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Key Points:
- Agricultural census database covers Amazon basin municipalities from 1950 to 2012
- Harmonized database groups crops and pastures by cropping system, C3/C4, and main crops
- We explored correlations between groups and the extent of agricultural lands

Supporting Information:
- Figures S1–S12
- Table S1
- Table S2
- Table S3

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Spatial and temporal contrasts in the distribution of crops and pastures across Amazonia: A new agricultural land use data set from census data since 1950

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Abstract Amazonia holds the largest continuous area of tropical forests with intense land use change dynamics inducing water, carbon, and energy feedbacks with regional and global impacts. Much of our knowledge of land use change in Amazonia comes from studies of the Brazilian Amazon, which accounts for two thirds of the region. Amazonia outside of Brazil has received less attention because of the difficulty of acquiring consistent data across countries. We present here an agricultural statistics database of the entire Amazonia region, with a harmonized description of crops and pastures in geospatial format, based on administrative boundary data at the municipality level. The spatial coverage includes countries within Amazonia and spans censuses and surveys from 1950 to 2012. Harmonized crop and pasture types are explored by grouping annual and perennial cropping systems, C3 and C4 photosynthetic pathways, planted and natural pastures, and main crops. Our analysis examined the spatial pattern of ratios between classes of the groups and their correlation with the agricultural extent of crops and pastures within administrative units of the Amazon, by country, and census/survey dates. Significant correlations were found between all ratios and the fraction of agricultural lands of each administrative unit, with the exception of planted to natural pastures ratio and pasture lands extent. Brazil and Peru in most cases have significant correlations for all ratios analyzed even for specific census and survey dates. Results suggested improvements, and potential applications of the database for carbon, water, climate, and land use change studies are discussed. The database presented here provides an Amazon-wide improved data set on agricultural dynamics with expanded temporal and spatial coverage.

1. Introduction

The Amazon basin holds around 8 million km^2 of forests comprising the largest continuous area of tropical forests and an important global carbon reservoir. Recent rates of forest loss make this region one of the deforestation hotspots at the global scale [*Baccini et al.*, 2012]. Land cover change in Amazonia can induce feedbacks on global [*Cox et al.*, 2000, 2004] and regional [*Makarieva and Gorshkov*, 2007; *Loarie et al.*, 2010] climate by inducing reduction of evapotranspiration and increasing vegetation albedo where short vegetation replaces tropical forest with a feedback to decreased regional precipitation [*Bonan*, 2008] and CO_2 emissions to the atmosphere. The type of vegetation replacing forests, for example, crops or pastures, plays an important role in these climate feedbacks [*Loarie et al.*, 2011].

Although deforestation during the last century in Amazonia has been largely attributed to pasture expansion [*Houghton*, 2010], recent research suggests complex dynamics of land use change where crops and pastures play direct and indirect roles in deforestation, for example, by replacing forests or pushing other land uses into forest areas, respectively [*Morton et al.*, 2006; *Barona et al.*, 2010; *Lapola et al.*, 2010; *Macedo et al.*, 2012]. Furthermore, understanding drivers of land use change can help improve the development of future land use change scenarios for the Amazon region [*Soares-Filho et al.*, 2006; *Lapola et al.*, 2010; *Le Page et al.*, 2010; *Arima et al.*, 2011] by accounting not only for deforested areas but also for type of vegetation and land uses that replace forests.

The objective of this study is to develop a spatial data set of the historical distribution of crops and pastures across Amazonia using agricultural census and survey data that cover all Amazonian countries. We expect

Table 1. Land Cover Distribution by Country in Amazonia for 2008 [*Blanco et al.,* 2013][a]

Country	Country (%)	Forest (%)	Agriculture (%)	Other (%)[b]
Brazil	66.1	64.4	73.4	75.1
Bolivia	8.2	7.6	11.2	7.7
Peru	11.2	11.0	12.9	9.2
Ecuador	1.8	1.6	0.5	0.5
Colombia	5.2	6.2	0.5	3.0
Venezuela	2.3	2.7	0.3	0.8
Guyana	2.6	3.0	1.0	1.8
Suriname	1.9	2.3	0.1	1.5
French Guyana	1.1	1.4	0.1	0.3
Total (%)	100.0	80.9	16.4	2.6
Total (ha $\times 10^3$)	864,274	699,549	142,203	22,520

[a]Country fractions indicate country shares of the study area. Land cover areas are presented as fraction of each class total area (columns) and as fractions of the study area (two bottom rows).
[b]Infrastructure, water bodies, and salt marshes.

this work to be used as a source of data to improve studies on vegetation-climate feedbacks and carbon dynamics and to set the basis for refinement of future land use change scenarios.

2. Materials and Methods

2.1. Agricultural Census and Survey Data and Maps of Administrative Units

We systematized historical crops and pastures data from agricultural census for countries within Amazonia. The study area corresponds to boundaries defined by other important Amazon modeling initiatives [*Soares-Filho et al.,* 2006], except for Guyana and French Guiana, whose share of agricultural lands within the basin is less than 1.5% of total nonforest lands (for 2008, Table 1). For each available census or survey, we collected total area for each crop, pastures, fallow, and abandoned lands, forest areas (within the productive units), livestock, and number of farms. Only main crops types were available from Brazil, although we could not find the definition used by IBGE (Brazilian Institute of Geography and Statistics) to select those on each census. Scientific names of crops were systematized from common names reported by data providers. They were then classified by C3/C4 photosynthetic pathways as well as by annual or perennial cropping systems. Historical changes of the administrative unit areas and boundaries were, in some cases, reconstructed to match census data with administrative boundaries and spatial location for the corresponding dates.

Most census and survey data began to be widely available in the second half of the last century, starting in 1950 and obtainable up until the present day (Peru has an earlier census in 1929 that was not available). Specific dates of available agricultural census and surveys for each country are shown in Table 2. Agricultural censuses for Brazil (1960), Ecuador (1974), and Peru (1961, 1972) were digitized from original source documents available from national statistics institutes. The rest were available from online sources (Table 3). Maps of administrative units were usually available in vector format for the more recent dates.

Data have been matched with maps at the second administrative unit level in most cases (i.e., municipality level or similar), except for Colombia, Suriname, and Ecuador where only the first level data on administrative boundaries were available (departmental). Because administrative units are divided into smaller ones forward in time, the development of the administrative unit maps that match each census date was often based on aggregating municipalities into larger original units. We started with the most recent existing official map in digital format and reconstructed the past administrative maps backward in time for each census date based on scanned political maps. The adjustments account for a reconstruction of municipality boundaries, for example, based on historical political maps or relational keys depicting boundary evolution as municipalities become subdivided into smaller sized units (details on methods and data sources in Table 3). The 1995 data set for Colombia has aggregated data for all Amazonian departments from agricultural surveys, and department values were derived proportional to the area of each administrative unit.

For Brazil data from 1995, 2000, and 2006, this study is based on the work of *Barona et al.* [2010] which relied on systematized surveys, censuses, and databases from the Brazilian Institute of Statistics and Geography

Table 2. Time Chart of Agricultural Census Data Collected for This Study[a]

Decade	Year	BO	BR	CO	PE	EC	VE	SU
1950	1950	✓						
1960	1960		✓					
	1961				✓			
1970	1972				✓			
	1974					✓		
	1975		✓					
1980	1980		✓					
	1984	✓						
1990	1994				✓			
	1995		✓	✓				
2000	2000		✓			✓		
	2005	✓		✓				
	2006		✓					
	2008						✓	
	2009							✓
2010	2012				✓			

[a]When no data was available, the corresponding year is not shown as a line in the table. BO: Bolivia, BR: Brazil, CO: Colombia, PE: Peru, EC: Ecuador, VE: Venezuela, SU: Suriname.

[*IBGE-SIDRA*, 2006]. In order to obtain consistent data, they aggregated units to match boundaries of the coarsest unit across these three dates. For the 1960 and 1975 census dates in Brazil, we used a municipality relational key that indicates the aggregation/disaggregation of municipalities through time [*Reis et al.*, 2011; *Barretto et al.*, 2013]. Administrative unit reconstruction for Peru (1961, 1972) and Bolivia (1950) was done by using scanned political maps from dates as close as possible to census dates. In a few cases where we lacked information about boundary changes across time, spatial units and census/surveys data were further aggregated into known coarser units. We lacked data for some census-date combinations: in Brazil 1960 (1 municipality) and 1975 (3), Bolivia 1984 (11), and Peru 1961 (15), 1972 (7), 1994 (1), and 2012 (1). These gaps represent 13% of the country area within our study area in Bolivia for the 1984 census and 6% of the country area in Peru for the 1961 census. Boundary data for administrative unit AMC6097006, in Brazil 1960, were missing, and values were assigned to nearby municipalities; it is a known source of error.

Censuses do not always report the same variables and gaps in variables exist across countries and dates. For example, fallow lands are only reported in Peru (all censuses), Venezuela 2008, Ecuador 2000, and Bolivia 1984 (Table S1 in the supporting information).

2.2. Systematization of Crop Data

Census data collected information for a total of 407 crop types for which we identified 216 here with their scientific names and family in order to harmonize all censuses data. We did not identify in the literature 191 crops from Peru 2012 and 1994 (172 and 19 crops, respectively). All crops not identified were aggregated to the "others" census category which covers $<$6.8% of any of the country's total agricultural areas. Peru 2012 reports 2334 associated crops that were not identified by scientific name representing 8% of total croplands. Bolivia reports 13.4% of total cropland areas with crop associations whose crop types are not described in the census.

Crops across countries and census dates were aggregated into three groups (details in the supporting information Table S2). The first group aims at distinguishing annual and perennial crop types. Perennial crops refer to long-term cultivation systems that do not require replanting after harvest, such as coffee and cocoa. Annual crops require replanting after harvest with yearly cycles. Sugarcane was the only crop with inconsistent classification across censuses, being classified as perennial in Colombia and annual elsewhere. The second group separates crops by C3 and C4 photosynthetic pathways. Finally, the third group is related to the physiognomic component of importance for consumption or industrialization (cereals, fibers, flowers, fruits, herbs, industrials, legumes, nuts, tubers, vegetables, and other). A detailed description of this grouping is excluded in the following sections but available with the data set. Finally,

Table 3. Data Sources for Agricultural Data and Administrative Unit Maps and Summary of Methods Used to Harmonize the Data Sets[a]

Country	Year	Agricultural Census		Administrative Map		Administrative Level/Name
		Source	Method	Source	Method	
Brazil	1960	*IBGE* [1967a, 1967b, 1967c, 1967d]	1	*Reis et al.* [2011]; *IBGE* [2007]	5	3/Municipality
	1975	*IPEA* [2012a]	2	*Reis et al.* [2011]; *IBGE* [2007]	5	3/Municipality
	1980	*IPEA* [2012b]	2	*IBGE* [2011, 2007]	4	3/Municipality
	1995	*IBGE-SIDRA* [2006]	2	*Barona* [2009]	5	3/Municipality
	2000	*IBGE-SIDRA* [2006]	2	*Barona* [2009]	5	3/Municipality
	2006	*IBGE-SIDRA* [2006]	2	*Barona* [2009]	5	3/Municipality
Colombia	1995	*MADR, DANE, SISAC* [1995]	2	*IGAC* [2011]	6	2/Department
	2008	*MADR, IGAC* [2008]	2	*IGAC* [2011]	6	2/Department
Ecuador	1974	*INEC* [1976a, 1976b, 1976c, 1976d]	1	*IGM* [1975]; *DICE* [2012]	3	2/Province
	2000	*INEC, MAG, SICA* [2002]	2	*DICE* [2012]	6	2/ Province
Peru	1961	*MHC, DNEC* [1968a, 1968b, 1968c, 1968d, 1968e, 1968f, 1968g, 1968h, 1968i, 1968j, 1968k, 1968l, 1968m, 1968n, 1968o, 1968p, 1978]	1	*IGM* [1970]; *CODESI* [2011]	3	3/Province
	1972	*ONEC* [1976a, 1976b, 1976c, 1976d, 1976e, 1976f, 1976g, 1976h, 1976i, 1976j, 1976k, 1976l, 1976m, 1976n, 1976o, 1976p, 1976q]	1	*IGM* [1970]; *CODESI* [2011]	3	3/Province
	1994	*INEI* [2002]	2	*INEI* [2002]; *CODESI* [2011]	6	3/Province
	2012	*INEI* [2013]	2	*INEI* [2002]; *CODESI* [2011]	6	3/Province
Bolivia	1950	*INE, MACA, FAO* [1956]	2	*INE, MACA, FAO* [1956]; *IGM* [1988]; *CIAT* [2011]	3	3/Province
	1980	*INE, MPC* [1989]	2	*IGM* [1988]; *INE, MPC* [1989]; *CIAT* [2011]	3	3/Province
	2005	*UPC* [2010]	2	*IGM* [2005]; *CIAT* [2011]	6	3/Province
Suriname	2009	*Ministerie van Landbouw-Suriname* [2009]	2	*GADM* [2012]	5	2/District
Venezuela	2008	*MAT* [2008]	2	*GADM* [2012]	5	3/Municipality

[a]Methods used are (1) census data digitized from hardcover format, (2) census data collected from digital sources, (3) scanned maps used as a reference to reconstruct administrative boundaries based on original digital vector sources, (4) administrative units for Brazil in 1980 reconstructed from a table indicating the evolution in time of municipalities boundaries (based on creation date, actual, and corresponding previous municipality for any date in which dis/aggregation of units occurred), (5) data from other sources, and (6) official available vector data.

scientific names were collected for each crop type from several online sources. The number of cattle units and fallow lands in each administrative unit was also collected and presented in Figures S1 and S2 in the supporting information.

Each one of these groups, except for the physiognomic one, and its evolution in time are presented here by municipality, country, and for the whole Amazonia in terms of their fractional coverage. Crop fractional coverage is presented as the ratio of cropland to pasture area (CPR), perennial to annual crops area (PAR), and C4 to C3 photosynthetic pathways for agricultural areas (C4C3R) not including pastures. We also present the planted to natural pastures ratio (PNP). Natural pastures are defined in censuses as pastures that were not planted by farmers and therefore can include both native grasslands and those that have been degraded and are now covered, for example, with invasive species. We present municipality ratios and their spatial correlation with the fraction of total agricultural lands per municipality as a preliminary exploration of the data set. Agricultural lands account here for both pastures and croplands. We also present main crops maps, where “main” indicates for those crops whose total aggregated area accounts altogether for at least 70% of the total cropland area of Amazonia.

3. Results

3.1. Spatial and Temporal Resolution of Census Data

Available agricultural censuses for the Amazon basin cover the second half of the twentieth century from 1950 (in Bolivia) until 2012 (Peru). Brazil has the most systematic record with censuses every decade (six in total; see Table 2) during this period, followed by Peru with four censuses (Table 2). Other countries have only one or two dates of census available (Table 2). Ecuador has the older latest census in 2000. For Brazil,

Table 4. Number, Maximum, and Minimum Size of Administrative Units per Agricultural Census Used in This Study

		Administrative Units			
			Size (10^3 km^2)		
Country	Year	Number	Mean	Largest	Smallest
Bolivia	1950	58	13.72	88.04	0.21
	1984	60	13.26	88.04	0.21
	2005	63	12.63	88.04	0.21
Brazil	1960	189	30.11	633.64	0.44
	1975	283	20.11	408.33	0.19
	1980	377	15.04	186.72	0.19
	1995, 2000, 2005	463	12.29	200.25	0.23
Colombia	1995	7	70.20	109.26	25.90
	2008	7	70.20	109.26	25.90
Ecuador	1974	4	29.09	51.91	10.62
	2000	6	19.40	29.88	10.61
Peru	1961	84	11.63	159.68	0.53
	1972	87	11.24	159.68	0.53
	1994	106	9.05	121.71	0.53
	2012	110	8.72	121.71	0.53
Suriname	2009	10	16.39	126.53	0.19
Venezuela	2008	4	46.91	70.43	19.00

Peru, and Bolivia, a few departments had no data on specific census dates, leaving a few areas with a lower census count than the rest of the country.

All countries tend to increase the number of administrative units with time, and therefore, the mean size of an administrative unit decreases with time (Table 4). Brazil, after 1995, has constant administrative units since [*Barona*, 2009] standardized maps for all the dates after 1995. Bolivia and Peru tend to have small changes in the size of administrative units. Ecuador has the smallest number of units and the largest mean size (except for Brazil in 1960).

3.2. Crop Types

Across all censuses and surveys, we identified 216 crops from 84 families. The most important families were Leguminosae (16 crop species), Graminae (7 species), Rosaceae (11 species), Solanaceae (11 species), and Rutaceae (9 species). We grouped these crops into 137 annual and 79 perennials crops (Table S2 in the supporting information). In the case of Brazil only the most important crops (as selected by IBGE) are accounted for, leaving country level comparisons biased, since usually crops total area are highly uneven. The number of unidentified crops is larger than the 19 aggregated here since the "other crops" category already exists in censuses. The total area within this category covers a relatively small fraction of the Amazon basin, less than 1.2% or less than 6.8% of total agricultural or crop lands respectively across all the countries.

3.3. Agricultural Lands

The distribution of agricultural land across all the municipalities within each country is presented in Figure 1. The increase of agricultural land fraction over time suggests poles of deforestation from (i) the Andean Cordillera to Amazonian lowlands, a north-south axis over the western side of the region along Peru, Colombia, and Ecuador, (ii) from the south and east of Brazil to central Amazonia, (iii) from the North to South in Venezuela, and (iv) from the Atlantic coast along the Amazon River (Figure 1).

Brazil shows the largest variation of agricultural area across its municipalities (followed by Peru) with a larger range of values compared to other countries (Figure S3 in the supporting information). The distribution of agricultural land for Colombia and Ecuador is calculated from a small total number of administrative units (Table 3) and is thus difficult to compare with the one of other countries. Bolivia and Peru show a decrease of the variation of agricultural land for more recent times, suggesting some convergence among municipalities. Fallow land areas are relatively smaller compared to agricultural lands (we currently do not include fallow lands as part of agricultural lands; see Figure S2 in the supporting information).

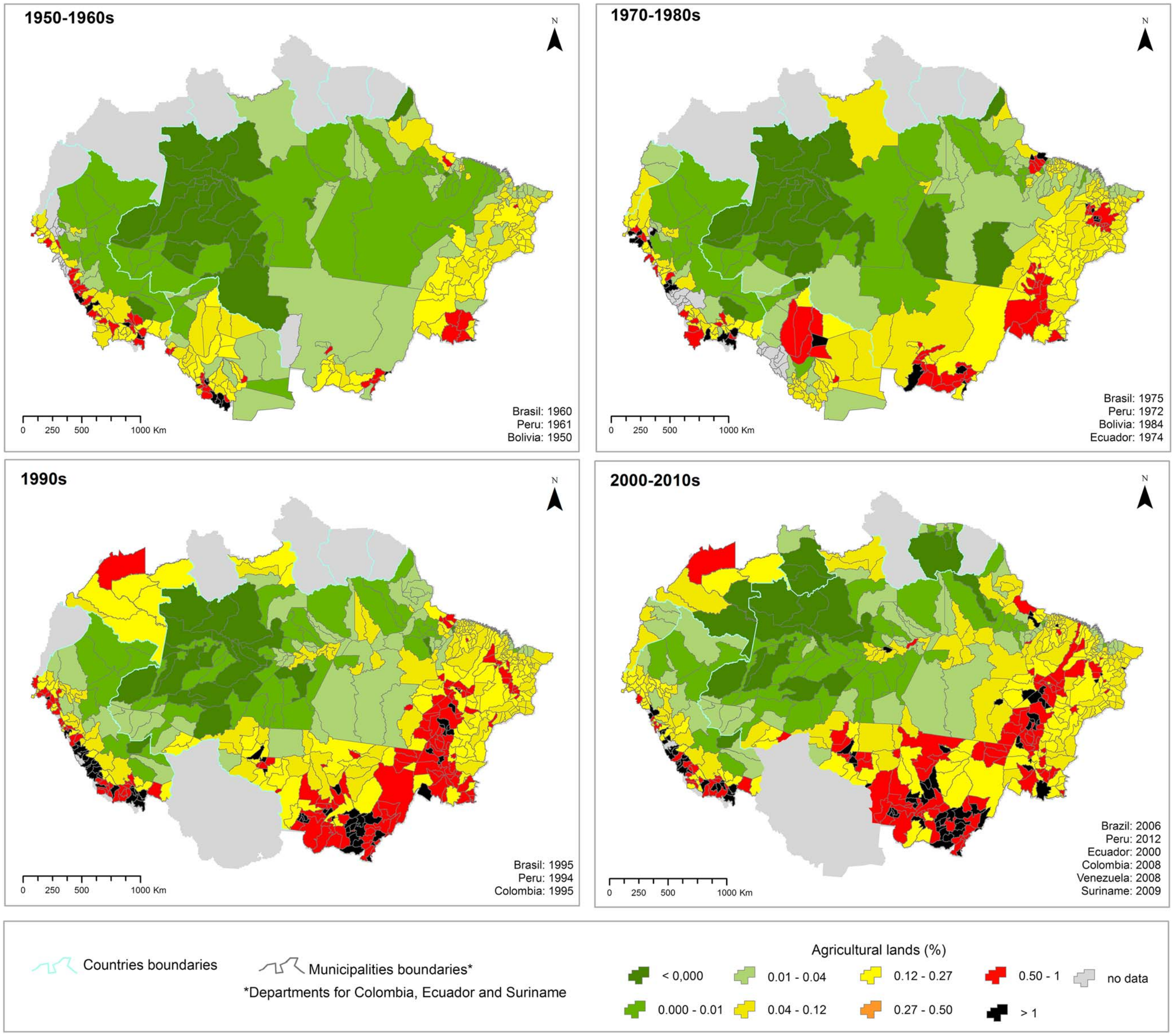

Figure 1. Fraction of agricultural lands in each administrative unit across groups of two consecutive decades in Amazonia. Specific census dates used for the map are indicated for each period.

3.4. Crops and Pastures

The cropland to pastureland ratio (CPR) and total agricultural land, including both natural and planted pasture according to censuses, of each country are shown in Figure 2. As expected all countries increased their agricultural lands with time, except for Colombia that shows a 30% reduction between 1995 and 2008 (Figure 2). All countries across the whole period have an area of pastures (including natural and planted productive pastures) at least four times larger than croplands (CPR ratios <0.25, Figure 2), except for Venezuela (2008) where CPR is 1.6. Colombia has the lowest CPR (0.04-0.05), and Peru and Venezuela have the highest (0.19–0.25 and 1.6, respectively). Peru has a decreasing trend of CPR during 1960–1970, followed by an increase in the later censuses of 1994 and 2012. Brazil shows an increasing trend of CPR, except for a drop in 1980, resulting into a near doubling of CPR from 0.1 to 0.19 between 1960 and 2006 (Figure 2). Colombia (1995–2008) shows decreasing CPR with time. Bolivia shows no trend (1950–1984; see Table S3 in the supporting information).

Although Brazil has the largest fraction of agricultural lands within the basin across the whole period, Bolivia and Peru (which together have a share of only 1.47% of the whole basin agricultural lands) combined

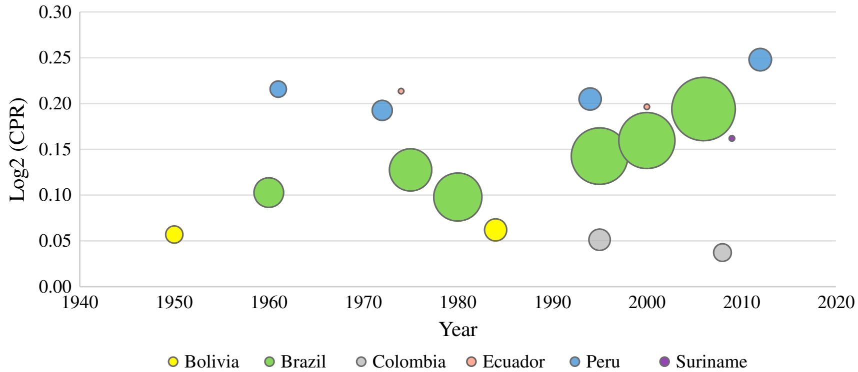

Figure 2. Crop-to-pastures ratio for countries within the Amazon basin. The area of each bubble shows the fraction of agricultural lands in each country of the Amazon basin. Ecuador and Suriname are shown oversized (multiplied by 2.5 and 15, respectively) since they have <1% of the total Amazon share while the largest value refers to Brazil 2006 with 8.68%). Venezuela 2008, not shown, has a CPR of 1.16 and 0.004% of the Amazonian agricultural lands.

aggregated a similar amount of agricultural lands than Brazil (2.08%) during the period 1950s to 1960s (Figure 2). Between 1960 and 1975, Brazil's agricultural lands sharply increased to cover 4.12% of the country, further increasing to 9.06% in 2006. The contribution of Ecuador to agricultural land fraction always remained relatively small (<0.05%). Bolivia, Colombia, and Peru have a similar share of agricultural lands in more recent times (since the 1980s) ranging between 0.72 and 1.23%.

Although country level CPR always shows a larger area of pastures relative to croplands, there are large variations within each country. In each country, several municipalities show high CPR values, as seen from the distribution of CPR among municipalities in Figure S4 in the supporting information, particularly in Brazil (1960), Peru (1961), Bolivia (1984), and Colombia (2008). For example, the maximum CPR found was for Casiquiare in Venezuela 2008 (CPR = 4537), which resulted from 0.05 ha of pastures and 227 ha of cropland areas. Still, all countries have municipalities with larger crops than pastures area, except for Colombia 1995 (Figure S4 in the supporting information).

We found significant a ($p < 0.0001$) negative correlation (Spearman ranked correlation coefficient) of −0.43 between CPR and the fraction of agricultural land of the municipalities, using data for all countries and years in the regression (Figure 3 and Table 5). Country-specific correlations between CPR and the fraction of agricultural land (all years, $p > 0.0001$) for Brazil (−0.42) are close to the average of all Amazonian countries (Figure 3). The correlations obtained from Brazilian municipalities across years have values similar than when using the full data set, suggesting that Brazil probably drives the Amazonian average correlation value, since it has the largest number of municipalities. Correlations for Peru are more negative than the average (−0.73) of Amazonia. In Peru, these correlations increased with time from −0.70 to −0.77, except in 1972 (Figure 3 and Table 5). Other countries have nonsignificant correlations, probably due to their smaller number of observations. This result suggests that as the agricultural frontier advances in each municipality, the extent of pastures increases relative to crops. Importantly, an opposite relationship is found in the southern part of the Mato Grosso state in Brazil (a northwest to southeast axis between Sorriso and Alto Taquari municipalities) where CPR increased with increasing fraction of agricultural land (Figure 3).

3.4.1. Pasture Lands

Census data distinguish between planted and natural pastures in most cases, except Bolivia 1950. *Barona et al.* [2010] used aggregated data for both pasture types for Brazil in 2000. Natural pastures usually dominate the total pasture land areas. For example, Peru and Bolivia have over 94% of their pasture lands with natural pastures across all censuses. Suriname 2009 and Venezuela 2008 have 68 and 73% of their pasture lands with natural cover. Brazil shows a strong decrease in the fraction of natural pastures from 95% in 1960 to 20% in 2006 with the largest changes in southern municipalities of our study area (Figure 4) (see Table S3 in the supporting information). Colombia and Ecuador have less than 10% of natural pastures. Cattle number per hectares of pastures (Figure S1 in the supporting information) increases over time with a rather higher density over Brazil since 2000 and lower elsewhere (over highland countries probably due to increased density of other species), except for southern Bolivia in 1984 showing

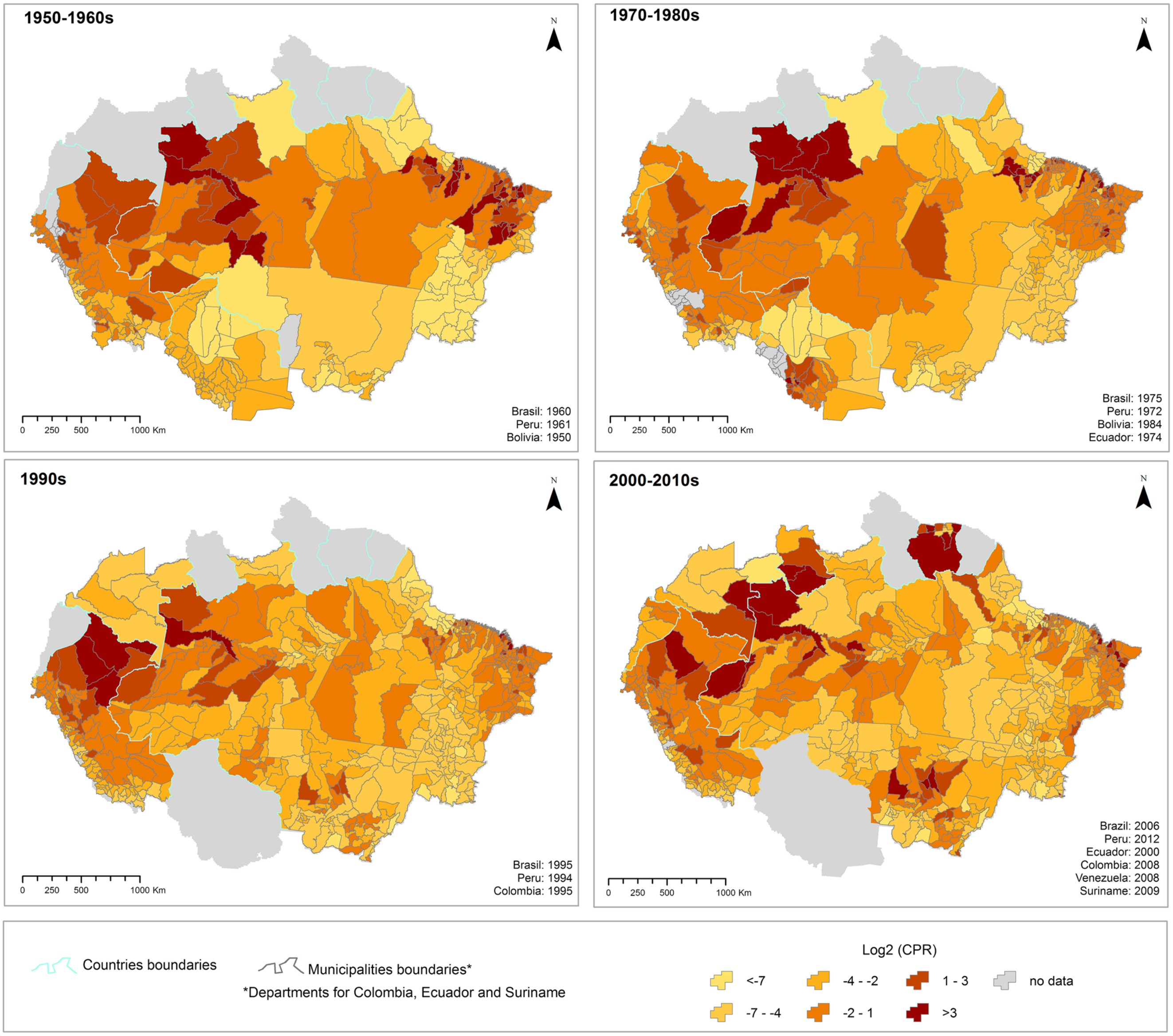

Figure 3. Crops/pastures ratio (Log2(CPR)) across groups of two consecutive decades in Amazonia. Specific census dates used for the map are indicated for each period.

relatively high values. Cattle number showed significant correlations with the fraction of pastures of the municipalities, particularly for Brazil (decreasing trends with time) and Peru (increased trends with time, except for 2012; data not shown).

PNP variability across municipalities is largest for Peru (and increases with time) and Bolivia and smallest for Ecuador and Colombia, probably due to the small number of municipalities. Brazil variability is reduced in more recent census. Only Brazil in 1995 and 2006, Ecuador, and Colombia have a larger fraction of their PNP values above 1 (Figure S5 in the supporting information).

PNP shows no significant correlation for the global data set (including all censuses and dates) probably as a result of correlations between Peru and Brazil (the only two countries with significant correlations) of opposite sign (0.20 and −0.69 for Brazil and Peru, respectively) (Table 5). Brazil's lower correlation for grouped censuses data results from opposite correlation signs across census dates from negative significant values in 1960, no significant trends in 1975 and 1980, and increasing positive correlation values in 1995 and 2006. Peru has negative significant correlation values across all census dates indicating

Table 5. Spearman Correlation Coefficients (ρ), Number of Observations (n), and p-Values Between Fraction of Agricultural Lands per Municipality and Crops and Pastures Ration (CPR), Perennial and Annual Crops Ratio (PAR), and C4-C3 Photosynthetic Pathway Ratio (C4C3)

	CPR			PAR			C4C3			PNP		
	n	ρ	p	n	ρ	p	n	ρ	p	n	ρ	p
All country-years	2750	−0.43	<0.0001	2743	−0.31	<0.0001	2733	0.20	<0.0001	2234	0.02	0.4412
Bolivia	109	−0.26	0.0065	107	−0.07	0.4465	107	0.07	0.4740	51	−0.02	0.8679
Brazil	2237	−0.42	<0.0001	2237	−0.37	<0.0001	2237	0.20	<0.0001	1774	0.20	<0.0001
Colombia	14	−0.27	0.3376	7	−0.71	0.0802	7	−0.39	0.3359	7	−0.21	0.5997
Ecuador	10	−0.39	0.2373	10	−0.16	0.6235	10	0.14	0.6758	10	−0.04	0.8987
Peru	368	−0.73	<0.0001	368	−0.64	<0.0001	368	0.25	<0.0001	379	−0.69	<0.0001
Suriname	10	−0.66	0.0475	nd	nd	nd	nd	nd	nd	9	0.43	0.2203
Venezuela	4	−0.80	0.1659	4	−0.80	0.1659	4	0.20	0.7290	4	−0.80	0.1659
Bolivia—1950	58	0.11	0.4009	58	−0.49	0.0002	58	0.02	0.8513	nd	nd	nd
Bolivia—1984	51	−0.34	0.0157	49	0.27	0.0571	49	0.21	0.1529	51	−0.02	0.8679
Bolivia—2005	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Brazil—1960	188	−0.47	<0.0001	188	−0.17	0.0204	188	0.31	<0.0001	188	−0.48	<0.0001
Brazil—1975	283	−0.46	<0.0001	283	−0.47	<0.0001	283	0.18	00030	283	−0.01	0.9063
Brazil—1980	377	−0.30	<0.0001	377	−0.47	<0.0001	377	−0.26	<0.0001	377	−0.10	0.0632
Brazil—1995	463	−0.35	<0.0001	463	−0.45	<0.0001	463	0.32	<0.0001	463	0.28	<0.0001
Brazil—2000	463	−0.49	<0.0001	463	−0.39	<0.0001	463	0.35	<0.0001	Nd	nd	nd
Brazil—2006	463	−0.41	<0.0001	463	−0.38	<0.0001	463	0.27	<0.0001	463	0.34	<0.0001
Colombia—1995	7	0.25	0.5403	nd	nd	nd	nd	nd	nd	7	−0.21	0.5997
Colombia—2008	7	−0.79	0.0543	7	−0.71	0.0802	7	−0.39	0.3359	nd	nd	nd
Ecuador—1974	4	−0.60	0.2987	4	−0.60	0.2987	4	0.60	0.2987	4	−0.40	0.4884
Ecuador—2000	6	−0.66	0.1417	6	−0.26	0.5653	6	0.14	0.7494	6	0.20	0.6547
Peru—1961	74	−0.70	<0.0001	74	−0.56	<0.0001	74	0.21	0.0777	84	−0.77	<0.0001
Peru—1972	80	−0.64	<0.0001	80	−0.56	<0.0001	80	0.32	0.0051	80	−0.60	<0.0001
Peru—1994	105	−0.78	<0.0001	105	−0.75	<0.0001	105	0.19	0.0500	106	−0.81	<0.0001
Peru—2012	109	−0.77	<0.0001	109	−0.67	<0.0001	109	0.27	0.0047	109	−0.58	<0.0001
Suriname—2009	10	−0.66	0.0475	nd	nd	nd	nd	nd	nd	9	0.43	0.2203
Venezuela—2008	4	−0.80	0.1659	4	0.80	0.1659	4	0.80	0.1659	4	−0.80	0.1659

that the fraction of natural pastures increased as the fraction of total pasture lands increased for each municipality (Table 5).

3.4.2. Perennial and Annual Cropping Systems

Amazon mean perennial to annual crop ratio (PAR) shows a larger fraction of annual crops (mean municipalities PAR values and standard deviation of 0.32 ± 3.92). Mean PAR values and standard deviations between countries vary between 0.11±0.06 and 0.72±6.40 (for Venezuela and Bolivia, respectively), while Ecuador mean PAR is an outlier at 1.99 ± 1.46. Brazil seconds in variability with a mean value of 0.223 ± 3.97. PAR values for specific dates remain between 0.01 and 0.85 for all countries and standard deviations in the same order of magnitude, except for Peru 2012 (1.08 ± 2.29), Ecuador 2000 (2.75 ± 1.43), Brazil 1980 (1.18 ± 9.62), and Bolivia 2005 (1.57 ± 1.47). Brazil has mean PAR values of ≤0.7 across all censuses except for 1980 showing a large increase in mean values (see Table S3 in the supporting information). Brazil 1980 also shows one of the largest dispersion in municipality values contrasting with other census dates that have the lowest dispersion. Venezuela, Ecuador, and Colombia also have the lowest value dispersion, probably due to the small number of municipalities within the study area (Figure S6 in the supporting information).

A significant negative correlation of −0.31 was found between PAR and the fraction of agricultural lands of the municipalities of Amazonia. This indicates that as the fraction of agricultural lands increases in each municipality, the ratio of perennial to annual crops tends to decrease (Figure 5). The spatial pattern of PAR is relatively stable over time (Figure 5), with a larger ratio of perennial to annual crop areas mostly over Peruvian lowlands where municipalities seem to increase annual crops fraction over time. Country level correlations between PAR and agricultural land fractions are only significant (<0.0001) for Brazil and Peru (−0.37 and −0.64, respectively). These correlations are also stable between decades, ranging between −0.38 and −0.77 in both countries. Brazil 1960 was found without significant correlation.

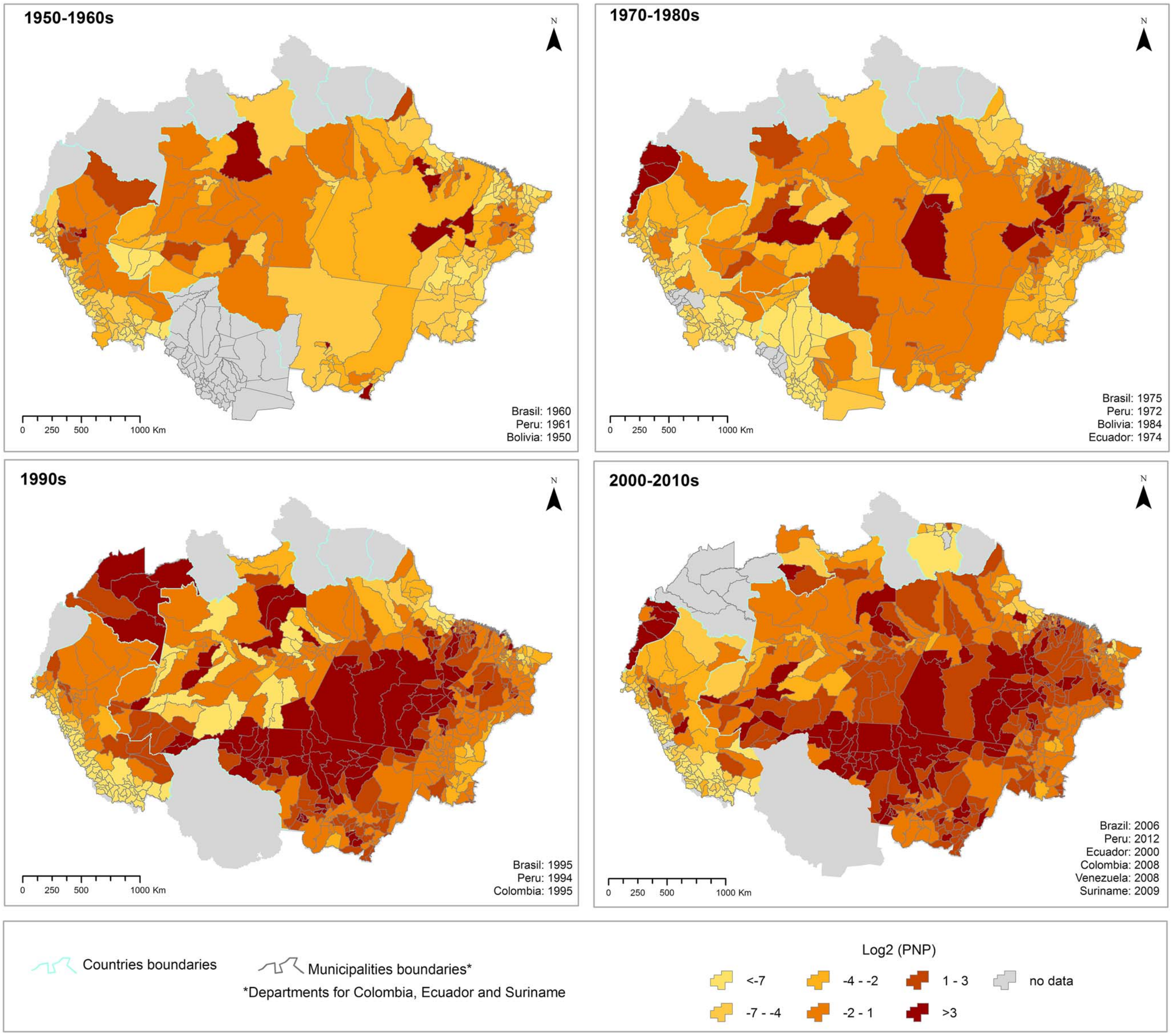

Figure 4. Planted/natural pastures ratio (Log2 (PNP)) across groups of two consecutive decades in Amazonia. Specific census dates used for the map are indicated for each period.

3.4.3. Photosynthetic Pathways

The Amazonia mean C4 to C3 crop type ratio (C4C3R) is 0.64±3.54. The fraction of C3 crops is thus on average larger than that of C4 crops, and stable values of the C4C3R ratios are found across countries and decades, ranging between 0.2 ± 0.09 and 1.0 ± 7.07 for Venezuela 2008 and Brazil 2006, respectively. The distribution of the C4C3R ratio across individual municipalities also shows a large range (Figure S7 in the supporting information). A weak positive correlation (0.20, $p < 0.0001$) was found between C4C3R and the fraction of agricultural lands across all municipalities of the data set (Table 5 and Figure 6). Statistically significant correlation values are also found at country scale in Peru (0.25) and Brazil (0.20) that have enough municipalities to calculate a correlation. The correlation between C4C3R and agricultural land fraction does not seem to change much over time, with values ranging between 0.35 and 0.18. Only Brazil has significant correlations and 1980 shows a contrast with C4C3R of -0.26 (Table 5).

3.4.4. Main Crops

Cassava, potato, cotton, rice, corn, wheat, and soybean were found to be the main crops of Amazonia. Main crops are defined as those crops whose total aggregated area over a two-decade period account for at least

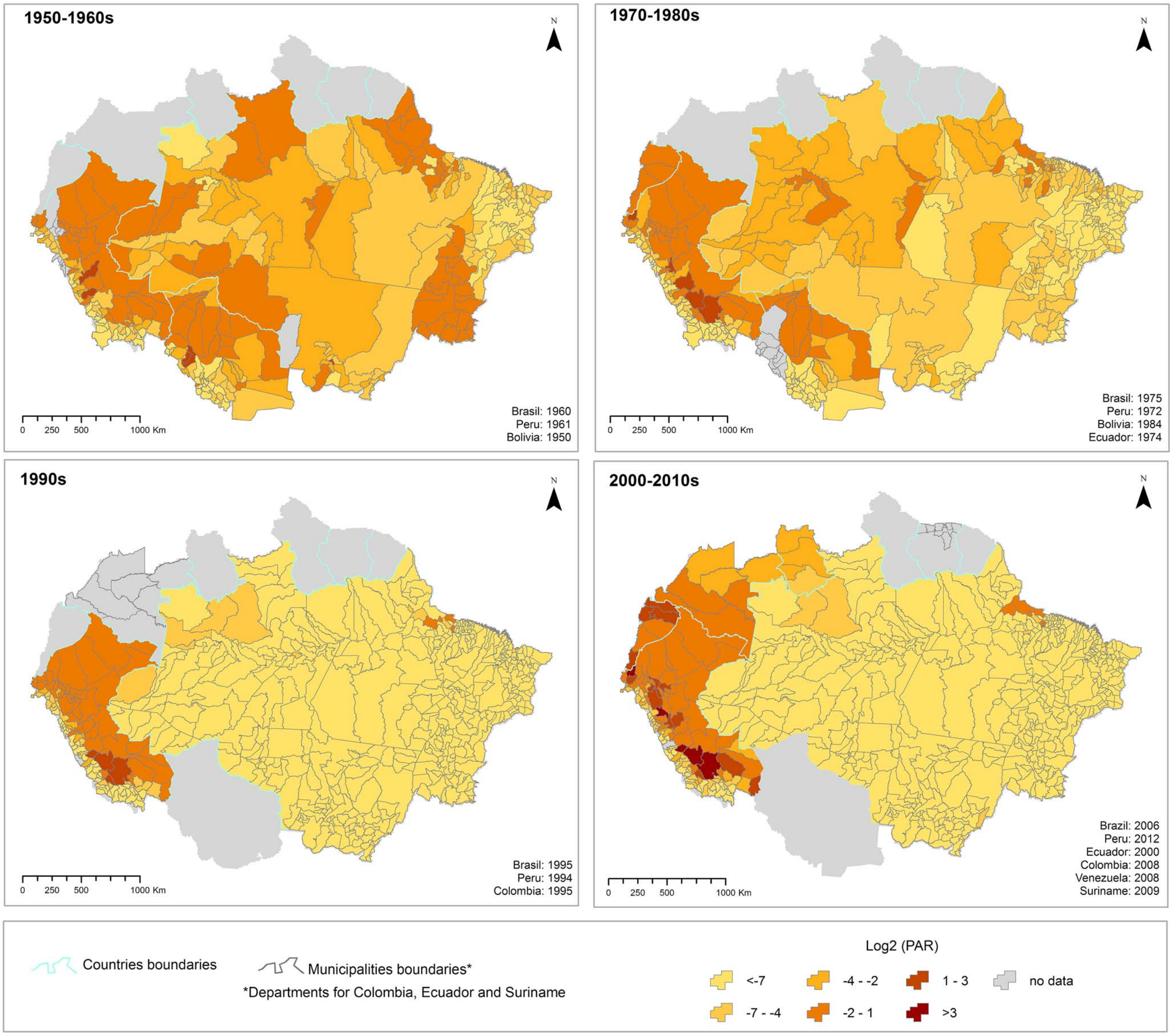

Figure 5. Ratio of perennial/annual crops (Log2 (PAR)) across decades in Amazonia. Specific census dates used for the map are indicated for each period.

70% of the total cropland area of Amazonia. Their spatial distribution is shown in Figures 7 and 8 (and Figures S8–S12 in the supporting information). We found that the number of main crops tends to diminish from 6 during the 1950s to 1960s to 3 in the 2000s when soybean, corn, and rice, in the same order of importance, account for 78% of Amazonian croplands.

Cassava is an important crop (in terms of area relative to croplands) in municipalities with lower fraction of agricultural lands (Figure S8 in the supporting information). Cassava is important for subsistence and shifting cultivation farmers in forest frontier municipalities [*Simon et al.,* 2005]. Potato belongs mainly to highlands of Peru and Bolivia and is almost nonexistent elsewhere, probably due to cold climate requirements (Figure 7). Cotton seems important in midaltitude Peruvian municipalities but mostly in southern Mato Grosso state in Brazil since 1990 and Southeast Maranhão state in 1950s to 1960s (Figure S9 in the supporting information). Rice is restricted to lowlands, due to crop climate requirements, and is found mostly in municipalities with larger fraction of agricultural lands (Figure S10 in the supporting information). The fraction of rice cultivated areas shows a peak in 1970s to 1980s and declined afterward, although with widespread distribution, in more

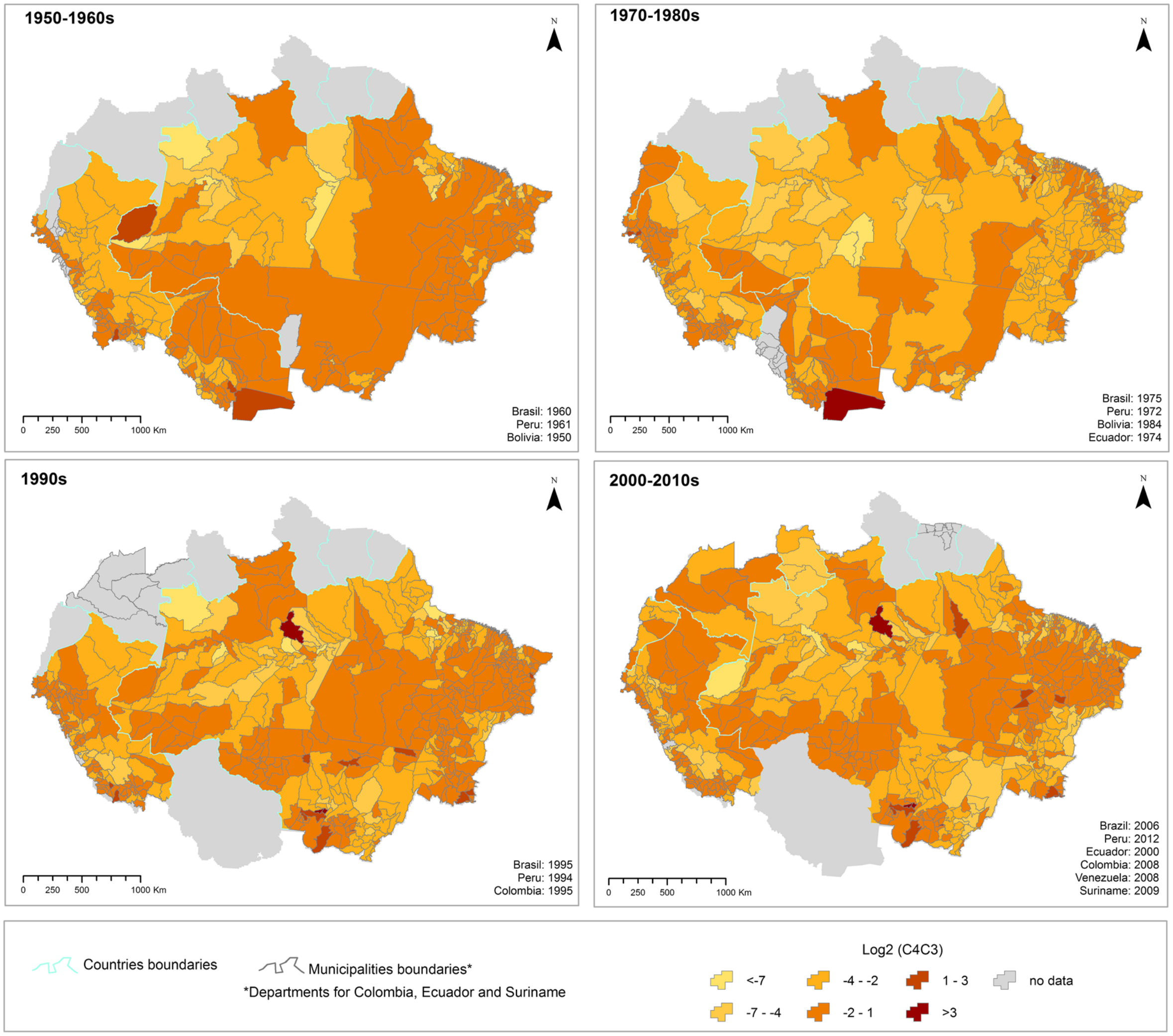

Figure 6. Ratio of C4 to C3 cropland area (Log2 (C4C3R)) in each municipality across groups of decades. Specific census dates grouped for each map are indicated for each period.

recent times. Wheat belongs mostly to highlands of Peru and Bolivia, with a declining relative importance since the 1990s compared to the 1950–1980 period in those areas (Figure S11 in the supporting information). Corn has a widespread distribution in municipalities with both high and low fractions of agricultural lands (Figure S12 in the supporting information). Soybean shows a sharp increase over southeastern Brazil since the 1990s and more recently also in the northern Brazilian state of Roraima (Figure 8).

4. Discussion

We compiled and harmonized a new agricultural land use data set that characterizes crops and pastures in Amazonia according to cropping system (annual or perennial), photosynthetic pathway, and crop physiognomy based on successive agricultural censuses and surveys in countries of the Amazon basin since 1950. Our data set incorporates seven countries within Amazonia, providing a new information resource that treats the entire region. The legal Amazon in Brazil has been the main focus in most of the literature, even though it only covers around two thirds of the region. Although similar studies have covered larger spatial domains [i.e., *Ramankutty et al.,* 2008], specific dates [i.e., *Morton et al.,* 2006; *Macedo et al.,* 2012], or disaggregated spatial distribution of census data using land cover maps from remote sensing [*Cardille and Foley*, 2003], we present here a unique data set in terms of its temporal and spatial coverage. We have harmonized data from all existing censuses and surveys and reconstructed (in most

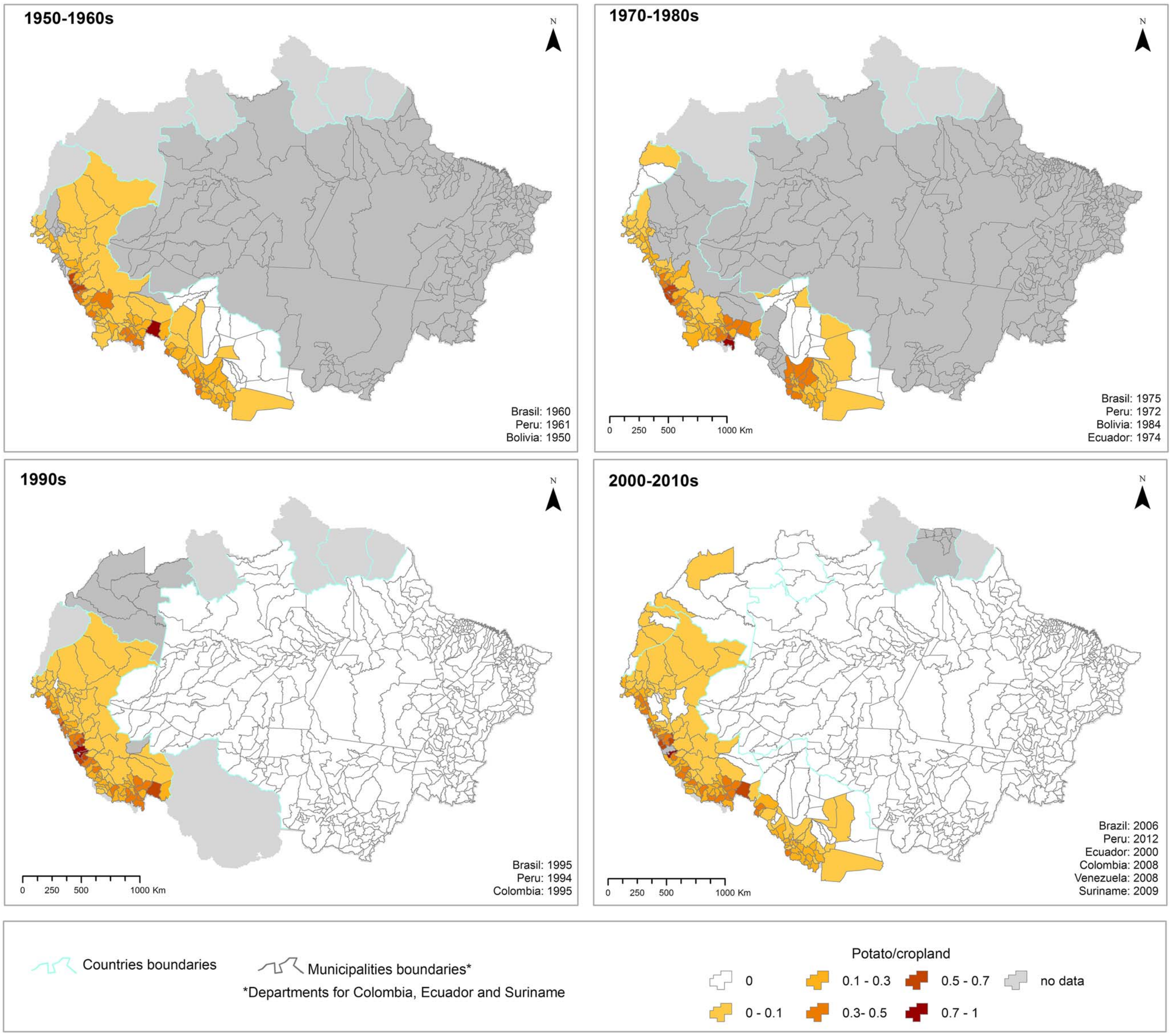

Figure 7. Fraction of potato among total croplands (not including pasture lands) for each administrative unit. Specific census dates used for the map are indicated for each period.

cases) the boundaries of corresponding administrative units (to their second level or municipalities). We have also systematized scientific names for all reported crops across countries to facilitate further use of the data set.

The lack of data quality assessments on the used sources limits an uncertainty quantification, since census validation efforts were not reported. Comparison with previous census or other data sources (i.e., surveys) has been used to identify systematic errors [*Wunder*, 1999]. Brazil census data quality on crops and pastures (both planted and natural) is expected to be reliable, in particular for recent times (since 1995) as increased funding augmented the number of units directly sampled [*Cardille and Foley*, 2003]. According to *Cardille et al.* [2002], census officials report that crop planted area is reliable for the census date, particularly for farmers having access to formal financial aid, although interannual variability of crop areas can be high compared to pasture areas which are more stable. Identifying uncertainties on data collected for intercropped systems presents varying degrees of difficulty; for example, some censuses (Bolivia 1950, 1984, Peru 1994, 2012, Ecuador 2000) identified associated crops separately (from annual or perennial only areas) although not always identifying the specaific crops species associated (we only included total areas for associated crops). Peru 1961 does not report crop associations. Crop planted areas (as provided in this data set)

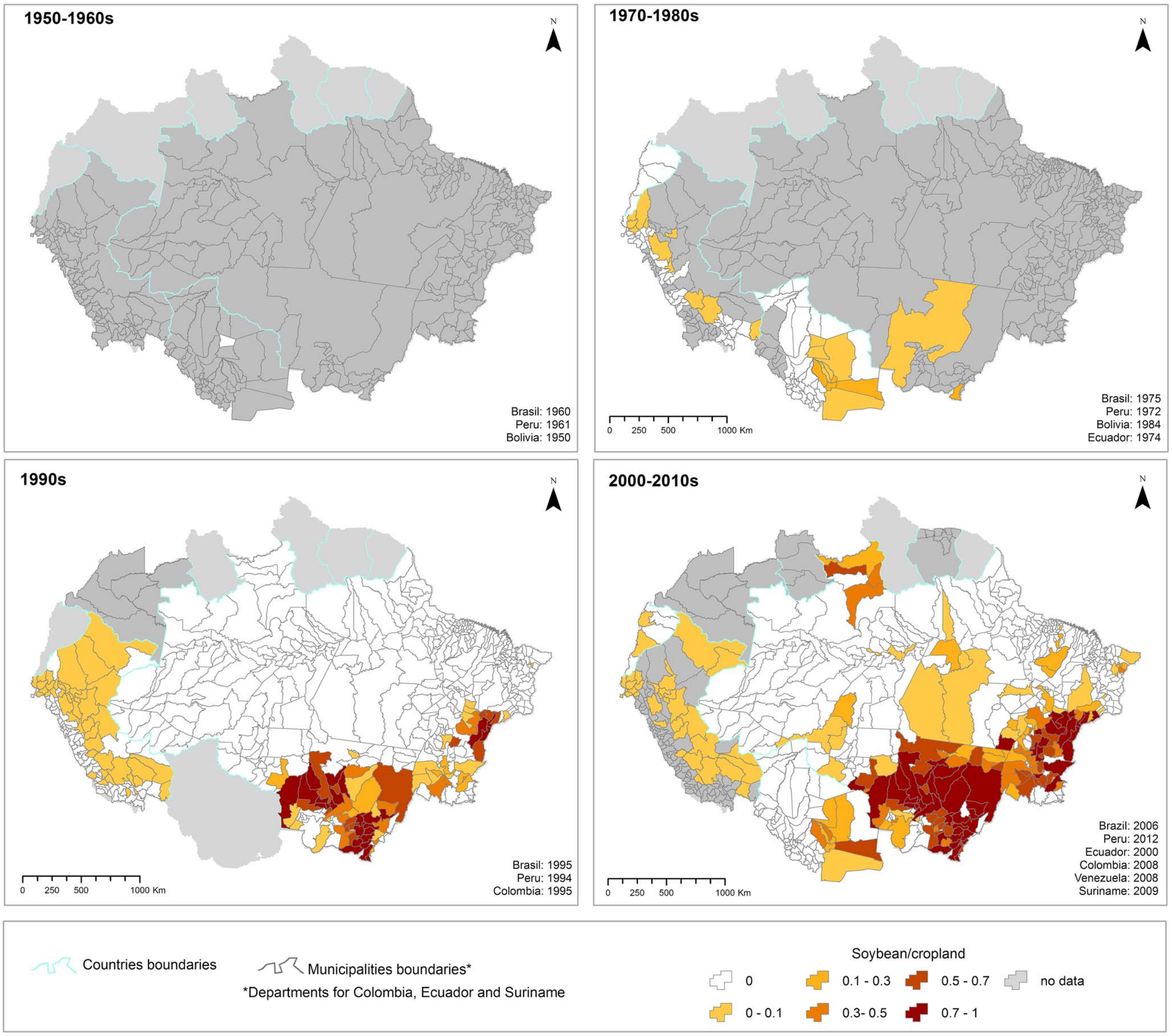

Figure 8. Fraction of soybean among total croplands (not including pasture lands) for each administrative unit. Specific census dates used for the map are indicated for each period.

usually refer to the area at the time of the census and do not account for crops or pastures that might replace or share the same land at other times (i.e., of the same year) [*Ramankutty et al.,* 2008] which potentially induces to double counting issues for other census variables (i.e., harvested area) where the same area is accounted for more than one crop (A. Simões, personal communication with IBGE, 2015) [*Monfreda et al.,* 2008]. Bolivia (any date) and Colombia 2008, for example, do not distinguish between planted and harvested area. For Brazil (any date) and Ecuador 1974 when permanent crops (with cropping cycles longer than one year) were intercropped with annual crops in a specific farm, only the permanent crop type and its area was reported (personal communication) reducing the potential effects of double-counting issues in our data set. For other dates this is not clarified (Peru 1961 or Suriname 2009). Approaches to correct for double-counting have been attempted, for example, by assessing the potential for multiple cropping systems based on agroclimatic variables [*Monfreda et al.,* 2008]. Data collection/reporting issues [*Monfreda et al.,* 2008] should be further explored, for example, unrealistically high livestock number per unit of area in municipalities with relatively small agricultural land fractions in central Amazonia, which should be treated accordingly as spurious in the data set. The area of a census establishment (i.e., farm) is assigned to the municipality where the headquarters of the farm is administratively located, or where most of the farm area is located if there is no administrative address (personal communication). This could explain fractions of agricultural lands larger than the municipality (Figure 1) in our data set. Similar data sets types have been used in combination with land cover data to understand deforestation drivers in Amazonia, for example, between 1980 and 1995 for Legal Amazonia (smaller region than the one studied here) where net increases in agricultural lands were attributed to crop expansion, increase in planted pastures (through deforestation), and decrease in natural pastures (abandoned grasslands and savannah) [*Cardille and Foley*, 2003]. These approaches used municipality level census data to estimate land use proportions (similar to the data presented here) that are then assumed to be equally distributed across the agricultural matrix from remote sensing [*de Espindola et al.,* 2012], while others developed more complex models to assign land use classes across remotely sensed land use types [*Cardille and Foley*, 2003; *Leff et al.,* 2004; *Monfreda et al.,* 2008].

Other studies have performed analysis using some of the sources presented here with a focus on finding deforestation drivers, with findings similar to those presented here. For example, an increasing CPR over Mato Grosso concurred with an increased share of soybean farms on agricultural lands for 2006 [*Macedo et al.,* 2012] and potential pastures displacements into Pará [*Barona et al.,* 2010] and Rondonia and Amazonas [*Arima et al.,* 2011] where we found a decrease in CPR. Our data show that nearby areas in southern Tocantins and Maranhao also show a sharp increase in soybean areas while keeping constant CPR values, potentially indicating different dynamics. The decrease in CRP for Brazil 1980 census (Figure 2) results from a general wider distribution of croplands across every state, something that was reversed in the following years [*Leite et al.,* 2012].

Negative correlations found in Peru between PNP and the fraction of pasturelands of the municipalities could indicate that increased areas of productive pasture lands occur over natural pastures (over highlands) that are not accounted in censuses when not under productive systems. Natural pastures were the dominant land use since 1940 in Brazil, with expanding areas and intensity until 1970 when planted pastures appeared and began replacing natural pastures in 1980 [*Leite et al.,* 2012]. This shifting trend can explain the change in correlation sign between PNP and the municipality fraction of pasturelands.

Effects of historical land cover change on climate have been studied at the global [*Cowling et al.,* 2007], regional [*Beltrán-Przekurat et al.,* 2012], and local scales [*Arvor et al.,* 2012; *Dubreuil et al.,* 2012], where the replacement of forests by crops and pastures in Amazonia and its climate feedbacks could trigger a future *savannization* trend in the region [*Pires and Costa*, 2013]. Furthermore, the fraction of crops and pastures and their parameterization in land surface models have been identified as an important source of uncertainty in attribution studies of global land use change on regional climate [*Pitman et al.,* 2009]. The temporal and spatial CPR trends presented here extend for the first time to the whole basin, instead of Brazilian Amazonia where most of the literature focuses. The data have high potential for further analysis, in particular before 1980, when the extent of agricultural land within the Amazon basin was shared by several countries in relatively similar magnitudes, while for later dates Brazil dominates.

C4C3R data could also support studies on land use change feedbacks on Amazonian climate. Previous research found a decrease in surface temperature when crops replace C3 grasslands and an increase when crops replace woody vegetation or C4 grasslands, due to higher LAI in C4 grasslands compared to C3 type crops. These results are related to a change in the Bowen ratio resulting from increased latent heat. Effects on precipitation were relatively smaller [*Beltrán-Przekurat et al.,* 2012] although other authors found regional effects on precipitation due to C4-vegetation presence [*Cowling et al.,* 2007].

The distribution of C3 and C4 vegetation types also determine differences in the exchanges of CO_2, water, and energy between land and surface. Amazonia mean (across all periods) C4C3R 0.64±3.53 shows a larger fraction of C4 agriculture than the global C4C3R ratio of 0.19, according to *Still et al.* [2003], with only Venezuela 2008 approaching the global average. Our municipal scale data could help improve carbon studies that have so far used the coarser level C4 crop fractions on their analysis [*Still et al.,* 2003; *Gibbs et al.,* 2008; *Monfreda et al.,* 2008; *Meiyappan and Jain*, 2012] losing detail on the spatial patterns and across time at least for Amazonia. Errors due to lack of data on natural C3/C4 mixed grasslands are expected to be nonsignificant since they mostly belong to extra-tropical areas, except for a narrow strip over the Andes in our study region [*Sterling and Ducharne*, 2008]. Further disaggregation of the pasture class by photosynthetic pathway could be based on temperature gridded data [*Monfreda et al.,* 2008].

It is worth noting that changes in the area of forests, crops, and pastures patterns can only be explained by a combination of policy, accessibility, biophysical, and socioeconomic drivers framed in historical pathways of change [*de Souza Soler et al.,* 2009]; therefore, the temporal coverage of census data presented here could prove valuable. Our longer temporal and spatial approach could serve the purpose of understanding trends in less recently deforested lands where most of the forest was lost a few decades back. More research is needed to understand land change dynamics within nonforest frontier municipalities. This can help understand indirect causes of deforestation as well as dynamics between crops and/or pastures over heavily intensified municipalities.

CPR analysis can also help understand land use change dynamics. For example, in Mato Grosso, pastures remain the dominant land use after deforestation, although an increased rate of conversion of forest to croplands (combined with pastures to crop transitions) was found in the early 2000s, probably driven by high soybean prices, that resulted in increased CPR values over Mato Grosso for 2006 [*Macedo et al.,* 2012] (Figure 3). Furthermore, during the first half of the 2000s, the absolute increase in croplands in Mato Grosso was mainly from replacing pastures (76%) than by replacing forests (26%). This was the case especially in later years (2006 onward) when 91% of the expansion occurred on previously cleared lands due to a decline in commodity prices and policy measures to decrease deforestation rates [*Macedo et al.,* 2012]. However, the data presented here cannot capture gross gains or losses in areas between crops, planted/natural pasture lands needed to explain deforestation drivers, and further refinement using remote sensing data is required. Accounting for fallow lands could be also helpful in this sense and is a potential improvement of the database presented here.

Crops type data have been also useful to understand land use change drivers, for example, the increase in soybean, cotton, and corn fraction in Mato Grosso (Figures S8, S9, and S12 in the supporting information) resulted from an increase in agricultural intensification where areas with double cropping systems (soybean-corn or soybean-cotton on each year) increased from 6% to 30% between 2000 and 2007 [*Arvor et al.,* 2012]. Productivity data (not presented here) are also needed since it has been the driver for increased soybean production (i.e., record production in 2009/2010) instead of deforestation, in Mato Grosso and Rondonia [*Rudorff et al.,* 2011].

Verburg et al. [2011] discussed land use/cover data issues for global change studies highlighting temporal, spatial, and thematic/definition consistency issues. Temporal issues to address in future uses of our data set relate to the lack of systematic dates where long periods without data between two census dates could potentially hide changes in land use dynamics. Changes in the census field implementation (not always documented) also induce a temporal bias. For example, the level of resources and effort allocated to the production of each census or differences in the date/season represented by the census which may produce land use bias in areas of multiple cropping [*Wunder*, 1999]. Studies aimed at analyzing finer-scale or temporal evolution of land use in Amazonia might need to develop spatially consistent units of analysis based on the data presented here in order to reduce bias from differences across time and between countries in municipality (Table 4) and agricultural areas (Figure 1). This can be achieved by either aggregating municipalities forward in time to keep common administrative boundaries of comparable areas [i.e., *Barona et al.,* 2010] or disaggregating census data based on land cover data from remote sensing sources [*Leite et al.,* 2012]. *Anderson et al.* [2015] compared several existing approaches to downscale census (or similar) data sources to improve the spatial representation of the data and found discrepancies mainly due to methodological issues and choices of sources, such as remote sensing data, to define cropland extent. Furthermore, many of these studies focused on understanding the drivers of deforestation and land use change dynamics within agricultural lands, requiring consistent definitions of natural versus planted pastures or rangelands which are difficult to distinguish from sparse forest areas [*Ramankutty et al.,* 2008; *Verburg et al.,* 2011] and whose definitions are not always detailed. Although these categories are present in the database, there were not discussed here.

5. Conclusions

We presented a harmonized database of agricultural censuses and surveys for Amazonia covering countries within Amazonia since 1950 at the municipality level. We described the spatial patterns of agricultural lands, crops, and pastures distribution, annual to perennial cropping systems, planted to natural pastures, and main crop types. Significant correlations were found between these patterns and the fraction of crops and pasture lands. Our database should encourage improved studies on land use change dynamics, water, and carbon cycles at regional and global scales.

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