, whose land cover appears similar to natural systems in many areas.

Satellite-based studies demonstrate the clear benefit of high spatial resolution and repeatability, and have formed the foundation for what we know about deforestation in Brazilian Amazônia. Unfortunately, studies based on only satellite data are best suited and perhaps limited to analysis of land cover, and cannot easily provide information about the actual uses of land that has been converted. As a result, a substantial gap exists between our ability to sense land cover and the needed knowledge of the density and pattern of agricultural land use within Brazilian Amazônia. Spatially explicit snapshots of cropland and pasture, created by fusing the patterns of land cover to census-based broad-scale quantifications of land use, can begin to bridge this gap. Models of land-use change and abandonment can provide the crucial link to better understanding not only the state of converted land (as expressed in the static maps of land use through time) or the additions to the pools of

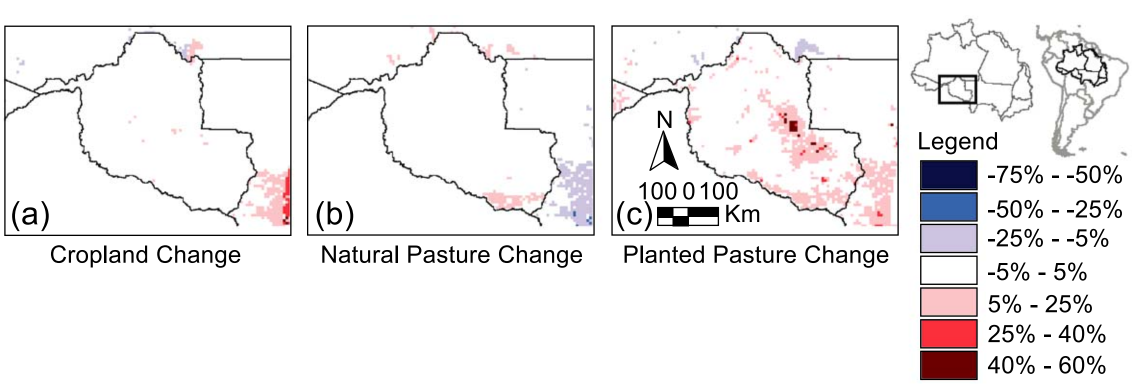

Fig. 8. Agricultural land use change in Rondônia between 1980 and 1995. This state saw minimal change in cropland (a) and natural pasture (b), but a very large increase in planted pasture (c) during the period. In this figure, loss/gain figures indicate a percent of each 5-min (~ 9 × 9 km) cell that changed. Thus, a change of +20% in a given grid cell represents about $0.20 \times 9 \times 9$ km = 16.2 km^2.

land in use (as expressed in land-cover studies), but the long-term fate of that land as it passes through cycles of active use and abandonment. The flexibility of these models suggests the opportunity for collaboration between social scientists and remote sensing specialists to synthesize our understanding of land-cover change and land-use change across the basin, with the goal of better understanding the current variation in these dynamics through time in Brazilian Amazônia.

The images presented here show the overall increase in agriculture throughout the basin and estimate, according to contemporary information, the changes in major land uses that occurred between 1980 and 1995. Land-use changes were not spatially uniform; rather, different apparent land-use dynamics operated throughout the basin. In eastern Pará and northern Tocantins, cropland and natural pasture were replaced with planted pasture, while in Mato Grosso, both cropland and planted pasture increased dramatically during the period. Rondônia had little cropland or natural pasture in either time period, and the increase in planted pasture is probably largely attributable not to conversion from other land uses but to deforestation.

Because biogeochemical processes in Brazilian Amazônia can vary according to human land-use history, and because land-use changes can feed back into the economics and demographics of the region, a realistic, spatially explicit time series of land use across the region should be a high priority for researchers. Detailed information contained in censuses presents a largely untapped resource that, when combined with satellite imagery, can greatly expand our knowledge of the uses of land converted in this region. The mapped land-use time series and the models explaining how they are linked to deforestation rates can broaden our understanding of the many impacts of the changes in Brazilian Amazônia over the past two decades.

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