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Patterns of land use, extensification, and intensification of Brazilian agriculture

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Abstract

Sustainable intensification of agriculture is one of the main strategies to provide global food security. However, its implementation raises enormous political, technological, and social challenges. Meeting these challenges will require, among other things, accurate information on the spatial and temporal patterns of agricultural land use and yield. Here, we investigate historical patterns of agricultural land use (1940–2012) and productivity (1990–2012) in Brazil using a new high-resolution (approximately 1 km^2) spatially explicit reconstruction. Although Brazilian agriculture has been historically known for its extensification over natural vegetation (Amazon and Cerrado), data from recent years indicate that extensification has slowed down and was replaced by a strong trend of intensification. Our results provide the first comprehensive historical overview of agricultural land use and productivity in Brazil, providing clear insights to guide future territorial planning, sustainable agriculture, policy, and decision-making.

Keywords: Brazilian agriculture, extensification, intensification, land use change, sustainable agriculture

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Introduction

A growing world population combined with increasing per capita income and consumption (especially of animal proteins) has stimulated discussions about how to produce enough food to meet the global demand (Godfray *et al*., 2010). To guarantee global food security, current production would need to be approximately doubled over the next 35 yr (Tilman *et al*., 2011). This enormous challenge has led to a renewed focus on agricultural production in regions that have the capacity to meet this vastly increased demand.

Brazil is one of these countries with high capacity to increase agricultural production, having a generally favorable climate and vast areas that are suitable for agriculture. Indeed, Brazil is already one of the ten major exporters of agricultural products in the world (FAO, 2015) and it is expected to continue to increase production and export. Recently, the Brazilian Ministry of Agriculture (*Ministério da Agricultura, Pecuária e Abastecimento* or MAPA) estimated that Brazilian grain production will increase by 29.4% and beef production by 23.3% between 2015 and 2025 (MAPA, 2015). In the same period, soybean and maize exports (in grain) are predicted to increase by, respectively, 51.2% and 42.1%, and beef exports by 37.4% (MAPA, 2015).

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In Brazil, agriculture activities have been the main driver of deforestation (Gibbs *et al*., 2010), a major source of greenhouse gas emissions (Leite *et al*., 2012; Calvin *et al*., 2015; Chaplin-Kramer *et al*., 2015), biodiversity loss (Chaplin-Kramer *et al*., 2015), and alteration of the water and soil characteristics (Scheffler *et al*., 2011; Hunke *et al*., 2015). Nevertheless, Brazilian grain production has roughly doubled since 2005 despite reductions in deforestation rates during the same period. Moreover, the last 5 yr have seen widespread adoption of more sustainable agricultural practices through the National Program for Low Carbon Agriculture (Brasil, 2012). Such an increase in production coupled with enhanced environmental protection cautiously supports the view that Brazil has the potential for large-scale sustainable development of its agriculture to meet global food security goals.

Increasing yield without increasing the area under agriculture or causing significant environmental degradation is known as sustainable intensification and has been proposed as one of the main strategies to provide global food security (Balmford *et al*., 2005; Rudel *et al*., 2009; Strassburg *et al*., 2014). Achieving sustainable intensification in Brazil within a relatively short time period will be an enormous political, technological, and social challenge. As a starting point for policy development, it is essential that decision-makers have accurate information on the spatial and temporal patterns of agricultural land use and yield in the Brazilian territory. Using this information, it should be possible to identify areas and land uses (e.g., crops, livestock) with the greatest capacity for sustainable increases in yield.

Many studies have mapped recent agricultural areas, investigating the dynamics of the conversion between natural vegetation, pasturelands, and croplands (especially soybean) in Brazil. However, many of these studies had limited spatial coverage, such as a single state (Morton *et al*., 2006; Rudorff *et al*., 2010; Macedo *et al*., 2012; Arvor *et al*., 2013), a biome (Barona *et al*., 2010; Sano *et al*., 2010; Beuchle *et al*., 2015; Ferreira *et al*., 2015) or were restricted to a limited period of time (Morton *et al*., 2006; Barona *et al*., 2010; Macedo *et al*., 2012; Arvor *et al*., 2013; Beuchle *et al*., 2015; Graesser *et al*., 2015). Given the large size of Brazil, its enormous vegetation diversity and agriculture heterogeneity, the development of national agricultural and conservation policies requires an accurate reconstruction of historical land use maps for the entire country. It is only through the lens of history that the current geographic trends in land use can be fully understood and accurate future projections made.

The first historical-spatial description of Brazilian agriculture land use for the entire country was provided by Leite *et al*. (2012), who reconstructed the agricultural areas in Brazil from 1940 to 1995, at a spatial resolution of 5′ (approximately 9 × 9 km). However, this database was restricted to mapping general croplands and pastures (natural or planted). Crop-specific maps are required for the continued development of sustainable agriculture policy, and these remain unavailable for Brazil. Moreover, to become policy-relevant this database needs to be updated to include more recent time periods.

In addition to precise land use data, sustainable agriculture policy requires accurate information about agricultural extensification and intensification. Agricultural extensification is the increase of agriculture output through the expansion of agriculture area. In contrast, intensification is the increase in productivity on existing agricultural lands – often through the use of improved cultivars, irrigation, fertilizer, biocides, and mechanization – and without land conversion (Foley *et al*., 2011). Some scientists have argued that intensification is essential to spare natural areas (Balmford *et al*., 2005; Rudel *et al*., 2009; Strassburg *et al*., 2014). However, others suggest that increasing yields makes agriculture more profitable and therefore creates further financial incentives to increase the rate of conversion of natural habitat at agricultural frontiers (Ramankutty & Rhemtulla, 2012; Barretto *et al*., 2013; Lapola *et al*., 2014).

Here, we investigate historical patterns of agricultural land use and productivity in Brazil. We begin with a description of land use patterns in Brazil based on a new explicitly spatialized database of agriculture areas. We then reconstruct the historical distributions of cropland and pastureland by combining agricultural census data and remote sensing data for the whole of Brazil from 1940 to 2012 at 30″ spatial resolution (approximately 1 × 1 km). Pastureland maps are divided into planted and natural pastures from 1940 to 2012, and cropland maps are divided into the three main crops cultivated in Brazil (sugarcane, soybean, and maize) from 1990 to 2012. Together, these land uses comprise about 90% of all agricultural land use in the country (including double crops). Finally, we provide yearly maps of soybean, maize, and sugarcane yield and yearly cattle stocking rate from 1990 to 2012. Our main objectives are to: (i) characterize agricultural land use change in Brazil and the productivity of four agricultural products (soybean, maize, sugarcane, and cattle); (ii) describe the patterns of yield of soybean, maize, and sugarcane, and the stocking rate of cattle for the entire country; and (iii) explore the productivity–agriculture area relationship for the three crops and cattle to better understand the dynamics of extensification–intensification, especially in the Amazon and Cerrado agricultural frontiers.

Materials and methods

Region of study

Brazil has 27 federal units (26 states and one Federal District) divided into five regions (Fig. 1). With 850 million ha of area, Brazil contains six biomes: Amazonia, Atlantic Forest, Caatinga, Cerrado (Brazilian savanna), Pampas (grasslands), and Pantanal (Fig. 1).

The most recent agricultural frontier in the country is located in the MATOPIBA region (Fig. 1). MATOPIBA is an acronym created from the first two letters of the states of Maranhão, Tocantins, Piauí, and Bahia – although the frontier region comprises only part of Cerrado biome in these states, with an area of 7.4 million ha (de Miranda *et al*., 2014). This new Cerrado agricultural frontier is characterized by rapid changes in land cover and land use for cropland, especially soybean, and agricultural intensification through the adoption of new technologies. However, to date there is no detailed information available on land use, productivity, and the extensification–intensification relationship in this region.

Land use data sources

We use an similar approach to that used in previous global (Monfreda *et al*., 2008; Ramankutty *et al*., 2008) and Brazilian (Leite *et al*., 2011, 2012) agricultural land use reconstructions. Specifically, our reconstruction is based on a combination of remote sensing data – to provide the land use localization –

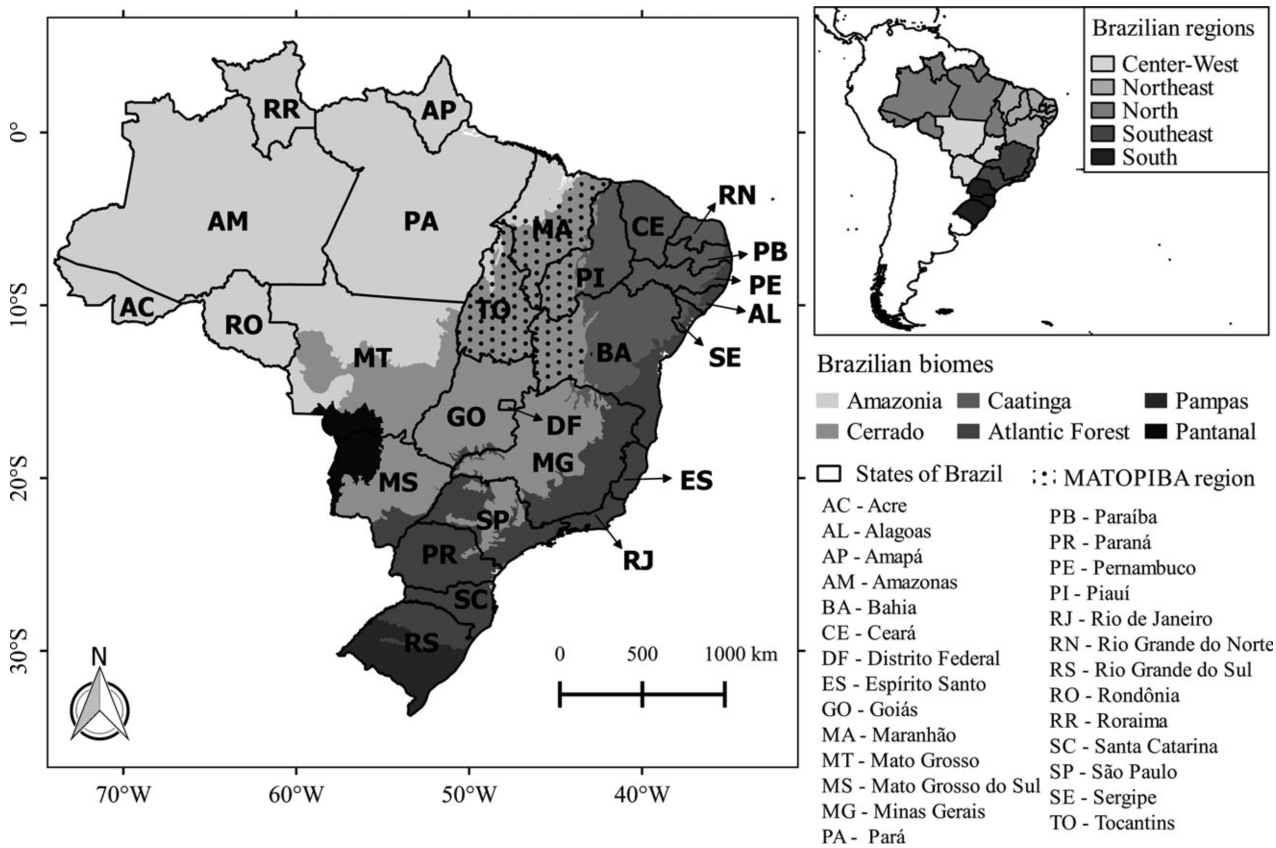

Fig. 1 Location of the study area, with identification of the Brazilian states, regions, and biomes and the location of MATOPIBA (new agricultural frontier located in the states of Maranhão, Tocantins, Piauí, and Bahia).

and census or inventory data – to identify type and amount of the agricultural land use.

We use the 30-m global forest cover change maps developed by Hansen *et al*. (2013). These maps include global tree cover extent for the year 2000, with forest loss allocated annually from 2001 to 2012. Trees are defined as vegetation taller than 5 m, and the tree cover is expressed as a percentage per pixel. Originally, these tree cover maps had approximately 30 × 30 m spatial resolution, but we changed the resolution to 30″ (approximately 1 × 1 km) by summing the pixels in grid for our analysis. Starting with the inverse of tree cover in each pixel for the year 2000, which represents the nonforest areas, we combine this 2000 nonforest map with the forest loss map for each year to provide nonforest maps for 2000–2012.

The nonforest maps are converted into agricultural land use maps using agricultural census data provided by the Brazilian Institute of Geography and Statistics (IBGE – *Instituto Brasileiro de Geografia e Estatística*) and compiled by the Institute of Applied Economic Research (IPEA – *Instituto de Pesquisa Econômica Aplicada*). Brazilian census data were performed in 1940, 1950, 1960, 1970, 1975, 1980, 1985, 1995, and 2006 at the municipality level. In these surveys, land uses are classified into three categories: cultivated areas (the sum of permanent and temporary crops), natural pasture, and planted pasture. Permanent crops are defined as cultures that last for several seasons, while temporary crops need to be replanted after each harvest. Banana, orange, grape, and coffee are examples of permanent crops, while rice, maize, soybean, and sugarcane are examples of temporary crops. Natural pasture refers to nonplanted areas where original vegetation is grass. Planted pasture is characterized by planted grass species for animal grazing, usually established after tilling, liming, and fertilizing the soil. Total agricultural land use is the sum of cultivated areas, natural pasture, and planted pasture.

It should be noted that there are differences in the definition of total agricultural land use area and cultivated area in Brazilian census data. Agricultural land use area is the area modified for agricultural purposes (livestock, cultivation, or fallow areas). Cultivated areas correspond to the area planted with a specific crop in a given year. In the land use area category, double-cropped areas are counted only once, while the sum of the cultivated area of each crop planted in a municipality in a year could be greater than the land use area if the farmers of the municipality adopt double cropping.

To construct the specific area and yield crop maps, cultivated area and production of soybean, sugarcane, and maize, yearly data were obtained from the Municipal Agricultural Survey in the IBGE database at the municipality level from 1990 to 2012. From this same database, we also obtained the number of cattle in each municipality, from 1990 to 2012, to construct cattle stocking rate maps.

Total agricultural land use data processing at the polygon scale

Although all census data were collected at the municipality level, we use the minimum comparable area (MCA) as unit for the historical reconstruction. An MCA consists of the smallest set of municipalities with a stable boundary over time. Brazil had 1577 municipalities in 1940 and 5572 municipalities in 2013, and new municipalities are created almost every year in the country, normally by the division of one unit into two new ones. We defined one set of MCAs for each of the following time periods: 1940–1995, 1950–1995, and 2000–2012. Firstly, 1502 MCA polygons were defined for the period 1940–1995. However, municipalities were large in 1940 and each MCA aggregates data from several contemporary municipalities. Thus, to avoid inaccuracies due to these large MCAs, we defined 1823 MCA polygons for the period 1950–1995. We use the 1940–1995 MCAs to create only the 1940 maps, and the 1950–1995 MCAs to create all maps in the period 1950–1995. For more recent years (2000–2012), MCA polygons were the same as the micro regions, which are the small units that aggregate municipalities with similar economic and social characteristics.

In some MCAs, the total agricultural land use from census data was greater than the MCA area. To correct for this inconsistency, we calculate the amount of total agricultural land use area that needed to be removed to match the MCA area (in percentage) and we apply this proportion to the adjusted total agricultural land use, cropland, natural pasture, and planted pasture data. In 1940, the total agricultural land use from census data was greater than the MCA area in six MCAs in a universe of 1502 MCAs. Between 1950 and 1995, the number of MCAs that lost agricultural area varied from nine to 23 in a universe of 1823 MCAs.

Between 2000 and 2012, we estimate year-to-year total agricultural land use data for each municipality in two steps. Firstly, we calculate the annual increase or decrease rate between two census data for each MCA census data (Eqn 1):

$$\Delta U_{\mathrm{MCA}} = \frac{\left(U_{\mathrm{MCA}}^{2006} - U_{\mathrm{MCA}}^{1995}\right)}{U_{\mathrm{MCA}}^{1995}}, \tag{1}$$

where ΔU_{MCA} is the variation of the amount of total agricultural land use in each MCA, U_{MCA}^{2006} is the amount of total agricultural land use in a micro region from 2006 census data (km^2), and U_{MCA}^{1995} is the amount of total agricultural land use in a micro region from 1995 census data (km^2).

Second, we consider that all municipalities in an MCA converted land use at the same annual rate as the MCA (Eqn 2):

$$U_k^t = U_{k \in \mathrm{MCA}}^{1995} \cdot \left[1 + (t - 1995) \cdot \frac{\Delta U_{\mathrm{MCA}}}{(2006 - 1995)}\right], \tag{2}$$

where U_k^t is the estimated total agricultural land use in a municipality k in the year t (km^2) for $2000 \le t \le 2012$ and $U_{k \in \mathrm{MCA}}^{1995}$ is the amount of total agricultural land use from 1995 census data in a municipality k (km^2). In the end of this process, these estimated data are filtered to avoid estimated land use areas greater than the polygon area. The mean area lost with this filter is 0.14% of the estimated total agricultural land use area in Brazil between 2000 and 2012.

The same process we used to obtain total agricultural land use data was used to obtain the amount of cropland and natural pastureland for each municipality for 2000 to 2012. Planted pastureland for each municipality is calculated as the difference between total agricultural land use, cropland, and natural pasture data.

The planted area data for soybean, maize, and sugarcane from 1990 to 2012 are filtered to avoid individual crop areas greater than the total cropland area at each polygon. The mean individual crop area lost in this process is 0.03%, 0.02%, and 0.01%, respectively, for the inventory data for soybean-, maize-, and sugarcane-planted area in Brazil between 1990 and 2012.

Land use data disaggregation to 30″ resolution

To convert gridded nonforest maps ($\mathrm{NONF}_{i,j \in k}^t$, in km^2) into total gridded agricultural land use maps, we calculate the fraction of total agricultural land use in municipality k in year t ($2000 \le t \le 2012$) by dividing the estimated total agricultural land use area (U_k^t, in km^2) by the total nonforest area in the municipality [$\sum_{i,j \in k} \mathrm{NONF}_{i,j}^t$, in km^2; Eqn (3), Fig. 2a]. We then multiply this fraction by the nonforest map ($\mathrm{NONF}_{i,j \in k}^t$). Finally, we divide the result of this calculation by the pixel area ($A_{i,j}$) to express the final total agricultural land use maps as a percentage of area per pixel ($\mathrm{ALU}_{i,j}^t$, in %):

$$\mathrm{ALU}_{i,j}^t = 100 \cdot \frac{\left(\mathrm{NONF}_{i,j \in k}^t \cdot \frac{U_k^t}{\sum_{i,j \in k} \mathrm{NONF}_{i,j}^t}\right)}{A_{i,j}}, \tag{3}$$

where i and j are, respectively, the coordinates of rows and columns of the pixels in the map. The resulting maps can have agricultural land use area in a pixel >100% of the pixel area, especially if the remote sensing nonforest area is lower than the census agricultural area at the municipality level. During the period of reconstruction, only about 4% of the pixels have this problem. We correct these data through an iterative procedure, using Eqn (4), to adjust the pixel values only for MCAs with at least one pixel with land use area >100% of the pixel area:

$$\mathrm{LU}_{i,j}^t = 100 \cdot \frac{\left[1 - \exp\left(-0.01 \cdot F \cdot \mathrm{ALU}_{i,j}^t\right)\right]}{\left[1 - \exp\left(-0.01 \cdot F \cdot P_{\mathrm{MCAmax}}^t\right)\right]}, \tag{4}$$

where $\mathrm{LU}_{i,j}^t$ is the final corrected map in a year t (%); F is a factor of distribution for each micro region; and P_{MCAmax}^t *is* the maximum land use pixel value in a MCA in the $\mathrm{ALU}_{i,j}^t$ map (in %). The intent of this equation is to compress the range of $\mathrm{ALU}_{i,j}^t$ (from 0 to P_{MCAmax}^t) into the range 0 to 100% of the pixel area through the distribution of the exceeding agricultural areas to the other pixels of the MCA. Equation (4) acts at the pixel level where F for each polygon is chosen in an iterative process. For a MCA with at least one pixel with agricultural land use proportion >100% of the pixel area, we first identify the maximum land use pixel value in the MCA. We then start the iteration with a very low F value ($F = 10^{-9}$). The

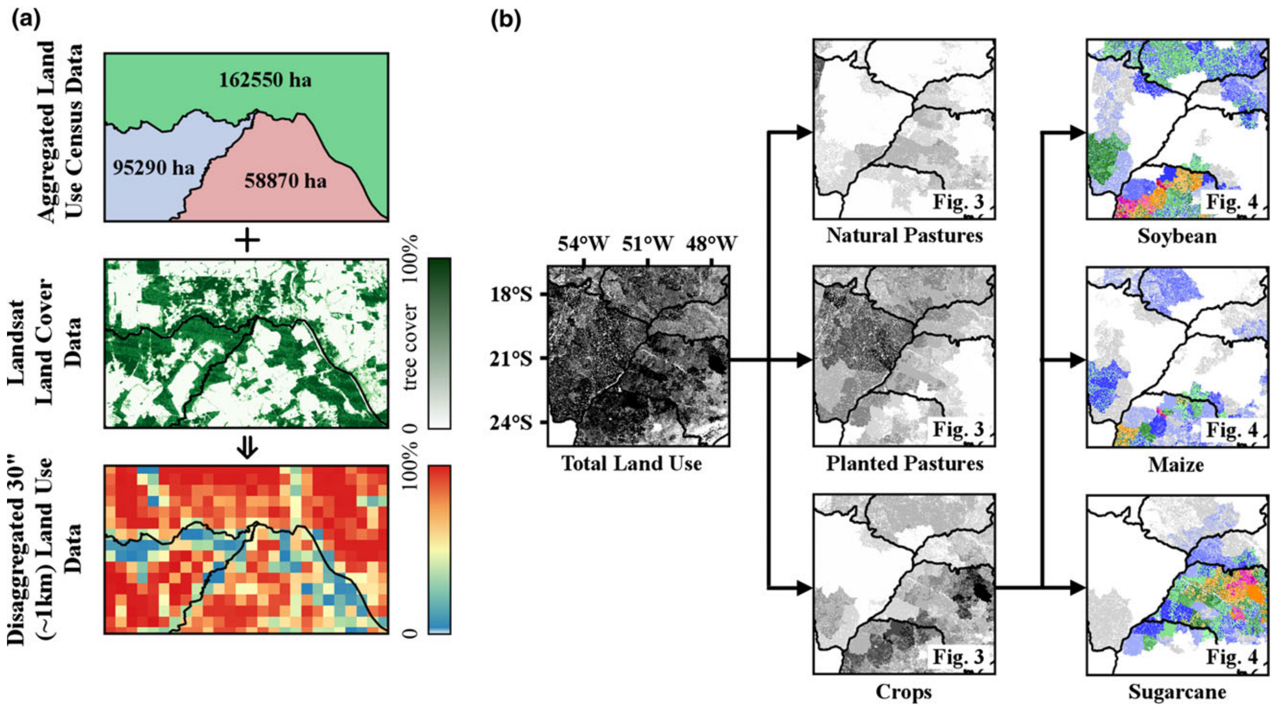

Fig. 2 Steps for the database development. (a) Disaggregation. To create the disaggregated 30″ (~1 km^2) land use data, we merge land use census data aggregated by municipality with Landsat derived land cover map (Hansen *et al*., 2013). (b) Split process. Total land use maps are split into maps of croplands, natural pasturelands, and planted pasturelands. After that, croplands maps are split into maps of soybean, maize, and sugarcane planted area.

equation calculates the new proportion of agricultural land use area used in each MCA pixel. The new agricultural land use area allocated at the MCA is then calculated, and the resulting agricultural land use area is compared with the estimated agricultural land use polygon area. In each iteration, F is incremented and the equation is reapplied using the new F value. The procedure is iterated until the absolute error of the resulting agricultural land use polygon area is lower than 0.001% of the estimated land use polygon area. With this transformation, the pixels initially without deforestation remain with zero agricultural land use value and the other pixels received additional agricultural area.

For the census years 1940 to 1995, the agricultural land use maps are obtained in a process similar to that expressed in Eqn (3). As remote sensing data from Hansen *et al*. (2013) database are not available before the year 2000, we use the 2000 nonforest map as a base for the geographic distribution of agriculture between 1940 and 1995. The fraction of total agricultural land use at the municipality k in a year t [for t = (1940, 1950, 1960, 1970, 1975, 1980, 1985, 1995)] is calculated by dividing the total agricultural land use from the census data in the year t by the total nonforest land area in the municipality in the year 2000. Then, we multiply the municipality grid cells from the nonforest map in the year 2000 by this fraction of total agricultural land use at the municipality k in the year t. The final total agricultural land use maps are expressed as a percentage of area per pixel.

The total agricultural land use maps – for census years between 1940 and 1995 and yearly from 2000 to 2012 – are further divided into maps of cropland and pasturelands (natural and planted pasture; Fig. 2b) using the following procedure: (i) we calculate the proportion of cropland/pasturelands use in a municipality k in a year t by dividing the cropland/pasturelands area by the total agricultural land use area in this municipality k in the year t; (ii) we multiply the total agricultural land use map in the year t by the proportion of cropland/pasturelands use of that grid cell.

To complete the time series, a linear interpolation is carried out between the census years and between 1995 and 2000 for the total agricultural land use, croplands, and pastureland maps. Finally, this same method – using the proportion of the crop-specific use in a municipality k in the year t multiplied by the total cropland use of that grid cell in the year t – is used to split total cropland maps into soybean-, maize-, and sugarcane-planted area maps from 1990 to 2012.

Soybean, maize, sugarcane, and livestock productivity maps

The maps of agricultural productivity are constructed for 1990 to 2012. We calculate the soybean, maize, and sugarcane yield by dividing the production of the MCA by the total crop area extracted from the crop-specific maps for the MCA. Finally, we allocate the productivity data for all MCA pixels. For the cattle stocking rate maps, we divide the amount of cattle heads in the MCA by the total pasture area in the MCA. We eliminate stocking rate of cattle data from the map if the MCA has pasture area <100 ha. In general, one to seven MCAs had

<100 ha between 1990 and 2012 and the mean lost area was approximately 50 ha per MCA. Stocking rate of cattle >8 head ha^{-1} occurred in a maximum of six MCAs. We consider 8 head ha^{-1} to be a high value that may be the result of overestimation of cattle herd size or underestimation of the pastureland in these MCAs. For that reason, stocking rates >8 head ha^{-1} were adjusted to 8 head ha^{-1} – this maximum rate accounted for <0.1% of the total amount of cattle head in Brazil from 1990 to 2012.

Regional productivity–agriculture area relationship

To better understand the extensification–intensification relationship, we generate four graphical summaries of data, each one contrasting the area and productivity of soybean, maize, sugarcane, or cattle. These figures include the productivity–agriculture area relationship for the consolidated agricultural regions and for the emergent regions of each commodity during the study period. In addition, we indicate the production isolines, expressed in millions of tons (or heads) and identify the top 5% most productive areas in the regions selected. We calculated the top 5% with the agricultural productivity maps to obtain the soybean, maize, and sugarcane yield and the stocking rate of cattle for each municipality in the year 2010 only. The top 5% most productive areas are identified by the simple process of organizing the land use area (in pixels) in increasing order and identifying the productivity value of the 95% percentile for each region studied.

Comparison with other land use databases

There are no other products with the temporal range and spatial scale that could fully validate our land use database. Validation was therefore achieved through comparison between three existing land use databases for the Amazon and Cerrado biomes for the most recent years.

The patterns of our total cropland and total pastures maps for 2012 were compared with the map produced by the TerraClass 2012 project (INPE, 2014) and the TerraClass Cerrado 2013 project (INPE, 2015). The TerraClass project aims to map land use and land cover changes in the Brazilian Amazon based in the land cover change maps from the PRODES project (Program for the Annual Estimation of Deforestation in the Brazilian Amazon) and remote sensing data from Landsat. This project has already produced freely available land cover maps for the years 2008, 2010, and 2012 at 30 m spatial resolution. We grouped the 16 classes of the TerraClass 2012 map in four categories: natural vegetation (primary and secondary forest and reforestation), cropland (annual cropland and land use mosaic), pastureland (livestock production in grass species predominance areas, livestock production in grass associated with shrubs areas, regeneration with pasture, pasture mixed with bare soil, and deforestation), and other uses (urban area, mining, not forest, water, not observed area, and other uses).

TerraClass was extended for the Cerrado biome (TerraClass Cerrado) that has one freely available land cover map for the year 2013. For adequate comparison, we grouped the 13 classes of the TerraClass Cerrado map in four categories: natural vegetation (natural forest and naturally not vegetated), cropland (annual crop, permanent crop, and land use mosaic), pastureland, and other uses (urban area, mining, planted forest, bare soil, water, not observed, and other uses). Finally, the Amazon and Cerrado maps, which originally have vector format, were converted to a 30″ grid to be compared against our database.

In addition to TerraClass, Rudorff *et al.* (2015) describe the expansion of the first harvest soybean-, maize-, and cotton-planted area and the land use change associated with this expansion in the Cerrado. The authors conducted a land use and land cover classification using Landsat and MODIS images for the 2000/2001, 2006/2007, and 2013/2014 crop calendar years. As the IBGE planted area data include first and second harvest and maize frequently is used as second crop, only soybean-planted area can be directly compared between Rudorff *et al.* (2015) and our database for 2001 and 2007.

Results

In the following sections, we describe our reconstructed historical land use data and the historical productivity for soybean, maize, sugarcane, and cattle. We define significant land use as grid cells with at least 10% agricultural land use.

Patterns of the agricultural land use in Brazil

In 1940, total agricultural land use was 106 million ha (Fig. 3a) concentrated in South, Southeast and Center-West regions, especially in Rio Grande do Sul, São Paulo, Minas Gerais, Mato Grosso do Sul, and Goiás. Large areas of agricultural land use were established throughout the country until 1985, when Brazil achieved its greatest agricultural land use area (231 million ha, Fig. 3a). Although agriculture keeps expanding toward Center-West and North regions, total agricultural land use in Brazil started to decrease after 1985 due to abandonment or conversions to other nonagricultural land uses in the eastern region. Between 2000 and 2010, total agricultural area grew again (to 220 million ha), although not reaching 1985 levels. In this period, agriculture in Northeast region resumed its growth, especially in the states of Maranhão and Piauí.

Pasturelands always contributed most to total agricultural land use, but the proportions of natural and planted pastureland dramatically change over time (Figs 3b–h). For 1940, natural and planted pastureland data are not individually available in the census data; therefore, we show the total pastureland (planted + natural) in Fig. 3b, with the remark that pasturelands were mostly natural at that time.

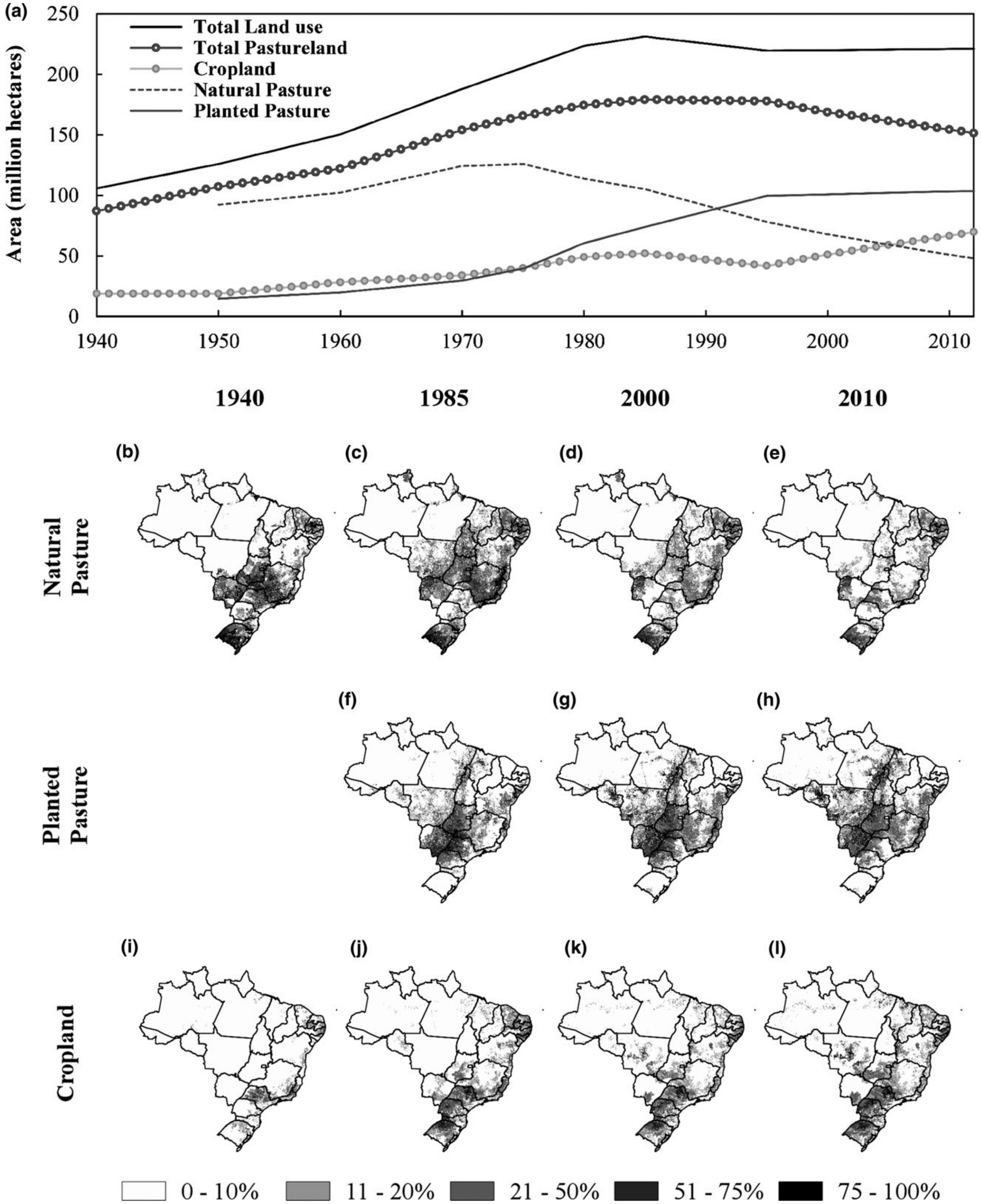

Fig. 3 Agricultural land use in Brazil. (a) Land use area from census data in million ha from 1940 to 2012, natural pastureland in Brazil from (b) 1940, (c) 1985, (d) 2000, and (e) 2010 in percent of the pixel area, planted pastureland in Brazil from (f) 1985, (g) 2000, and (h) 2010 in percent of the pixel area, total cropland in Brazil from (i) 1940, (j) 1985, (k) 2000, and (l) 2010 in percent of the pixel area. For the 1940s, natural and planted pastureland data are not individually available in the census data. We show the total pastureland (natural + planted) in b, with the remark that pasturelands were mostly natural at that time.

Natural pasture area expanded until 1975 (Fig. 3a–e), after which areas with natural pasture were replaced by more profitable planted pasture areas. Natural pastures still are predominant in the Pampas (located in southern Rio Grande do Sul) and Pantanal (located in western Mato Grosso do Sul). Planted pasture expanded during the study period (Fig. 3a, f–h), especially in the Cerrado biome. Brazil reached peak total pasture area in 1985 (179 million ha, Fig. 3a), after which pastureland areas reduced due to abandonment or shifts to croplands. Between 1985 and 2010, planted pasturelands expanded in eastern Pará, Rondônia, and Acre, following the main rivers and roads in the North region.

Cropland areas experienced a gradual expansion between 1940 and 2010 (Fig. 3a, i–l). In 1940, croplands were concentrated in northern Rio Grande do Sul, São Paulo, coastline of the Northeast region, and some parts of Minas Gerais, Rio de Janeiro, and Espírito Santo. By 1985, croplands had expanded around the previously consolidated regions and in the states of Paraná, Santa Catarina, southern Mato Grosso do Sul, and Goiás. After 1985, crops quickly increased in the interior of Brazil, extending into Mato Grosso, Goiás, eastern Bahia, some parts of Pará and Amazonas. Large areas of cropland were abandoned in the Northeast region in 1980s and 1990s probably due to the persistent drought in this region, returning between 2000 and 2010.

Although Brazilian farmers plant a diverse mixture of crops, here we analyze only soybean, maize, and sugarcane (Fig. 4a–h). These three crops account for 72% of crop area (including double cropping) and about 90% of the production of temporary crops in Brazil. Since 1990, large areas of soybean are found in South region and, in low concentration, in some parts of São Paulo, Minas Gerais, Mato Grosso do Sul, Mato Grosso, Goiás, and western Bahia (Fig. 4a). After 1990, soybean extended northward, further moving into the Cerrado, and new soybean crop areas began to appear in Mato Grosso and MATOPIBA (Fig. 4b).

Maize is an omnipresent product in Brazilian culture and small amounts are found in almost all municipalities of Brazil, as this crop frequently is associated with subsistence agriculture. In 1990, the highest concentration of maize crops, probably for commercial purpose, lies in northern Rio Grande do Sul, Santa Catarina, Paraná, and northern São Paulo (Fig. 4c). Between 1990 and 2010, maize reduced in São Paulo and Minas Gerais, but new areas appeared in Mato Grosso do Sul, Mato Grosso, and in central Bahia (Figs 4c, d). More recently, regions with the highest concentration of soybean also have the highest concentration of maize, such as regions in center of Mato Grosso, southern Mato Grosso do Sul, southern Goiás, Paraná, and northern of Rio Grande do Sul. This indicates that maize is being grown as a second crop in these regions (Arvor *et al.*, 2013, 2014).

By 1990, significant areas of sugarcane were found in São Paulo (Fig. 4e), with high concentrations in northern Rio de Janeiro and in northeast coastline (Sergipe, Alagoas, Pernambuco, Paraíba, and Rio Grande do Norte). Between 1990 and 2010, new areas mainly appeared on the periphery of previously observed sugarcane growing centers in São Paulo and Paraná (Fig. 4g, h). In this period, low concentration of sugarcane crop areas appeared in Goiás, Mato Grosso do Sul, and Mato Grosso. Nonsignificant sugarcane areas can also be found in several states, probably because sugarcane is also used as livestock feed for smallholders.

The total pastureland was used in the cattle density analysis. Between 1990 and 2010, total pastureland extensification occurred in North and Center-West regions, while reductions were observed in the South, Southeast, and Northeast regions (Fig. 4g, h).

Patterns of the crop productivity and cattle density

Soybean yield increased throughout the country between 1990 and 2010 with mean yield increasing from 1.7 to 2.9 t ha^{-1} (Fig. 4i, j). In 1990, soybean productivities at significant areas ranged from 0.57 to 2.4 t ha^{-1} and the highest yields were found in the South and Center-West regions (Fig. 4i). In 2010, mean soybean yield was 2.39 t ha^{-1} with a higher productivity of 3.4 t ha^{-1} and a lower productivity of 1.8 t ha^{-1}. In this year, the highest soybean yields were found especially in Paraná state (Fig. 4j).

Between 1990 and 2010, mean maize yield increased 2.5 t ha^{-1}, from 1.8 to 4.3 t ha^{-1} (Fig. 4k, l). Mean maize yield at significant areas in 1990 was 2.2 t ha^{-1} (ranged from 0.01 to 4.3 t ha^{-1}) with some regions in Paraná and Goiás characterized by very high productivity (Fig. 4k). In 2010, maize yields ranged from 0.04 to 9.5 t ha^{-1}. In this year, the highest maize productivities were located in South region (Fig. 4l) with western Bahia characterized by yields of >8 t ha^{-1}.

Mean sugarcane yield increased from 60.8 to 78.3 t ha^{-1} between 1990 and 2010 (Fig. 4m, n). Sugarcane productivity varied substantially between São Paulo and the Northeast region. In São Paulo, mean yield increased from 76 t ha^{-1} in 1990 to 84 t ha^{-1} in 2010, with some regions reaching 110 t ha^{-1} in this period. Sugarcane yield at significant areas in São Paulo ranged from 62.4 to 93.8 t ha^{-1} in 1990 and from 70.9 to 110.8 t ha^{-1} in 2010. In the Northeast region – especially the states of Sergipe, Alagoas, Pernambuco, Paraíba, and Rio Grande do Norte – mean productivity

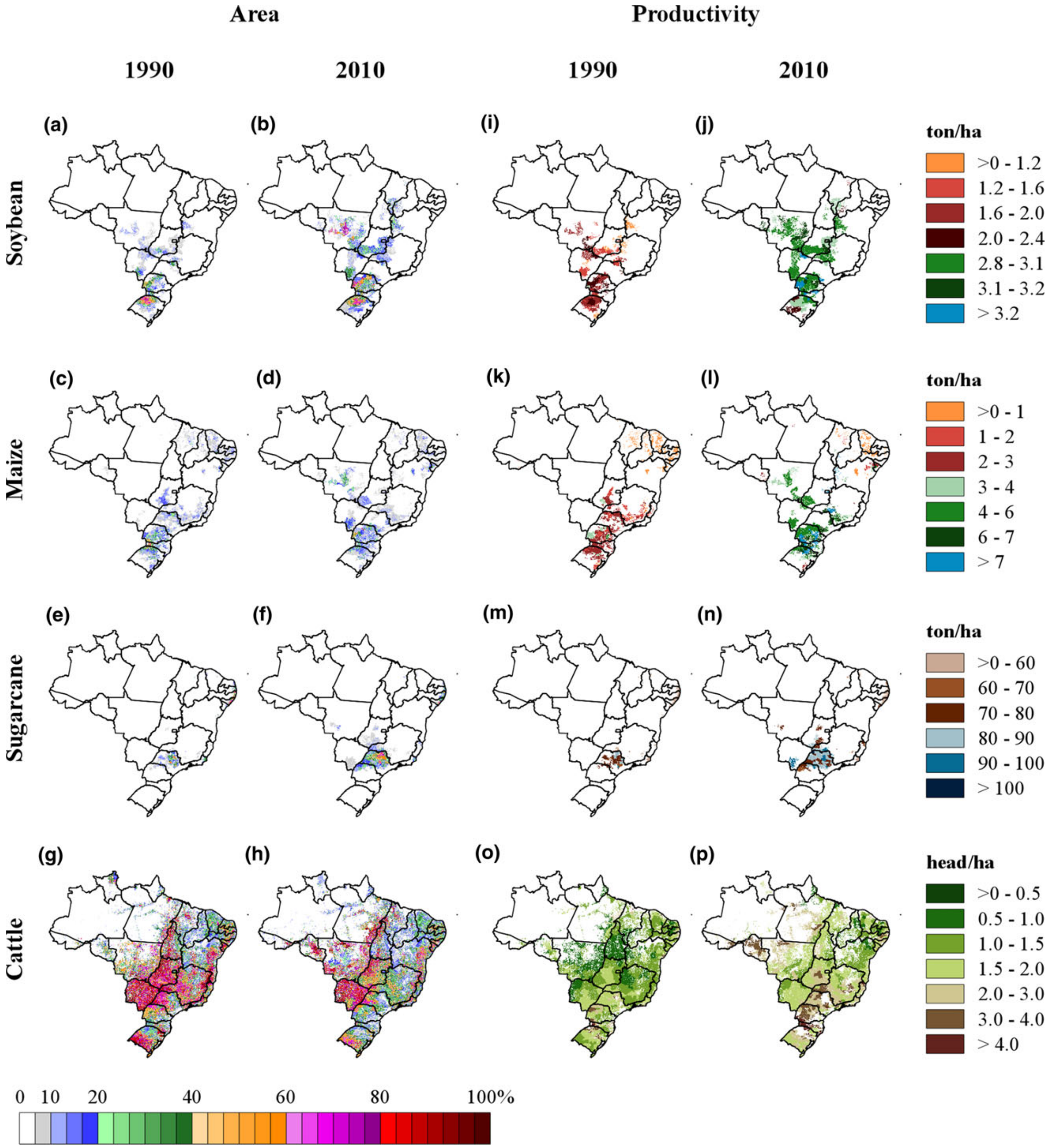

Fig. 4 Planted area of (a) soybean in 1990, (b) soybean in 2010, (c) maize in 1990, (d) maize in 2010, (e) sugarcane in 1990, and (f) sugarcane in 2010 in percent of the pixel area. Total pastureland area in (g) 1990 and (h) 2010 in percent of the pixel area. Yield of (i) soybean in 1990, (j) soybean in 2010, (k) maize in 1990, (l) maize in 2010, (m) sugarcane in 1990, and (n) sugarcane in 2010. Stocking rate of cattle in Brazil in (o) 1990 and (p) 2010 in head per hectare. Data are not showed in this map if the micro region had pasture area <100 ha and stocking rate was limited in 8 head ha^{-1}.

increased from 48 to 55 t ha^{-1} between 1990 and 2010. Sugarcane yield in significant areas in the Northeast region ranged from 30.9 to 76.7 t ha^{-1} in 1990 and from 32.4 to 69.1 t ha^{-1} in 2010. A new sugarcane region in Mato Grosso do Sul had very high yield (99 t ha^{-1}) in 2010.

Cattle stocking rate increased slowly in Brazil between 1990 and 2010 (Fig. 4o, p). The mean cattle stocking rate was 0.82 head ha^{-1} in 1990 and 1.36 head ha^{-1} in 2010. During the study period, cattle density increased unevenly with many low-productivity regions (< 1 head ha^{-1}) and a few regions with high productivity (>4 head ha^{-1}). Between 1990 and 2010, the stocking rate of cattle was >4 head ha^{-1} in Rio Grande do Sul, Paraná, Santa Catarina, and São Paulo states and in parts of the Northeast region coastline, especially in Maranhão. Stocking rate of cattle grew quickly during 2000s in Minas Gerais, Paraná, Santa Catarina, Maranhão, Goiás, Mato Grosso, Rondônia, Acre, and Pará.

Productivity–agriculture area relationship

We analyzed the extensification–intensification relationship for soybean in Amazonia and Cerrado biomes, South and Center-West regions, and MATOPIBA (Fig. 5). These regions represent nearly 83% of the soybean crop area in Brazil. The increase in Brazilian soybean production came from both increases in productivity and expansion of the crop area (Fig. 5a). Amazonia soybean production increased 25-fold between 1990 and 2012 (from 0.3 to 7.6 million of tons), while planted areas increased from 0.2 to 2.4 million ha and productivity grew up from 1.8 to 3.1 t ha^{-1}. Between 1990 and 2010, the production of soybean in the Cerrado biome increased more fivefold (from 7.1 to 37.6 millions of tons) due to an increase in area (from 4.6 to 12.4 million ha) and a doubling in yield (from 1.5 to 3 t ha^{-1}). MATOPIBA also showed a remarkable increase in production, area, and yield between 1990 and 2012, with soybean production increasing 28 times (from 0.26 to 7.4 millions of tons), planted area increasing from 0.4 to 2.5 million ha, and yield increasing from 0.64 to 2.9 t ha^{-1}.

Soybean-planted area increased in the South region by 30% (from 6.2 to 9.2 million ha) and production more than doubled (from 11.5 to 25.9 millions of tons) between 1990 and 2010. In this region, soybean production reached 28.7 millions of tons in 2011, but it decreased to 17.9 millions of tons in 2012, while the soybean-planted area increased by approximately 0.9 million ha. The harvest from 2004/2005 and 2011/2012 in the South region had very low yield (about 1.4 t ha^{-1} in 2005 and 1.9 t ha^{-1} in 2012), probably due to climatic factors. The Center-West region had approximately 3.9 million ha of planted area in 1990 and produced 6.4 millions of tons of soybean. After 22 years, the area of soybean increased to 11.5 million ha and production increased to 35 million of tons. The Center-West curve is similar to Cerrado curve (Fig. 5a) due to the large overlap between the two regions.

Mean soybean yield was approximately 3 t ha^{-1} in 2012 for all analyzed regions, and in general, the highest soybean yields (top 5%) were not dramatically higher than the average in 2010. The yield gap (difference between mean productivity and the top 5%) was lowest in Cerrado, where the mean soybean yield was only 7.5% lower than the top 5%, and was greatest in the South region, when the mean soybean yield was 17% lower than the top 5%. The mean soybean yield was 8.5%, 10%, and 14% lower than the top 5%, respectively, in the Center-West region, MATOPIBA, and Amazonia biome.

Maize is produced mainly in the South and Center-West regions, accounting for nearly 66% of Brazilian maize production. In the Center-West region, maize crop area increased 3.6 times (from 1.5 to 5.3 million ha) while yield increased nearly threefold (from 2.1 to 5.9 t ha^{-1}) between 1990 and 2012 (Fig. 5b). In this period, maize production rose from 3.1 to 30.7 millions of tons in Center-West region. Maize crop area in the South region started with 4.8 million ha in 1990, ranged between 3.9 and 5.7 million ha, and was 4.6 million ha in 2012 (Fig. 5b). In this region, maize yield increased to 2.5 from 4.8 t ha^{-1} and production doubled (from 11 to 22 million of tons) between 1990 and 2012. The top 5% in South region (8.9 t ha^{-1}) is greater than in Center-West region (6.5 t ha^{-1}). In 2010, the mean yield was 31% lower than the top 5% in the Center-West region and was 36% lower than the top 5% in the South region.

Brazil has two main sugarcane production centers: in the Northeast region and in São Paulo/Paraná. In the context of sugarcane, the northeastern sugarcane region is formed by the states of Alagoas, Paraíba, Pernambuco, Rio Grande do Norte, and Sergipe. The two main sugarcane production centers represent nearly 70% of the sugarcane crop area in Brazil. Although mean sugarcane production in northeast Brazil ranged from 31.9 and 62.4 millions of tons, it was close to 60 millions of tons for many years between 1990 and 2010 (Fig. 5c). Moreover, sugarcane crop area in northeastern sugarcane region decreased by 23% (from 1.3 to 0.99 million ha) while the yield increased to 47.9 from 55.7 t ha^{-1}, which indicates a trend of intensification. The top 5% (62 t ha^{-1}) was very similar to the mean yield (55 t ha^{-1}) in the northeast Brazil, suggesting that most producers were working at their maximum capacity.

In São Paulo and Paraná states, the sugarcane yield was greater than that observed in northeastern sugarcane region between 1990 and 2012. In this period, mean sugarcane yield was 79 t ha^{-1} in the two more Southern states as compared to 51.8 t ha^{-1} in the Northeast states. São Paulo and Paraná experienced

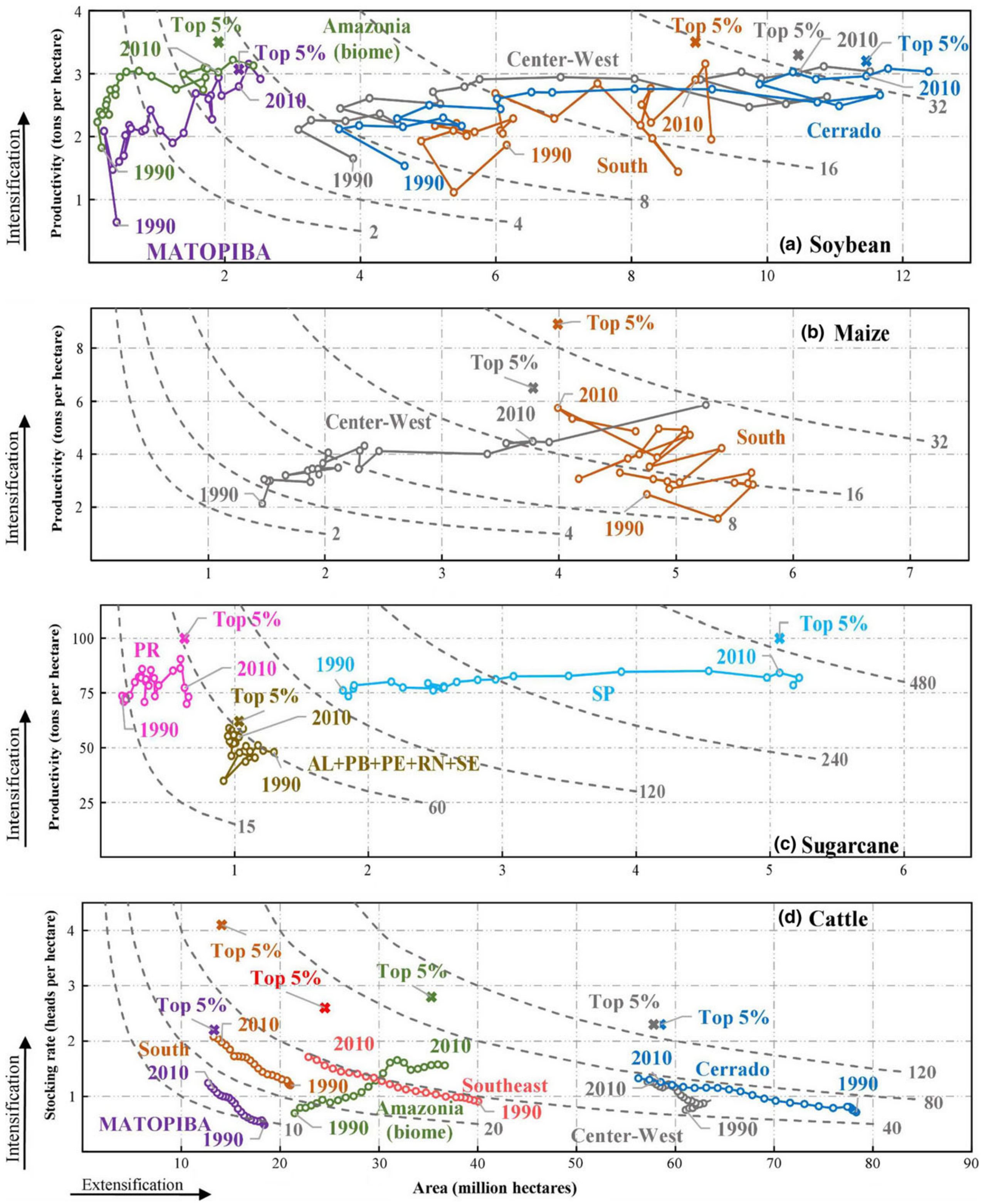

Fig. 5 Extensification-intensification analysis. Trends in (a) soybean planted area and yield for the Amazonia and Cerrado biomes, Center West and South regions and MATOPIBA, (b) maize planted area and yield for Center-West and South regions, (c) sugarcane planted area and yield for São Paulo and Paraná states and a region formed by the states of Alagoas, Paraíba, Pernambuco, Rio Grande do Norte, and Sergipe (AL + PB + PE + RN + SE), (d) pastureland areas and stocking rate of cattle for the Amazonia and Cerrado biomes, Center-West, South, and Southeast regions and MATOPIBA.

extensification in sugarcane-planted area. São Paulo had 1.8 million ha of sugarcane area in 1990 and 5.2 million ha in 2012. In this state, sugarcane production also increased from 137.8 to 406.2 millions of tons in 22 yr. Sugarcane-planted area in Paraná increased by 0.5 million ha (from 0.16 to 0.66 million ha) in area and production by 36.2 millions of tons (from 11.7 to 47.9 millions of tons) between 1990 and 2012. The top 5% was 100 t ha^{-1} in São Paulo and 95 t ha^{-1} in Paraná state. The yield gap was greater in Paraná, where the mean sugarcane yield was 22.7% lower than the top 5%, while in São Paulo, the mean sugarcane yield was 15.9% lower than the top 5%.

Finally, we studied the extensification–intensification relationship for cattle in Amazonia and Cerrado biomes, Center-West, South, and Southeast regions and MATOPIBA (Fig. 5d). These regions represent nearly 95% of the pasturelands in Brazil. Both total pastureland areas and stocking rate of cattle increased in Amazonia (Fig. 5d). Between 1990 and 2012, cattle numbers increased fourfold (from 14.9 to 57.2 million heads) in Amazonia biome due to an increase in pastureland area from 21.5 to 36.7 million ha and the increment of 2.5 times in stocking rate (from 0.69 to 1.56 head ha^{-1}). On the other hand, the Cerrado biome, Center-West, South, and Southeast regions and MATOPIBA show clear evidence of livestock intensification (Fig. 5d), with decreases in pasture areas associated with increases in stocking rates.

Pasturelands decreased in the Cerrado biome from 78.3 to 56.3 million ha while stocking rate of cattle grew from 0.7 to 1.3 head ha^{-1}, and total herd size increased from 55.8 to 74.6 million between 1990 and 2012. In the Center-West region, pasturelands decreased from 61.0 to 57.2 million ha and herd size increased from 45.9 to 72.4 million, increasing the stocking rate from 0.8 to 1.3 head ha^{-1} between 1990 and 2012. The South region had the greatest stocking rate of cattle in 1990 (1.2 head ha^{-1}) and in 2012 (2.1 head ha^{-1}). During the period of study, cattle herd size in the South region was nearly constant at 27 million and pasturelands decreased from 21 to 13.3 million ha. In Southeast region, the cattle herd size remained close to 38 million during the study period, although pastureland contracted from 40 to 22.9 million ha and stock rates increased from 0.9 to 1.7 head ha^{-1}. MATOPIBA pasturelands decreased by 5.7 million ha in the 22 yr analyzed (from 18.4 to 12.7 million ha) while production increased from 8.9 to 15.7 million heads and productivity gradually increased from 0.48 to 1.2 head ha^{-1}.

The yield gap was largest in the South region where the mean stocking rate of cattle in 2010 (1.97 head ha^{-1}) was 52% lower than the potential given current practices (the top 5% was 4.1 head ha^{-1}). In contrast, the lowest yield gap was found in the Southeast region, where the mean stocking rate (1.56 head ha^{-1}) was 40% lower than the top 5% (2.6 head ha^{-1}). In Amazonia, the mean stocking rate of cattle (1.56 head ha^{-1}) was 44% lower than the top 5% (2.8 head ha^{-1}). In the Cerrado biome and Center-West region, the mean stocking rate was 45% lower than the top 5% for cattle (2.3 head ha^{-1} in both areas). Finally, the mean stocking rate in MATOPIBA (1.13 head ha^{-1}) was 48% lower than the top 5% (2.2 head ha^{-1}) in 2010.

Intercomparison

In the TerraClass map, each pixel is classified as only one type of land use. Then, if it is indicated that there is pastureland in one pixel, 100% of the land use in this pixel is pastureland. On the other hand, our methodology produces maps with percentage of area with a land use. This methodological difference needs to be understood to compare the maps on Fig. 6.

The TerraClass project reports 44.2 million ha of pasturelands in Amazon in 2012 and 60 million ha in Cerrado in 2013. We estimate that total pasture in the year 2012 was 36.7 million ha in Amazon (17% less) and 56

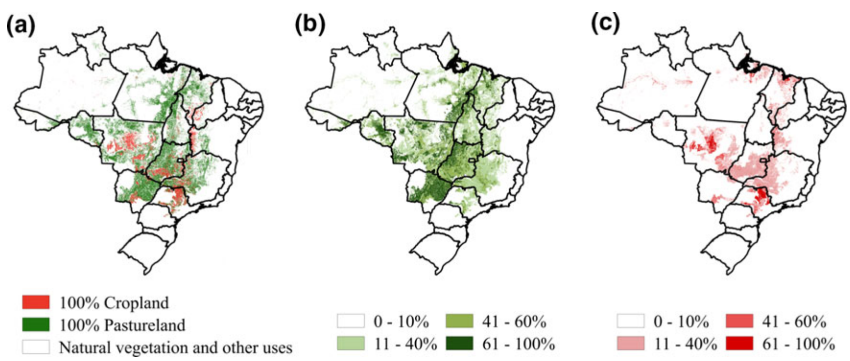

Fig. 6 Comparison between: (a) the TerraClass projects maps for Amazon in 2012 and Cerrado in 2013; (b) the 2012 total pastureland map and; (c) the 2012 total cropland map.

million ha in Cerrado (7% less). The patterns of pastureland identified in the TerraClass (Fig. 6a) and in the 2012 map produced in this study (Fig. 6b) agree in several regions. In both products, pasturelands are found near the highway that crosses Rondônia (BR-364), the Trans-Amazonica highway (BR-230) that crosses the Pará state from east to west, and along the BR-163 that connects Cuiabá (Mato Grosso) to Santarém (western Pará). Pasturelands also are predominant in both products in eastern Acre, around the state's capital, and in Mato Grosso do Sul. In the Cerrado, the overall pattern is similar, although the pasturelands in our maps are more widely distributed than in the TerraClass maps (Fig. 6). In MATOPIBA and Mato Grosso, for example, our map indicates more pixels with a small percentage of pastureland while TerraClass has fewer pixels with 100% of use.

According to TerraClass project, croplands occupy 5.2 million ha in Amazonia and 24.6 million ha in Cerrado. We estimate 8.2 million ha of cropland in Amazonia (58% more) and 24.3 million ha in Cerrado (1% less). In both TerraClass and our products, croplands are found mainly in the center and southeastern Mato Grosso, southern Mato Grosso do Sul, southern Goiás, western Minas Gerais, northern São Paulo, southern Maranhão, southern Piauí, and western Bahia (Fig. 6c). Cropland distributions are also more widespread in our maps than in the TerraClass maps, especially in Goiás and Minas Gerais states.

Our historical soybean-planted area database has an absolute error smaller than 10% when compared with Rudorff *et al.* (2015) report. Rudorff *et al.* (2015) found that Cerrado has 7.5 million ha of soybean-planted area in 2001 and 10.1 million ha, in 2007. We estimate 6.8 million ha of soybean-planted area in the Cerrado in 2001 (9% less) and 9.8 million ha, in 2007 (3% less). In MATOPIBA, Rudorff *et al.* (2015) estimated 0.9 million ha of soybean-planted area in 2001 while we estimated 1 million ha of this crop (1% more). For the year 2007, Rudorff *et al.* (2015) estimated 1.7 million ha while we report 1.8 million ha of soybean-planted area (6% more) in the new agricultural frontier.

Discussion

We aimed to characterize agricultural land use change and productivity in Brazil. The most general trends were probably the gradual replacement of natural pasturelands with planted pasture in several parts of the country since the 1970s and the rapid expansion of croplands since the 1980s in almost all states. In recent years, cropland and pastureland increased in Amazonia and Cerrado agricultural frontiers while agriculture areas in South, Southeast, and Northeast regions decreased (mainly after 1985). Barretto *et al.* (2013) observed that agricultural contraction has mainly occurred near metropolitan areas in Southeast regions and in semi-arid region in the Northeast region.

Soybean cultivation has been considered a powerful threat to the environment in Brazil (Fearnside, 2001) and has been identified as one of the main drivers of increases in cropland areas in Latin America (Gibbs *et al.*, 2010). Indeed, soybean areas have been quickly expanding (approximately 0.61 million ha year^{-1} between 1990 and 2012) and reached 25 million ha in 2012, 36% of the total cropland area in Brazil. Moreover, several regions with high concentration of soybean also have high concentrations of maize. These patterns may indicate double crop practice. This hypothesis can be verified in Mato Grosso: areas that have high concentrations of soybean and maize in our maps closely correspond to areas identified by Arvor *et al.* (2013) as 'double cropping systems with two commercial crops'.

Sugarcane areas have recently increased in Brazil due to increase in the fleet of dual-fuel (ethanol–gasoline) cars (Rudorff *et al.*, 2010). Sugarcane areas are mainly concentrated in the center and northern São Paulo state, which is responsible for approximately 60% of national production. We observed that pasturelands (natural and planted) contracted while sugarcane expanded in these areas. These findings are consistent with Rudorff *et al.* (2010), who found that sugarcane expansion occurred mainly over pasture and summer crop areas.

West *et al.* (2014) suggested reduction in natural vegetation conversion in Brazil as a strategy for agricultural sustainability and food security. Halting deforestation by agricultural expansion seems a wise strategy to avoid losses in productivity, especially in a climate change future (Lapola *et al.*, 2011; Oliveira *et al.*, 2013). However, it is not a simple task. Despite public efforts against deforestation, we estimated that 13 million ha of new agricultural areas was established between 2006 and 2012, of which 55% replaced Amazon rainforest and 24% replaced Cerrado. For a future that combines environmental protection with enhanced food security, Foley *et al.* (2011) suggests that agricultural expansion needs to stop. However, the authors highlight that diverse strategies need to be combined, such as closing yield gaps, and that no single solution will be sufficient. Identifying appropriate suites of potential strategies will require detailed analysis of historical trends in ecosystem services and the interaction between productivity and expansion of agricultural areas.

Although Brazilian agriculture has been historically known for extensification of agriculture at the expense natural vegetation (especially in the Amazonia and Cerrado), data from recent years indicate that extensification has slowed and intensification is increasing. For example, soybean extensification was accompanied by intensification in all regions analyzed. The increase in soybean-planted area in Center-West and South regions coincided with pastureland contraction in these regions, which may imply that soybean crop may have advanced over pasture areas (as demonstrated by Macedo *et al.* (2012) for Mato Grosso). In contrast, an increase in soybean-planted area in MATOPIBA coincided with pastureland contraction, but in this case, soybean-planted areas have advanced mainly over native vegetation (Rudorff *et al.*, 2015). The increment in soybean-planted area was proportionally greater than the increment in yield, but the new soybean crop areas had similar yield than the adjacent and consolidated areas.

Maize experienced extensification and intensification in the Center-West region, but not in the South region. Part of the area increment in the Center-West is probably due to the adoption of double cropping, and not conversion of natural vegetation into maize. São Paulo and Paraná states clearly experienced sugarcane extensification, characterized by increases in area and little increase in yield. Low increases in yield probably occurred because, in general, new sugarcane producers adopt adjacent practices allowing them to quickly reach sugarcane yields similar to consolidated areas.

Cattle density increased approximately 21% between 1990 and 2012, but the slow process of technology transfer appears to be keeping the Brazilian cattle stocking rate near to 1.0 head ha^{-1} in several parts of the country. Such low values are indicative of an inefficient livestock system (Lapola *et al.*, 2014). Livestock intensification is possible, as demonstrated by some regions that recently reached high cattle stocking rates. Further research is needed to identify the current management in the most productive regions and to assess whether these farms are sustainable and whether their practices are transferable.

Anthropic activities have extensively modified the Earth's surface, and land use change is one of the most obvious manifestations (Foley *et al.*, 2005). Evaluating human impact on the environment and designing strategies for sustainable development requires spatially accurate descriptions of land use changes and identification of their drivers. Land use change significantly influences a variety of global processes. For example, the conversion of native vegetation to agriculture can change atmospheric characteristics at regional scales (Costa & Pires, 2010), alter energy and water balance (Anderson-Teixeira *et al.*, 2012; Stickler *et al.*, 2013), modify soil characteristics (Scheffler *et al.*, 2011; Hunke *et al.*, 2015), cause biodiversity loss (Chaplin-Kramer *et al.*, 2015; Newbold *et al.*, 2015), and disrupt important ecosystem services. Ramankutty & Foley (1998) suggest that accurate land use databases can be used directly within climate and ecosystem models. Indeed, our land use database could be used for a wide range of research, such as meteorology, hydrology, agronomy, ecology, conservation, and territorial planning. In addition, our analyses provide insights into the extensification–intensification relationship and new information on Brazil's newest agricultural frontier (MATOPIBA).

Although we provide a basic yield gap analysis – the relationships between average yields and the top yields – a more extensive analysis of the spatial and temporal variability of yields is a priority that will be explored in future studies. Yield gap analysis is a powerful tool to analyze deficits in agricultural technology and closing this gap could have a dramatic impact on food security (Godfray *et al.*, 2010; Foley *et al.*, 2011; Mueller *et al.*, 2012).

To characterize the agricultural land use change in Brazil and productivity of four agricultural products (soybean, maize, sugarcane, and cattle), we merged agricultural census data and remote sensing data for the whole country from 1940 to 2012 at 30″ spatial resolution. This 'data fusion' technique was first developed by Ramankutty & Foley (1998) and has subsequently been subject to several modifications and improvements. Leite *et al.* (2011) merged a satellite-derived land classification for 2000 at a spatial resolution of 5′ (approximately 10 × 10 km; Ramankutty *et al.*, 2008) with census data to analyze the geographic patterns of agricultural land use in Brazilian Amazon. This methodology has been validated by Leite *et al.* (2011) who concluded that the combination of census data and remote sensing data provides maps that are consistent with independent estimates of changes in land cover. More recently, Leite *et al.* (2012) used the same methodology to reconstruct geographically explicit changes in agricultural land use for the entire Brazilian territory.

We were able to generate high-quality land use and productivity maps for Brazil between 1940 and 2012. The reconstructed changes in land use patterns are consistent with the history of agricultural geography in Brazil, and our land use reconstruction had the same pattern as previously described by Leite *et al.* (2012). Nevertheless, some uncertainties and inaccuracies still need to be clarified.

Firstly, the Hansen *et al.* (2013) database contains maps of global tree cover for the year 2000, with forest loss allocated annually from 2001 to 2012. These tree cover maps have approximately 30 m spatial resolution, and trees are defined as vegetation taller than 5 m. Tropek *et al.* (2014) claim that the definition of 'forest' as trees taller than 5 m in height is problematic because monocultures, such as *Eucalyptus*, are considered forest. Moreover, it is not clear whether this satellite-based product considers permanent cultures, such as orange, mango, and guava, as forested or deforested areas. Tropek *et al.* (2014) also identified some areas with vegetation lower than 5 m (such as pineapple, banana, and soybeans) that were wrongly considered forests, although Hansen *et al.* (2014) argues that rigorous statistics are used to validate the maps. Nevertheless, Hansen *et al.* (2013) database provides annual nonforest maps for the entire Brazil.

Remote sensing captures only the top of the vegetation and provides relatively little information about land use (Leite *et al.*, 2012). In addition to the remote sensing data, our methodology used agriculture surveys and estimated data, which introduced other inaccuracies. First, we estimated annual total agricultural land use, cropland, and pastureland data for municipalities based on the micro region growth rate. Although it is a reasonable assumption, as a micro region is an administrative unit that aggregates municipalities with similar characteristics, each municipality could have a different agricultural development rate. Second, we extrapolated the trend between 1995 and 2006 census data to estimate annual data between 2007 and 2012. Until a new agricultural census data are completed, it will not be possible to verify the real error introduced by this step. Furthermore, the agricultural census data are another possible source of error because it cannot be independently verified. These inaccuracies due to the use of the agriculture surveys and estimated data are one of the main causes of the difference between the amount of pastureland and cropland in TerraClass and our database.

Another intrinsic error is that agricultural census data are allocated in all land areas considered as nonforest (no trees) in the smallest administrative unit used to create the maps. Thus, we cannot avoid allocating agriculture to unsuitable areas, such as urban areas, rivers, beaches, dunes, wetlands, and small dams. The Hansen *et al.* (2013) database may underestimate or overestimate forest loss, and this directly influences how the census data are spatialized. Underestimated forest loss areas are corrected by the procedure of Eqn (4) applied to 4% of the pixels located in approximately 2000 municipalities. In overestimated forest loss areas (areas where forest cover or leaf area index is lower) such as several Cerrado, Caatinga, Pampas, and Pantanal phytophysionomies, the census data are widely distributed in an AMC. This widespread distribution causes the difference between the land uses pattern in TerraClass map (Fig. 6a) and our database (Fig. 6b, c). Due to this possible allocation of agriculture into unsuitable areas and widespread distribution, our maps, while appropriate for large-scale patterns analysis, should not be employed in analysis of smaller areas than the AMC used to produce the maps.

Additionally, the agricultural reconstruction between 1940 and 1999 is primarily derived from the 2000 map. In this procedure, we implicitly consider that agricultural areas have never occupied areas wider than the ones with agricultural activities in 2000. For example, if there was agriculture in a region in the past that has been abandoned to vegetation recovery, it would not contain agriculture areas in the year 2000 and it would not be possible to correctly reconstruct agriculture in this region.

Future research efforts should also focus on the development of higher quality agricultural maps. Remote sensing can identify spatial patterns of land cover, but has difficulties distinguishing between land uses or specific crops, at least at the large scale. This problem may be partially alleviated by merging high-resolution satellites data, national inventories, and 'field truths'. The moderate resolution multispectral MODIS plus Landsat 8 data and data from the recently launched Sentinel-2A could provide robust crop mapping over time and space. In addition to the national survey data, new ancillary information is also required to create and validate the land use classification, such as georeferenced land use surveys of farmers. Future research will involve even higher volumes of data and will therefore demand considerable computational power. Fortunately, massive cloud-based computational platforms for Earth observation data processing should soon allow us to better identify and monitor croplands and pasturelands.

Acknowledgments

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