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Changes in secondary vegetation dynamics in a context of decreasing deforestation rates in Pará, Brazilian Amazon

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ABSTRACT

Tropical secondary vegetation is of particular interest as carbon sinks, potential lands for agriculture and livestock expansion, biodiversity conservation and ecosystem services. Until mid-2000s estimates of secondary vegetation in the Brazilian Amazon indicated a progressive increase of this cover, however after 2010, only 1197 km^2 of additional secondary vegetation were generated, while 42,040 km^2 were converted into other land-covers. Meanwhile, deforestation rates progressively decreased to be around 6000 km^2 in contrast to the peak of 27,772 km^2 in 2004, what suggests that changes in land-cover dynamics with respect to deforestation may be related to a reduction in secondary vegetation. Hence, in this paper, we work with the hypothesis that, in a context of decreasing deforestation rates, the historic pattern of progressive accumulation of secondary vegetation in the Brazilian Amazon changed as a consequence of the re-conversion of this cover, as well as other land-covers relevant in the process of regeneration, into different land-covers that expanded in this period. Our focus was then to investigate, on a regional scale, the spatiotemporal patterns of secondary vegetation with respect to different land-covers in Pará based on (i) a quantitative analysis of transitions between land-covers, and (ii) on clustering patterns of secondary vegetation cover and their relations with clustering patterns of pastures, small-scale and industrial agriculture. We found that more secondary vegetation was converted into land-covers that expanded in the period i.e. clean pasture, mechanized agriculture, and palm oil, with secondary vegetation and land-covers important for regeneration (i.e. small-scale agriculture and regeneration with pasture) experiencing an overall reduction and contributing less to the concentration of secondary vegetation after 2010. Clusters of high values (hotspots) of secondary vegetation prevailed in the north, while clusters of low values (cold spots) prevailed in the south of Pará, a pattern that is explained by different histories of occupation and deforestation dynamics, as well as distinct regional land dynamics in the past decade. As a first contribution to understanding the dynamics of secondary vegetation in a context of decreasing deforestation rates, our results show that the increased pressure to halt deforestation had effects over the dynamics of this land-cover, as well as over land-covers relevant to regeneration.

1. Introduction

Tropical secondary vegetation is of particular interest as carbon sinks (Aguiar et al., 2016; Neeff et al., 2005; Orihuela-Belmonte et al., 2013), potential lands for agriculture and livestock expansion (Pereira & Vieira, 2001; Strassburg et al., 2014), biodiversity conservation and ecosystem services (Benayas, Newton, Diaz, & Bullock, 2009; Chazdon et al., 2009; Klemick, 2011; Smith, Ferreira, van de Kop, Ferreira, & Sabogal, 2003). Ultimately the result of land-use and abandonment, the regeneration and permanence of secondary vegetation are largely influenced by environmental factors, and directly connected to land-use decisions (Chazdon et al., 2009, 2012; Guariguata & Ostertag, 2001;

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Holl, 1999; Laue & Arima, 2014; Lu, Moran, & Mausel, 2002; Moran et al., 2000; Mesquita, Ickes, Ganade, & Williamson, 2001; 2015; Perz & Skole, 2003). Among the environmental factors determining regeneration, an emphasis has been given to soil degradation, heavy rains, steeper sloped topography and reduced primary forest remnants (Bentos, Nascimento, & Williamson, 2013; Chazdon et al., 2009, 2012; Mesquita et al., 2001; 2015). In this respect, exception made to reduced primary forest remnants, all other environmental factors affect regeneration both directly, as determinants of ecological pathways of regeneration, and indirectly, as determinants of land-abandonment (Benayas, Martins, Nicolau, & Schulz, 2007; Laue & Arima, 2014; Mesquita, dos Santos Massoca, Jakovac, Bentos, & Williamson, 2015; Perz & Skole, 2003; Spera et al., 2014).

Soil depletion and changes in physical structure were found to negatively impact the initial stages of regeneration, in particular where heavy rains, constantly high temperature and frequent use of fire accelerate soil degradation (Guariguata & Ostertag, 2001; Lu et al., 2002; Moran et al., 2000). Heavy rains and accelerated soil degradation also increase propagation of plant and animal diseases (Laue & Arima, 2014; Perz & Skole, 2003) while steeper sloped lands, besides reducing the development of seedlings, may jeopardize agricultural activities, especially if mechanization is required (Benayas et al., 2007; Bentos et al., 2013; Laue & Arima, 2014; Spera et al., 2014). Therefore, these environmental factors as they require higher investments in agricultural inputs and negatively impact the success of agricultural activities may lead to land abandonment (Perz & Skole, 2003).

Costa (2004; 2009) emphasizes that the regeneration and persistence of secondary vegetation in the Brazilian Amazon are the results of three main land-use decisions: integration into a land-use system (e.g. small scale agriculture), land abandonment (e.g. degraded pastures), and intensification through the conversion of secondary vegetation into perennial or semi-perennial land-uses (e.g. industrial agriculture). Integration of secondary vegetation through fallow periods in small scale agriculture, for instance, makes of this cover an asset as it provides important ecosystem services (e.g. protect soils and increase fertility), and timber and non-timber resources (Coomes, Grimard, & Burt, 2000; Smith et al., 1999, 2003). In addition, the prevalence of small properties associated with small scale agriculture systems potentially favors the concentration of secondary vegetation (Almeida, Valeriano, Escada, & Rennó, 2010). In cattle ranching systems, secondary vegetation is a byproduct of forest clearing and establishment of pastures which, following rapid degradation, are eventually abandoned (Costa, 2004, 2009; Mesquita et al., 2015, 2001; Nepstad, Uhl, Pereira, & da Silva, 1996; Uhl, Buschbacher, & Serrao, 1988). Notwithstanding, investigations show that some practices adopted in pasture management (e.g. intensive grazing, use of fire, continued cutting, and reduction of primary forest remnants) can slow or even preclude regeneration (Mesquita et al., 2001; Nepstad et al., 1996; Uhl et al., 1988). Also, the prevalence of large properties implies more deforestation (Pacheco, 2009) which can affect regeneration by reducing primary forest remnants (Chazdon, 2012; Mesquita et al., 2001). Hence, small scale agriculture and cattle ranching are the main land-uses ontributing to regeneration (Costa, 2004; Nepstad et al., 1996; Uhl et al., 1988), while the recent expansion of industrial agriculture may be leading to a reduction in secondary vegetation (Butler & Laurance, 2009; Lameira, Vieira, & Toledo, 2015; Lees & Vieira, 2013; Vieira, Gardner, Ferreira, Lees, & Barlow, 2014).

Until the mid-2000s, absolute figures on secondary vegetation indicated a progressive increase in this cover in the Brazilian Amazon, with estimates being that 140,000 km^2 to 161,000 km^2 of deforested lands were under regeneration (Carreiras, Pereira, Campagnolo, & Shimabukuro, 2006; Lucas et al., 2000; Neeff, Lucas, Santos, Brondizio, & Freitas, 2006). In 2004, a total of 100,674 km^2 of secondary vegetation cover were estimated in this region, with more 50,141 km^2 secondary vegetation being detected between 2008 and 2010. However between 2012 and 2014, whether as a result of reduced deforestation or direct conversion of secondary vegetation into other land-covers, only 1197 km^2 were added to the total area occupied by secondary vegetation. Indeed, in this same period, around 42,040 km^2 of secondary vegetation was re-converted into other land-covers, particularly pasture (28,488 km^2) and mechanized agriculture (1884 km^2) (TerraClass, 2014).

Concomitantly to a reduction in the amount of secondary vegetation detected in this period, deforestation rates decreased from 27,772 km^2 in 2004 to 6000 km^2 in 2012, the lowest rate ever (Prodes, 2018), as a result of legal and alternative coercive measures which, in face of an uncontrolled process of deforestation, started to be implemented in 2004 by the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon-PPCDAM (Arima, Barreto, Araújo, & Soares-Filho, 2014; Lapola et al., 2014). At first, increased command and control operations and declaration of protected areas were the main focus of PPCDAM, soon later however, following the Environmental Crimes Law regulation, measures targeting not only offenders but whole production chains, in particular the beef and leather sectors, also started to be implemented which included restricted access to credit, and purchasing conditioned to registration in the Rural Registering System (CAR) (Arima et al., 2014; Borner, Kis-Katos, Hargrave, & Konig, 2015, 2014; Dalla-Nora, Aguiar, Lapola, & Wolter, 2014; Gollnow & Lakes, 2014; Lapola et al., 2014; Pacheco & Poccard-Chapuis, 2012; Rudel, Defries, Asner, & Laurance, 2009). These measures were also strengthened by alternative coercive measures defined through sector agreements that forced major industrial companies and retailers to commit to zero deforestation in the soybeans and beef production chains (Gibbs et al., 2015, 2016; Rudorff et al., 2011; 2012). Therefore, in this period, several forces affected, and potentially changed, the land-use dynamics of industrial agriculture and cattle ranching which, even in a context of reduced deforestation, exhibited a steady expansion (Pacheco & Poccard-Chapuis, 2012; Rudorff et al., 2011; 2012). However, the conversion of secondary vegetation at any stage of regeneration is omitted, lacking governance. In order to increase governance over this subject and reduce pressure over these areas, a State Normative Instruction establishing criteria to regulate further suppression of this cover was declared (Vieira et al., 2014).

In this study, we aim at understanding the changes in the dynamics of secondary vegetation following the decrease in deforestation rates after 2004. Our hypothesis is that the historic pattern of progressive accumulation of secondary vegetation changed as a consequence of the re-conversion of secondary vegetation and areas under regeneration into different land-covers which continued to expand even in a scenario of reduced deforestation in the Brazilian Amazon. Our focus was then to investigate on a regional scale the spatiotemporal patterns of secondary vegetation with respect to different land-covers in Pará. The diversified contexts of occupation, deforestation, and land-use due to facilitated access to land and development of infrastructure (roads, ports, slaughterhouses and other facilities) that boosted the expansion of cattle ranching and industrial agriculture makes Pará an ideal region to explore our hypothesis. To achieve our purposes, we combined two complementary spatiotemporal analyses: (i) first, we perform a quantitative spatiotemporal analysis of transitions between land-covers, with a special focus on transitions to and from secondary vegetation what provided the basis for an overall understanding of changes in the dynamics of this land-cover in the period, (ii) then, we detect and analyze clustering patterns of secondary vegetation to better understand the spatial distribution of this land-cover in Pará and how/if it has changed over time, (iii) finally, we relate clusters of secondary vegetation to clustering patterns of different land-covers including pastures, small-scale and industrial agriculture.

2. Methods

2.1. Study area

Since the 1970s, the State of Pará has been transformed by the rapid expansion of cattle ranching and industrial agriculture, particularly stimulated by the construction of roads, ports, slaughterhouses and other processing facilities in conjunction with facilitated access to lands (Bowman et al., 2012; Lameira et al., 2015; Walker et al., 2009). In 2014,[1] pastures covered 61.35% (or 12.5 million ha) of the total deforested lands in Pará, followed by secondary vegetation which occupied 25.44% (or 5.2 million ha) of these lands (TerraClass, 2014). Industrial agriculture (mechanized agriculture and palm oil), and small scale agriculture, represented by the Mosaic of Occupation land-cover class, covered 1.3% (or 265,640.7 ha), 1.06% (219,000 ha), and 2.21% (452,613.3 ha) of total deforested lands respectively, while areas of pasture under regeneration represented 7.76% (or 1.59 million ha) of total deforested lands.

Fig. 1 presents the study area and shows the quantitative evolution of deforestation rates between 2000 and 2014. Until the beginning of the 2000s, Pará was considered a hotspot of deforestation with rates being between 5237 and 7510 km^2. Following a peak of 8870 km^2 in 2004, the several legal and alternative coercive measures put in place to halt deforestation progressively led to a reduction in rates, with the lowest being recorded in 2012 when 1741 km^2 were lost.

2.2. Data processing

We used the TerraClass Initiative (TC) land-cover data to build a land-cover geographical database for 2004, 2008, 2010, 2012 and 2014. The TC Initiative is a long-term project that uses a combination of deforestation vector data (i.e. deforested polygons > 6.25 ha detected by Prodes) and satellite orbital images (Landsat-5/TM, MODIS and SPOT-5) which are classified using visual and semi-automatic techniques in 15 different classes (TerraClass, 2008; Almeida et al., 2016). Description of land-cover classes provided by the TerraClass Initiative was rigorously observed (TerraClass, 2008), being classes used in our analyses (i) secondary vegetation, (ii) mechanized agriculture, (iii) clean pasture, dirty pasture and regeneration with pasture, (iv) mosaic of occupation and (v) annual deforested land. Data on palm oil corps was detected in LANDSAT images (areas > 9 ha) in agreement with Benami et al. (2018) which, according to the authors, comprises nearly all palm oil crops cultivated in the Brazilian Amazon.

From these data sets we obtained masks that were applied to the whole data set to exclude: (i) 'not observed' areas (i.e. areas covered by clouds and their shadows); (ii) 'reforestation' areas (i.e. planted forests), and (iii) the palm oil areas to avoid their double counting as secondary vegetation cover. After masks were applied, processed data was organized as attributes in a database of 10 km × 10 km cells grid using the FillCell Plugin (TerraME) an add-on plugin to calculate attribute values for the cellular space using attribute tables of layers. Fill Cell Plugin allows information coming from different geometries (vectorial, raster, or cellular) to be homogenized and aggregated in a single spatial-temporal layer, providing a database for modeling and statistical analyses (Aguiar et al., 2012).

In order to improve our cluster analysis and avoid spurious (small and sparse clusters) of secondary vegetation and different land-covers, we homogenized the effect of deforestation by applying a deforestation threshold to cells (< 1%). Following this threshold, all cells having less than 100 ha of accumulated deforested by 2004 were excluded from the whole dataset. Land-cover classes used as attributes in our analyses are described in Table 1.

2.3. Spatiotemporal analyses of secondary vegetation dynamics

In order to understand changes in the secondary vegetation dynamics between 2004 and 2014, we performed two complementary spatiotemporal analyses:

i. Spatiotemporal analyses of secondary vegetation transitions - To uncover broad temporal trends we quantified and analyzed the overall changes in area for all different land-cover classes using polygons and a spatial analysis tool to compute the geometric intersection between features of 2004 and 2010 data sets, and between features of 2010 and 2014 data sets. In this step, data sets for intermediate years i.e. 2008 and 2012 were not included in the analyses.
ii. Cluster analysis - To identify spatiotemporal clustering patterns of secondary vegetation and different land-covers we used the cluster technique Getis-Ord Gi*. The Getis-Ord Gi* allows the identification of "cold spots" and "hotspots", corresponding respectively to clusters of cells with low and high values of a given attribute when compared to the whole study area. The local sum of a selected cell attribute and neighboring attributes (defined by a threshold distance) are compared proportionally to the sum of all features. If the calculated local sum differs from the expected local sum, and this difference is too large to be the result of randomness, statistically significant Z-score values and confidence levels (Gi-Bin) are returned. When the calculated local sum is significantly lower than the expected local sum, cold spots are detected, and when the calculated local sum is significantly higher than the expected local sum, hotspots are detected (Getis & Ord, 1992; Ord & Getis, 1995). Getis-Ord Gi* hotspots and cold spots cluster technique was chosen because, in opposition to other clustering analyses: (i) the number of clusters is not defined beforehand, better fitting to our purpose of an exploratory analysis of secondary vegetation dynamics throughout time; and (ii) all features in a given distance band are included instead of neighbor features only, which would eventually lead to spurious results especially when using short distance bands. Getis-Ord Gi* was processed as follows: (i) identification of the distance band by calculating the Moran's Global Index at different distances (from 513.6 m or 2 neighbors to 41,917.30 m or 2000 neighbors) and plotting the Z-score values in order to identify the distance where data reaches the maximum of autocorrelation and phenomenon is maximized (Getis & Ord, 1992) which, in this study, was 20,000 m; (ii) performing the cluster analysis for each year using the identified threshold distance, and (iii) selection of clusters with p values > 0.05. We identified and compared clusters using the following attributes:
   a) Secondary vegetation - we compared hotspots and cold spots following two alternative perspectives of secondary vegetation (i) percentage of secondary vegetation in each cell (SeVe), and (ii) percentage of secondary vegetation per deforested area in each cell (SeVe/De). Section 3.2.1 presents the results of these analyses.
   b) Land-covers - we performed an analysis of hotspots and cold spots of pastures (clean and dirty), regeneration with pasture, industrial agriculture (mechanized agriculture and palm oil) and small-scale agricultural. The focus was on understanding where and to which extent these clusters overlapped with hotspots and cold spots of secondary vegetation in different periods of time.

3. Results

3.1. Spatiotemporal analyses of secondary vegetation transitions

Fig. 2a illustrates changes in all land-cover classes analyzed between 2004 and 2014, and Fig. 2b shows the percentage of each class relative to the total land deforested until 2014. The most prevailing land-cover classes were clean pastures, and secondary vegetation, with small-scale agriculture, mechanized agriculture and palm oil being the least representative. Clean pasture (PaClean) (16.5%), mechanized agriculture (MecAg) (259.7%), and palm oil (PaOil) (28%) expanded in the period, while land-covers related to regeneration were reduced after 2010 i.e. small-scale agriculture (SmAg) (−29.4%),regeneration with pasture (PaRe) (−44.84%) and secondary vegetation (SeVe) (−2.8%).

Fig. 3 uncovers transitions among different land-covers in Pará between 2004 and 2010, and between 2010 and 2014. Flows from

[1] Absolute figures presented in this study may differ from raw non-processed data provided by TerraClass project as a result of masks applied (see Data processing for more details on masks application).

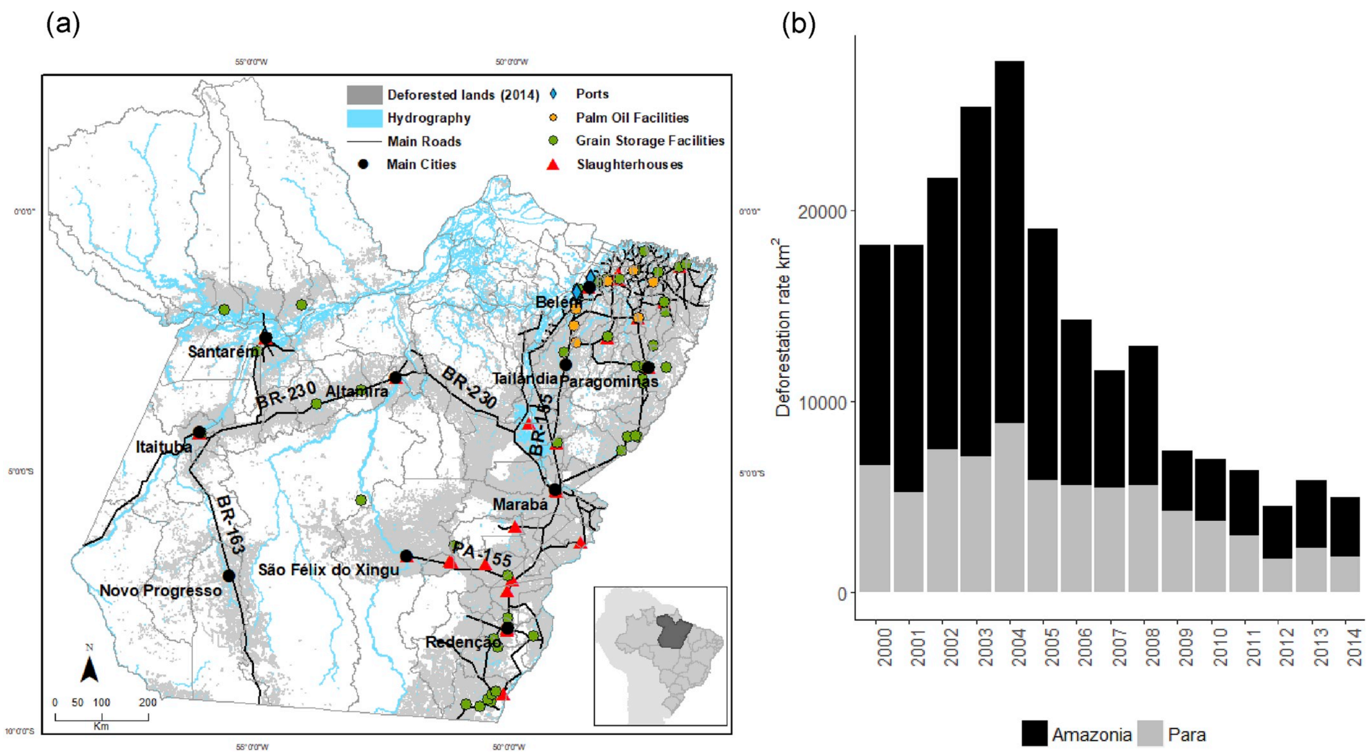


Fig. 1. (a) Pará limits and infrastructure network; (b) Deforestation rates in Pará and Brazilian Amazon between 2000 and 2014.

Table 1
Land-cover classes used as attributes in the 10 km × 10 km cells grid.

Attributes	Variable	Description (1)
Secondary vegetation	SeVe/De	Percentage (%) of secondary vegetation (SeVe) in relation to the deforested (De) area in each cell.
Pasture	PaClean/De	Percentage (%) of clean pasture in relation to the deforested (De) area in each cell. Clean pasture is a productive pasture with 90%–100% of herbaceous vegetation cover (grass species).
	PaDirty/De	Percentage (%) of dirty pasture in relation to the deforested (De) area in each cell. Dirty pasture is a productive pasture with 50% and 80% of herbaceous vegetation cover (grass species) in association with 20%–50% of sparse shrub cover.
	PaRe/De	Percentage (%) of regeneration with pasture in relation to the deforested (De) area in each cell. Regeneration with pasture is a non-productive pasture with 30%–60% of herbaceous vegetation cover (grass species) in association with 40%–70% of shrub cover and eventually occurrence of trees (0%–15%).
Industrial Agriculture	MecAg/De	Percentage (%) of mechanized agriculture in relation to the deforested (De) area in each cell. Mechanized agriculture covers areas with extensive annual agriculture with indications of high technological standards.
	PaOil/De	Percentage (%) of palm oil in relation to the deforested (De) area in each cell. Areas cultivated with palm oil crops in agreement with Benami et al. (2018).
Mosaic of Occupation (Small-Scale Agriculture)	SmAg/De	Percentage (%) of mosaic of occupation in relation to the deforested (De) area in each cell. Mosaic of occupation represents areas in which an association of diverse land-uses is found but, given the spatial resolution of satellite images these different land-uses cannot be separated. In this land-cover class, family agriculture is developed together with subsystems of pasture for traditional cattle ranching.
Deforestation	De	Deforested areas detected by PRODES in that specific year.

secondary vegetation into classes that expanded in the period show that, in face of a reduction in deforestation rates, the conversion of secondary vegetation into these land-uses increased 86.7% for clean pasture and 25.99% for mechanized. On the other hand, besides the previously mentioned reduction in classes important for regeneration, conversions from these classes into secondary vegetation were also reduced after 2010in −32.3% for small-scale agriculture, −24.5% for regeneration with pasture, and −25.3% for dirty pasture.

PaReg includes transitions for both dirty pasture and regeneration with pasture, while IndAg includes mechanized agriculture and palm oil.

3.2. Cluster analyses

3.2.1. Clusters of secondary vegetation between 2004 and 2014

Fig. 4a and b illustrate the hotspots and cold spots identified using the percentage of area of secondary vegetation per accumulated deforestation in cells (SeVe/De) in 2004 and 2014, respectively. Hotspots of secondary vegetation predominated in the Northeast and Northwest of Pará, with cold spots being the prevailing clusters in the South; particularly in the Southeast from where they extended towards the west by 2014.

As seen in Table 2, the area detected as cold spots (clusters of low values) of secondary increased 25.5%, while the area under hotspots (clusters of high values) showed an increase of 13.1%. This is in agreement with absolute figures that show an overall, although small, reduction in the area covered by secondary vegetation throughout the decade, what as previously shown, may be in part explained by increased transitions from secondary vegetation into land-covers expanding in the same period.

3.2.2. Clusters of secondary vegetation and different land-covers between 2004 and 2014

3.2.2.1. Secondary vegetation and pastures: clean pasture, dirty pasture,

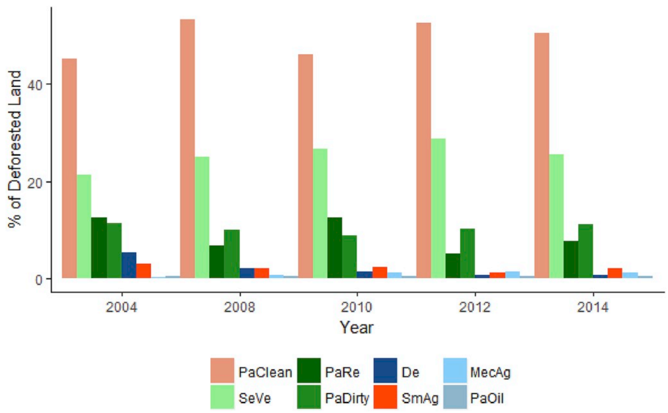


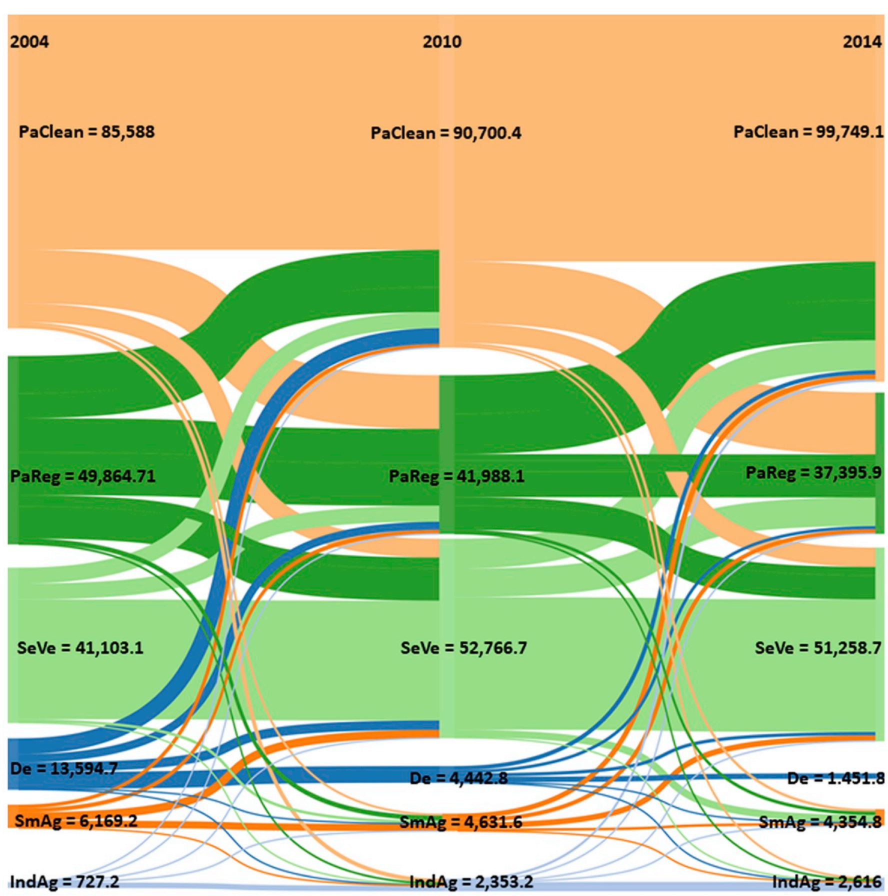
Fig. 2. Quantitative evolution of different land-cover classes in percentage of each class relative to total accumulated deforestation between 2004 and 2014.

and regeneration with pasture. Fig. 5 illustrates hotspots and cold spots of different classes of pasture detected using the percentage of each class in relation to the deforested area in cells, superimposed over hotspots and cold spots of secondary vegetation shown in the previous section. Hotspots of clean pasture are discernible in the south, overlapping cold spots of secondary vegetation (Fig. 5a and b), being this the prevailing pattern throughout time, although by the end of the decade clusters were broader and more concentrated around Novo Progresso and Redenção. On the other hand, cold spots of clean pasture are seen overlapping hotspots of secondary vegetation in the northwest and northeast, in an inverse relation with hotspots.

Hotspots and cold spots of dirty pasture show the same pattern identified for clean pasture, with cold spots in the north, overlapping hotspots of secondary vegetation, and hotspots in the south, overlapping cold spots of secondary vegetation. Especially towards the end of the analyzed period cold spots in the northeast, near Tailândia and Paragominas, and hotspots near Marabá are larger (Fig. 5c and d). For regeneration with pasture, hotspots and cold spots were stable, being hotspots found in the northeast and cold spots in the southeast and southwest (Fig. 5e and f).

As seen in Table 2, although the area under both types of clusters of clean pasture increased over time, cold spots expanded 82.7%, while hotspots increased only 21.8%, what is in agreement with absolute figures showing that throughout the decade clean pasture expanded only 16.5%. In addition, as seen in the transitions in the period, increases in this cover were mostly the result of re-conversion of other land-covers instead of its expansion over newly deforested lands, what may have contributed to slow down the expansion of this land-cover in the period.

For dirty pasture, the quantitative evolution of clusters shows that cold spots expanded considerably over time (130.2%), concomitantly to a reduction of −34% in the area under hotspots. Also noticeable is the reduction in the area under cold spots and hotspots of regeneration with pasture, which decreased by −61% and −25% respectively (Fig. 3). In this regard, results suggest that, in a scenario of increased pressure against the expansion of pastures over newly deforested lands, areas of pasture in different stages of regeneration could have been recovered through pasture management techniques.



PaReg includes transitions for both dirty pasture and regeneration with pasture, while IndAg includes mechanized agriculture and palm oil.

Fig. 3. Transitions between different land-covers for 2004–2010, and 2010–2014. Flows indicate transitions into different land-cover class and values over bars show area (in km ^{2}) of classes at each time-step.

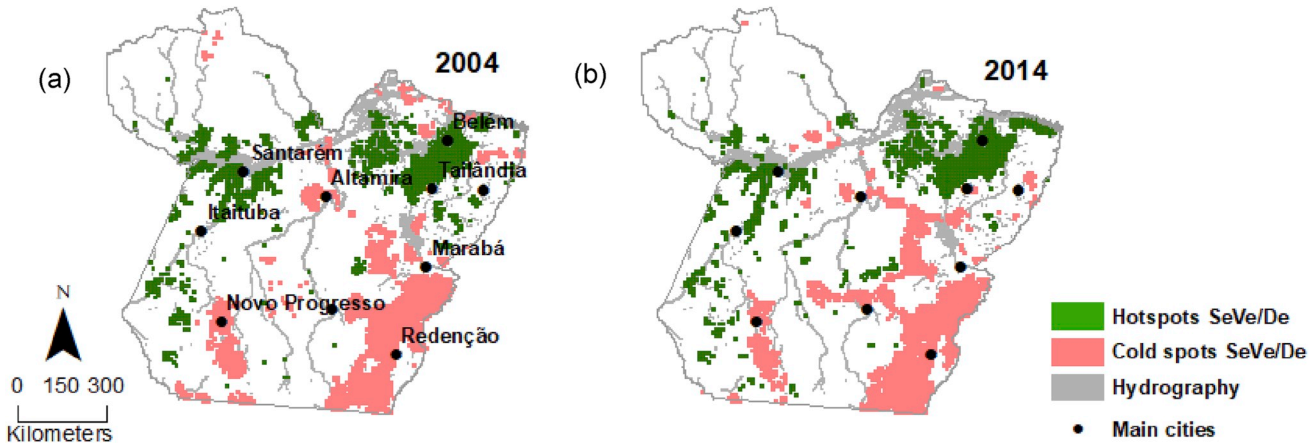


Fig. 4. Clusters of secondary vegetation secondary per deforested area (SeVe/De) in (a) 2004 (left) and (b) 2014.

Table 2
Quantitative evolution of hotspots of secondary vegetation and different land-covers between 2004 and 2014.

Land-cover	Cluster	Area in 2004 (ha)	Area (2014) (ha)	Total Change
Secondary vegetation	Cold spots	1,687,400	2,118,700	+25.5%
	Hotspots	6,934,500	7,844,200	+13.1%
Clean pasture	Cold spots	543,000	992,100	+82.7%
	Hotspots	8,959,600	10,916,300	+21.8%
Dirty pasture	Cold spots	55,500	127,800	+130.2%
	Hotspots	2,457,200	2,248,800	- 34%
Regeneration with pasture	Cold spots	143,200	55,888	- 61%
	Hotspots	2,604,800	1,955,069	- 25%
Mechanized agriculture	Cold spots	–	–	–
	Hotspots	104,000	594,400	+471.5%
Palm oil	Cold spots	–	–	–
	Hotspots	299,700	406,300	+35.5%
Small-scale agriculture	Cold spots	–	–	–
	Hotspots	1,752,700	1,375,100	- 20%

(1) Percentage of increase or decrease in the area of clusters (ha) with respect to the previous period.

3.2.2.2. Secondary vegetation and agriculture: mechanized agriculture, palm oil, and small-scale agriculture. Fig. 6 illustrates the hotspots of different classes of agriculture detected using the percentages of each class in relation to the deforested area in cells. Hotspots of mechanized agriculture were detected in the Northeast, Northwest and Southern regions of Pará (in 2014), and hotspots of palm oil were detected in the northeast (Fig. 6a and b). In all years, hotspots of small-scale agriculture were detected in the Northeast and Northwest Pará, with a small cluster appearing in the southeast (in 2014) (Fig. 6c and d). Given that both small scale and industrial agriculture are land-covers concentrated to specific regions of Pará, no cold spots were detected.

As seen in Table 2, hotspots of both mechanized agriculture and palm oil increased throughout the decade, although the increase in hotspots of mechanized agriculture was higher (+471.5%) in comparison to hotspots of palm oil (+35.5%). On the other hand, the area under hotspots of small-scale agriculture was reduced by −20%. The quantitative evolution of clusters of these land-covers is in agreement with absolute figures, showing that while industrial agriculture steadily expanded, an overall reduction in the area occupied by small-scale agriculture was detected.

4. Discussion

After a peak in deforestation rates in 2004, the Brazilian Government started conceiving and implementing a comprehensive set of measures to control deforestation in the Brazilian Amazon, Action Plan for the Prevention and Control of Deforestation in the Legal Amazon-PPCDAM (Arima et al., 2014; Borner et al., 2015, 2014; Dalla-Nora et al., 2014; Gibbs et al., 2016; Gollnow & Lakes, 2014). Foreseeing increased command and control operations, restricted access to credit, and purchasing conditioned to registration in the Rural Registering System (CAR), PPCDAM was also strengthened by sector agreements forcing traders and major slaughterhouses to commit to zero deforestation in the beef and soybean production chains (Arima et al., 2014; Lapola et al., 2014; Gibbs, 2015, 2016; Rudorff et al., 2011; 2012). In this scenario, pastures and industrial agriculture (mechanized agriculture and palm oil) continued to expand, suggesting that somehow the dynamics in already deforested lands changed to accommodate this expansion. Indeed, as our results show, in a scenario of reduction in deforestation rates, transitions from secondary vegetation into clean pasture and industrial agriculture increased, especially after 2010, while small-scale agriculture and regeneration with pasture, two land-covers important for regeneration, not only lost area but also contributed less to the accumulation of secondary vegetation, for transitions from these land-covers into secondary vegetation were reduced.

Despite few detailed investigations are available regarding how and where the pressure to reduce deforestation rates had an effect on slowdown pasture expansion over newly deforested lands, some studies suggest that actors not only effectively responded to disincentives (i.e. fines and embargo) (Borner, Wunder, Kannonnikoff, Hyman, & Nascmento, 2014; 2015), but also changed their strategies with respect to land management, especially in cattle ranching properties (Bowman et al., 2012, Pacheco & Poccard-Chapuis, 2012), being these processes particularly strong in regions with better infrastructure. In this regard, a land-management primary concern in this scenario of increased pressure regards pasture degradation, the primary link between pastures and regeneration, which is estimated to affect 50% of pastures in the Brazilian Amazon (Dias-Filho, 2015) and contribute to at least 13% (or 2.4 million ha) of the secondary vegetation cover mapped in the region between 2010 and 2012 (TerraClass, 2014). In Pará, the Northeast and Northwest are regions dominated by small properties and herds, where pastures management is less intensive, in contrast to the South, and in particular, the Southeast, where properties and herds are larger and pasture management more intensive, partially as a result of an increased demand of major industrial slaughterhouses whose operations are concentrated in this region (Pacheco, 2009; Pacheco & Poccard-Chapuis, 2012). These distinct features are therefore crucial to explain why high values of clean pasture in the south were overlapping clusters of low values of secondary vegetation, in opposition to the pattern identified in the North where clusters of high values of secondary vegetation overlapped clusters of low values of clean pasture.

Notwithstanding the crucial role that the land-use dynamics during the past decade has played in the spatial concentration of secondary

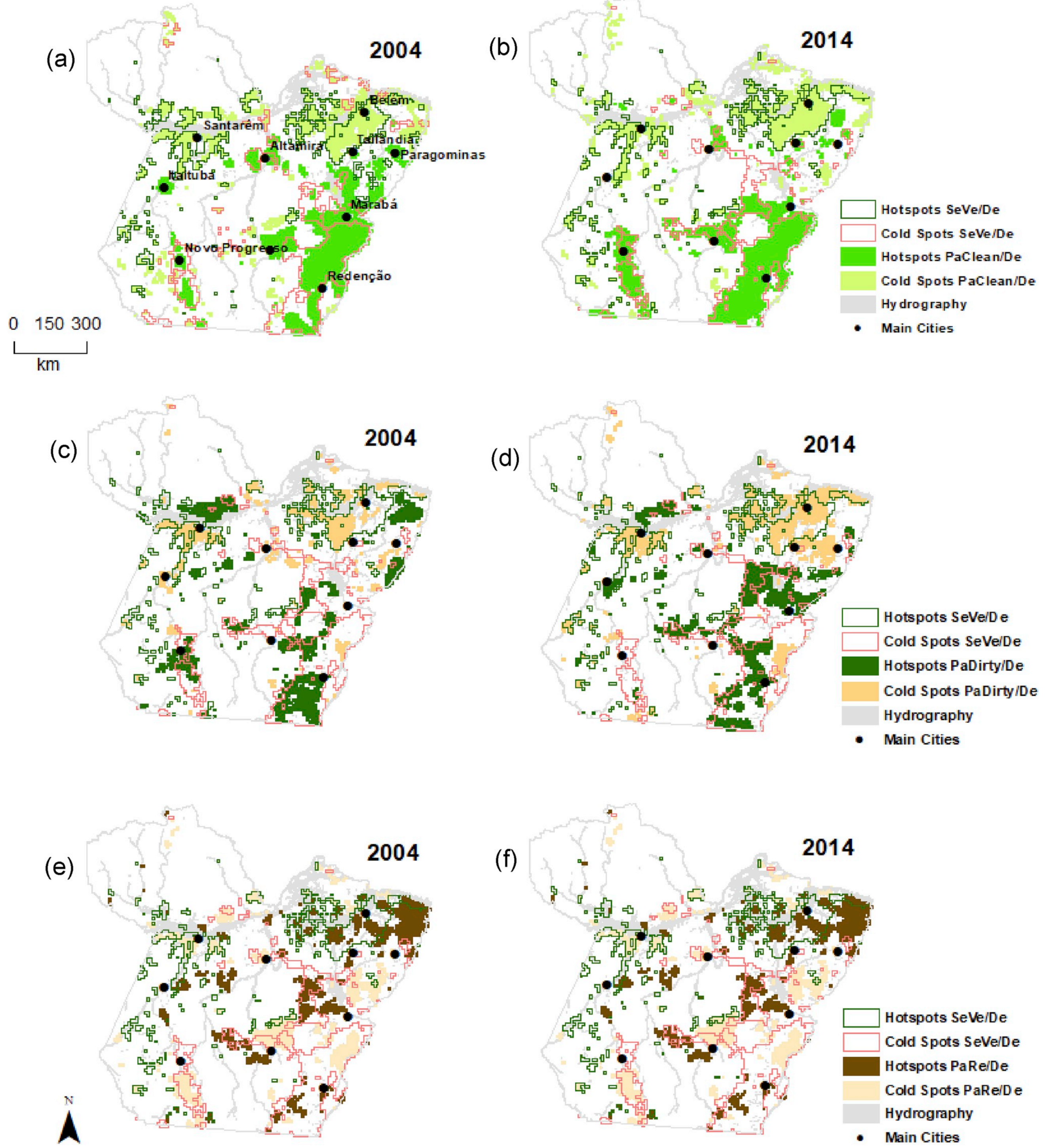


Fig. 5. Clusters of pasture identified superimposed over clusters of secondary vegetation in 2004 (on the left) and 2014 (on the right). Clean pasture (PaClean/De) in (a) 2004 and (b) 2014; dirty pasture (PaDirty/De) in(c) 2004 and (d) 2014; and regeneration with pasture (PaRe/De) in (e) 2004 and (f) 2014.

vegetation, north-south differences are also the result of differences in the history of occupation of these regions. Clustering of high values of secondary vegetation found in the Northeast and Northwest of Pará coincides with a longer history of occupation, where deforestation intensity is currently low. On the other hand, clusters of low values were detected in the southeast and southwest, more recently occupied regions, where deforestation is still intense or has just been reduced. Less forest regeneration was found on active frontiers of deforestation and occupation (3%), while regions with a longer history of occupation had more forest regeneration (25% of regeneration) (Perz & Skole, 2003). Similarly, Alves, Escada, Pereira, and Linhares (2003) found in Rondônia an increase in deforestation and the concurrent decline of secondary vegetation, a pattern that the authors suggested was related to land-use intensification that precluded land abandonment and reduced forest regeneration. Almeida et al. (2010), estimating secondary vegetation cover for the Brazilian Amazon, showed that increases in deforestation were also related to a reduction in secondary vegetation.

In addition to differences in the history of occupation, a prevalence of small properties and small-scale agriculture and their diversified land-use found in the North (Scatena et al., 1996; Watrin, dos, Santos, &

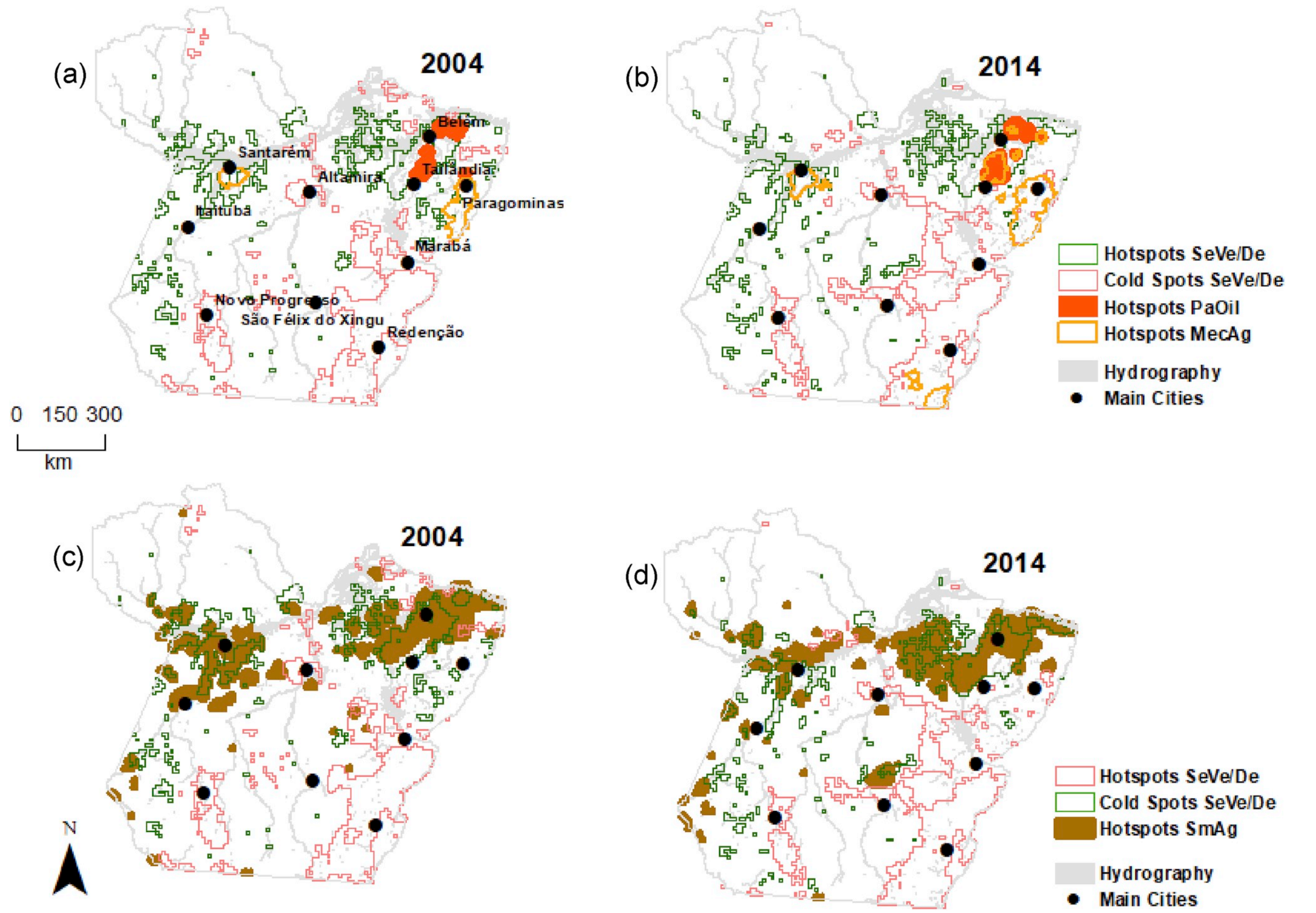


Fig. 6. Clusters of secondary vegetation and agriculture in 2004 and 2014. (a) and (b) Hotspots of large scale agriculture i.e. mechanized agriculture (MecAg) and palm oil (PaOil); (c) and (d) Hotspots of small-scale agriculture (SmAg).

Valério Filho, 1996; Watrin, Gerhard, & Maciel, 2009) configure environment-friendly landscapes, favoring regeneration and persistence of secondary vegetation. As a general rule, smallholders tend to diversify land-use strategies, integrating different productive activities with primary and secondary forests, configuring environment-friendly landscapes (Coomes et al., 2000; Klemick, 2011; Meyfroidt & Lambin, 2011; Prates-Clark, Lucas, & dos Santos, 2009; Smith et al., 1999; 2003). In the Peruvian Amazsss, Coomes et al. (2000) found that in small properties (< 45.21 ha), half of the lands were occupied by fallow forests, aging from 1 to 9 years which were differently managed, according to previously cultivated crops, and labor, capital and land availability. In the Bragantina region, Northeast of Pará, Smith et al. (2003) attributed the persistence of secondary vegetation to the fact the landholders had diversified income sources i.e. annual crops non-farm income, perennials, and secondary forest products.

Mechanized agriculture and palm oil have also shown to be important in the dynamics of secondary vegetation in a scenario of decreased deforestation. In 2005, following an international campaign exposing the connections between soybeans expansion and deforestation, traders operating in this sector signed the Soy Moratorium, a sector agreement to prevent the expansion of soybeans over newly deforested lands that as progressively inhibited the advancement of soybean over deforested lands (Rudorff et al., 2011; 2012). On the other hand, although the conversion of primary forests into palm oil has not been identified as a serious threat in the Brazilian Amazon, this production chain is internationally committed to zero deforestation, what has contributed to limit its expansion to previously cleared lands (Butler & Laurance, 2009). Despite their restricted spatial distribution, as our results show, hotspots of mechanized agriculture and palm oil not only overlapped hotspots of secondary vegetation in the North but, especially after 2010, expanded as a result of increased conversion from secondary vegetation into these land-covers, reinforcing previous studies that highlighted these land-covers as drivers of conversion of secondary vegetation in Pará (Pereira & Vieira, 2001; Vieira et al., 2014).

Finally, it is important to mention that so far, this is the first investigation focusing the dynamics of secondary vegetation in a scenario of decreasing deforestation rates, being this an important contribution to improve our comprehension on the dynamics of secondary vegetation in a different scenario (i.e. reduced deforestation), and to approach the side-effects of policies to reduce deforestation over secondary vegetation which, in spite of being already recognized as important for biodiversity conservation and climate stability (Aguiar et al., 2016; Benayas et al., 2009; Chazdon et al., 2009; Klemick, 2011; Lees & Vieira, 2013; Neef et al., 2005; Orihuela-Belmonte et al., 2013; Smith et al., 2003; Vieira et al., 2014) still lack mechanisms of good governance (Vieira et al., 2014). As Lennox at al. (2018) recently showed, secondary forests aged 40 years of regeneration exhibited a high degree of biodiversity resilience, recovering substantial undisturbed primary forests biodiversity, pointing out that across the first 20 years of succession, biomass recovered at 1.2% per year, equivalent to a carbon uptake rate of 2.25 Mg/ha per year, while, on average, species richness and composition recovered at 2.6% and 2.3% per year, respectively. By the same token, CDR (carbon dioxide removal) mechanisms become progressively important for climate stability, with afforestation, either through planted forests or natural regeneration, being secondary vegetation particularly relevant as an inexpensive and straightforward strategy to contribute for limiting global warming in 1.5 °C (IPCC, 2018, p. 32; van Vuuren et al., 2018). However, currently, secondary vegetation permanence is jeopardized not only as core potential areas for agriculture and livestock expansion (Pereira & Vieira, 2001; Strassburg et al., 2014) but also due to a lack of governance (Vieira et al., 2014).

5. Conclusions

Following a decrease in deforestation rates, more secondary vegetation was converted into land-covers expanding in the period i.e. clean pasture, mechanized agriculture, and palm oil. In addition, secondary vegetation and land-covers important for regeneration (i.e. small-scale agriculture and regeneration with pasture) experienced an overall reduction, having also contributed less to the concentration of secondary vegetation after 2010. Although the overall reduction in the area occupied by secondary vegetation was small, our results show that, as the current land dynamics in Pará progress, increased conversions of this land cover can be expected in the near future. At first, although this might sound as good news in the sense that policies against deforestation had a deterrence effect, side-effects of these policies in terms of a potential continued reduction of secondary vegetation and land-covers associated with regeneration should be thoroughly examined, especially considering the relevance of secondary vegetation for climate stability and biodiversity conservation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2019.03.001.

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