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Long-term assessment of oil palm expansion and landscape change in the eastern Brazilian Amazon

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ABSTRACT

In the Brazilian Amazon, land use and land cover changes (LULC) are extremely heterogeneous, in both spatial and temporal terms. Understanding the long-term trajectory of changes in LULC, and the resulting impact on landscape structure, is essential for the development of adequate, environmentally sound land use policies. To this end, we characterized the spatiotemporal aspects of LULC changes, and their effects on the landscape, in an agricultural backdrop of oil palm cultivation, based on a multi-temporal analysis of the period between 1991 and 2013. We classified Landsat images and analyzed landscape changes in 2588.72 km^2 of the oil palm expansion zone (*polo do dendê*), located between the municipalities of Moju, Acará, and Tailândia (called Moju region), northeastern Pará, Brazil. We found that, during this period, 47.7% of the primary forest was converted for other uses, degraded forest increased by 17%, and oil palm plantation increased by 11%. Thirty percent of the primary forest was converted to oil palm plantation during the 22-year study period, however, between 2005 and 2013, primary forest conversion to oil palm increased by just 2%. In contrast, changes in landscape structure were related to the fragmentation of the forest cover, leading to an increasing isolation of forest patches and reduction in the area of forest remnants. These data offer a clear warning sign that for future expansion of palm oil plantations in the Pará state we need to adopt strategies focused on landscape integrity, and develop initiatives towards the regulation of large areas of monoculture, helping guarantee the region's environmental sustainability.

1. Introduction

Land use and land cover changes (LUCC) result from the interaction between environmental, social, and human activities and economic factors (Geist and Lambin, 2002). In the Brazilian Amazon, the main concern about land use/cover is related mostly to the conversion of forest for cattle ranching and agriculture expansion (Vieira et al., 2008). This loss of forest cover can severely reduce the environmental sustainability of the region (Barlow et al., 2016), with consequences that include biodiversity loss, a depletion in ecosystem functioning, and increased climate variability.

By assessing fragmentation and degradation processes in large regions like the Amazon, land cover and landscape analysis increases ecosystem knowledge. During the past decade important advances have been made in understanding land-use change and shifts in land-uses after deforestation (Almeida et al., 2016; de Espindola et al., 2012; Müller-Hansen et al., 2017), but few studies have considered temporal changes in landscape structure (Colson et al., 2011)). Patterns of land use and landscape change are extremely heterogeneous, in both spatial and temporal terms, and post-deforestation land use trajectories follow a series of transitions that accompany changes in socio-ecological systems (Meyfroidt et al., 2018). Understanding the local, regional, and global socioeconomic and biophysical consequences of these change trajectories represents a major challenge for the development of effective, evidenced-based public policies for sustainability.

Significant oil palm (*Elaeis guineensis* Jacq.) production projects aimed at the food and cosmetics industries have been developed for over three decades in the Brazilian Amazon, especially in the state of Pará (which has 80% of national oil palm production) (Homma, 2010). Most extensive oil palm plantations were consolidated in this zone since the 1980s, and Pará has the most extensive planted oil palm area in Brazil (AGRIANUAL, 2015). However, the recent expansion of oil palm in the eastern Amazon is driven by the increased demand for food and biofuel (Homma and Vieira, 2012). After 2010, a new oil palm frontier has been established in Pará state, stimulated by the governmental Program for the Sustainable Production of Palm Oil (SPOPP) in Brazil.

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SPOPP provided mechanisms to ensure inclusive development and minimize negative environmental impacts of oil palm expansion in the Amazon and aimed to promote rural development, and to minimize conflict with primary forests and recover degraded lands (Brandão and Schoneveld, 2015). Public policies of this type have far-reaching consequences for land use, and entail substantial ecological and economic changes.

Ninety percent of the recent expansion in palm oil production occurred on land that was formerly pasture rather than forest (Benami et al., 2018). However, oil palm is as detrimental to regional biodiversity as other agricultural land-uses and is considered a 'high impact' land-use (Lees et al., 2015). Its expansion into Amazonia requires careful appraisal of the potential effects of this monoculture on the landscape. Such effects have been extensively studied in southeast Asia, where even low-impact management techniques have failed to conserve natural forests and landscapes (Edwards et al., 2010). Yet, landscape-level assessments associated with oil palm expansion in the Amazon region are missing.

Although oil palm cultivation does not constitute the majority of LULC in the Amazon, several questions remain about the changes induced by oil palm cultivation. In this context, the aim of this study was to analyze the long-term effect of LULC induced by oil palm cultivation in an area representative of the oil-palm zone in the Brazilian Amazon. With a focus on oil palm expansion over 22 years in eastern Pará, the most significant palm oil-producing state in Brazil, we assess both the extent of conversion of different land-uses to make way for oil palm expansion, as well as changes in landscape structure and forest fragmentation over the same period. This analysis was used to evaluate the impact of the oil palm expansion policy (SPOPP) in the region. We hypothesize that a) oil palm expansion has caused not only forest loss, but also the intensification of landscape fragmentation, and b) as of 2010, when SPOPP was instigated, forest fragments have become smaller and more isolated.

2. Methods

2.1. Study area

This study was carried out in three areas, totaling 2,588.72 km^2 of this oil palm zone, located in the municipalities of Moju, Acará, and Tailândia (called Moju region), northeastern Pará, Brazil. These areas are within the oil palm production zone in Pará, a region that presents the most appropriate climatic conditions for oil palm cultivation in Brazil (Ramalho Filho et al., 2010). Between 2006 and 2014, the area under oil palm plantation expanded to 2190 km^2 in this state (Benami et al., 2018) and production is around 900,000 tons of palm oil per year (FAPESPA, 2017).

The study areas were selected based on the representativeness of all stages of oil palm cultivation, defined as follows: under cultivation process (area 1: 958.24 km^2), area consolidated with oil palm (area 2: 951.38 km^2), and area at the beginning of cultivation (area 3: 680 km^2). It is noteworthy that, in area 3 oil palm cultivation began in 2013 (Fig. 1).

The study area is located in the Af-Koppen climate zone and annual precipitation in the region is between approximately 2500 and 3000 mm (de Moraes et al., 2005). The average annual temperature is around 25 °C, and the relative humidity is around 85% (IDESP Instituto de Desenvolvimento Econômico and Social e Ambiental do Pará, 2014). The soil of the study area is dominated by dystrophic yellow latosol (oxisol).

The vegetation is characterized by dense vegetation of alluvial plains in the lowland areas, and secondary vegetation and dense forests on the low plateaus and terraces (IDESP Instituto de Desenvolvimento Econômico and Social e Ambiental do Pará, 2014). The total forest area in Moju and Tailândia in 2015 was 4,386.8 km^2 (48%) and 1,998.30 km^2 (45%), respectively (INPE, 2017). Both municipalities have lost almost 50% of their total forested area.

These municipalities stand out as the largest producers of oil palm in the state of Pará, together accounting for 52% of the total production of this crop in the state (FAPESPA, 2017). Investigating this area of Pará state is especially important because the majority of the land deemed suitable for oil palm expansion by the Agro-Ecological Zoning (ZAE-*Zoneamento Econômico-Ecológico*) is located in this area.

2.2. Data

LULC change analysis was based on Landsat TM-5 images of 1991, 1995, 2001, 2005, 2010 and 2013, orbit/point 223-062 and 224-062, using bands 1 (blue), 2 (green), 3 (red), 4 (near infrared), 5 (average infrared), and 7 (average infrared), with a spatial resolution of 30 m, while Geocover images (GLCF, 2000) were used for georeferencing. We used Landsat-8 images from the United States Geological Survey (USGS, 2013), sensor OLI (Operational Land Imager), orbit/point 223-062 and 224-062, with a Geographic Coordinate System (GCS) projection and World Geographic System 1984 datum (WGS 84), using bands 2 (blue), 3 (green), 4 (red), 5 (near infrared), and 6 (shortwave infrared), with a spatial resolution of 30 m, and panchromatic image with a spatial resolution of 15 m. These images were also obtained from the USGS (2013), where they are available in orthorectified mode on the GLOVIS platform.

2.3. Methods

2.3.1. Land cover mapping

Land cover mapping was conducted in three phases. The first phase was the pre-processing, which was based on the extraction of images from the Geocover database (Souza Junior and Siqueira, 2013). In this phase, the interpolation algorithm was applied to 30 control points, based on the triangulation and resampling of the nearest neighbor, with a mean square error of less than one pixel (30 m). A radiometric correction was then conducted for the exclusion of interference, and an atmospheric correction to minimize the effects of cloud and smoke at the edges of the images (Carlotto, 1999). This processing converts the data in the image to digital numbers (DN) of surface reflectance (Souza, 2005).

During the second phase, a spectral library was established, which comprised the identification of pure spectral components for the calculation of their abundance in each pixel. The target components were: pure green vegetation pixels (GV), nonphotosynthetic vegetation (NPV), normalized differential fraction index (NDFI) (Souza Jr. and Siqueira, 2013), exposed soil, cloud, and shade. This process allowed the identification of the potential spectral curve for the selection of the final set of pure spectral components, using the Spectral Mixture Analysis (SMA) proposed by Adams (1995).

In the third phase, a decision-tree method was used to classify the target components (GV, NPV, NDFI, exposed soil, and cloud) as standardized variables. Programs ImgTools 2.0 and ENVI 4.5 were used for these analyses (Gardner et al., 2013; Souza and Siqueira, 2013). In the class edition mode, it was possible to minimize the classification error (confusion of areas of oil palm, secondary forest, and other classes that could not be recognized or classified), following the procedure applied by de Almeida et al. (2014). The degraded forest was identified through the SMA mixing model processing, and the NDFI composition was performed, joining the VG, NPV and soil fractions. Based on the assumption that the NDFI varies in the interval from -1 to 1, where intact vegetation is close to the value of 1 and the degraded forest is close to -1 (Souza and Siqueira, 2013).

Classified images need to be assessed for accuracy, before being used as input for any applications. So, the quality of the classification was evaluated using an error matrix, obtained by cross-referencing the field data with information from the classification map, to generate the Kappa index for 2013 (Hudson, 1987). A Kappa coefficient equal to 1

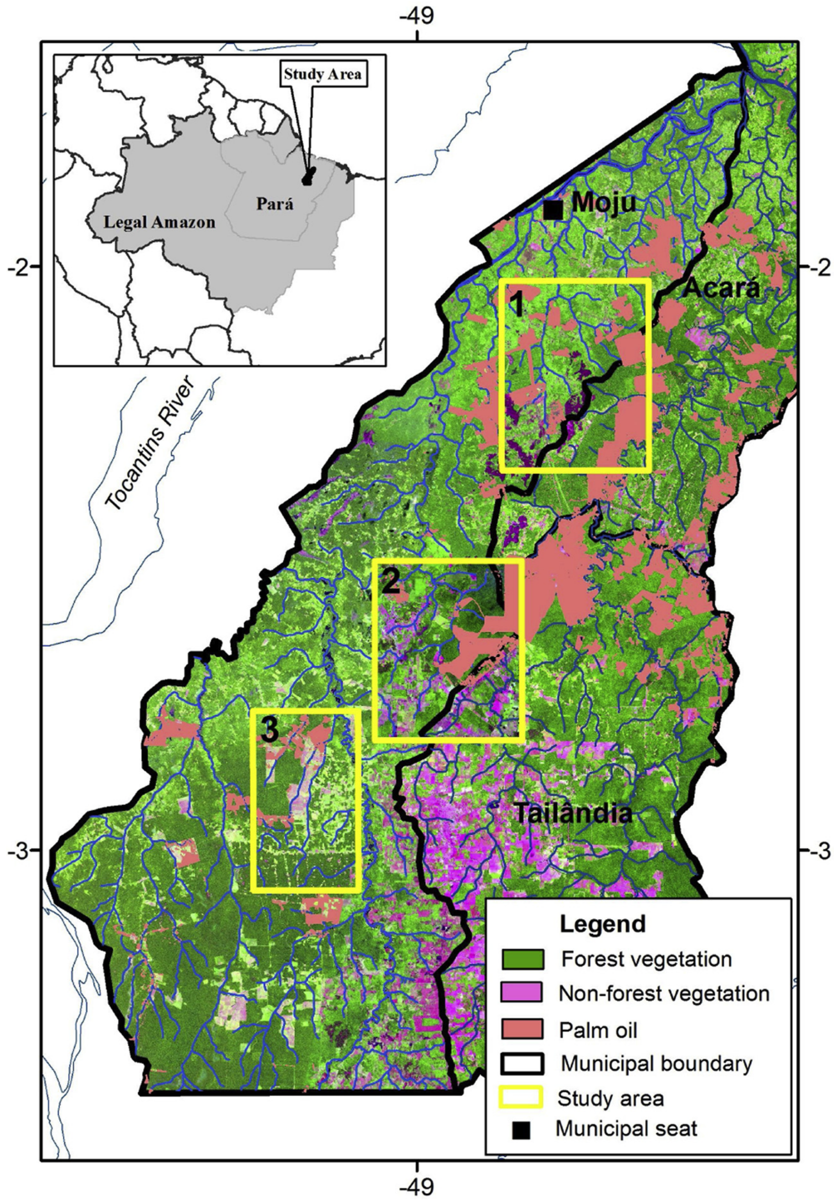

Fig. 1. Location of study sites (areas 1, 2, and 3) in Moju region, Pará sate, Brazil.

means perfect agreement whereas a value close to zero means that the agreement is no better than would be expected by chance.

The local vegetation was surveyed in the field between 2012 and 2013, with the primary aim of correcting the ambiguous classifications of land cover and use. Additional visits and informal interviews were also conducted to validate the accuracy of the classification.

We believe that this study allows for a comprehensive evaluation of oil palm cultivation in the Amazon as a whole, because the study focused on a representative area of the oil palm zone that is largely dominated by large-scale oil palm plantations, including both corporate and associated smallholder plantings.

2.3.2. Analysis of LULC trajectories

We made the trajectory analysis between 1991 and 2013 at the pixel-level for 2,588.72 km^2 of the studied area (areas 1, 2, and 3; Fig. 1). Changes in land use and land cover were defined by a time sequence of classes at the pixel level, which was described through the analysis of a temporal series of classified images (Coppin et al., 2004). The trajectories of land-cover change were defined by the successive transitions between land-cover categories over the observation years.

A categorical map that contained the pixel history, or the LULC trajectory, was created at the pixel level using a function COMBINE on ArcGIS (ESRI, 2010), where historical land-use maps (1991, 1995, 2001, 2005, 2010, and 2013) were combined into a single map, containing pixel history as an attribute. Assessing the resulting map table of attributes, a matrix of land-use trajectories was created. More frequent land-use trajectories ($>$ 1%) resulting in oil palm plantation in 2013 were evaluated. Land-use classes considered at this phase were: primary forest (PF), degraded forest (DF), secondary forest (SF), oil palm (OP), and farmland (FA).

Considering the total analyzed area of 2588.72 km2, there are about 120 possible combinations of trajectories that can result in OP; however, we considered only the most important ones (those accounting for greater than 1% conversion of the study area) to understand the pattern of LULC change.

2.3.3. Landscape structure

A grid of 654 landscape units of 2 km × 2 km (4 km^2) was established within the study area using the adaptive sampling approach (Thompson and Seber, 1996). Within the 4-km^2 grid, 150 of the 654 landscape units were selected randomly for the analysis of landscape structure. This grid was superimposed on the maps of the PF and OP plantations, obtained from multi-temporal classification. Four metrics were then considered for the analysis of landscape structure for the PF class (Ferraz et al., 2005): proportion of the landscape occupied (PLAND-total area of landscape occupied by patches), patch density (PD-number of patches per 100 ha), mean proximity (PROX-MN-mean isolation of patches based on proximity and size of patches of the same class within the search radius of 2 km), and the largest patch index (LPI), which quantifies landscape composition as the percentage of total landscape area encompassed by the largest patch. LPI has been widely used as an indicator of landscape fragmentation. Higher values of the PROX index indicate a greater proximity of fragments (Silva, 2013) and are considered to be a measure of the quantity of habitat within a landscape; in general, the lower the availability of habitat in the landscape, the greate the patch isolation (Fahrig, 2003). This analysis was conducted using Fragstats 3.3 (Mcgarigal, 2002).

To evaluate the significance of changes in landscape structure between the start (1991) and end of our time-series (2013), we evaluated all landscape metrics in 1999 and 2013. We then used one-way ANOVA followed by Tukey's post-hos testing (95%) to assess the differences. The statistical software used was STATISTICA 7 (Statsoft, Inc, 2004).

3. Results

3.1. Changes in land cover and land use

Six classes of land use and cover were identified – primary forest (PF), degraded forest (DF), secondary forest (SF), oil palm (OP), farmland (FA) and campinarana (CA). Cloud/shade (CL) and water (WL) were classified as "Others". Only the most frequent classes (PF, DF, SF, OP, and FA) were selected for the validation and trajectory analysis. The main classes and their description are shown in Table 1.

According to the confusion matrix report (Appendix 1), 88.06% overall accuracy and a Kappa index value of 0.85 were attained for the 2013 classification-map. In general, the map met the minimum accuracy requirements to be used for subsequent post-classification analyses.

The dominant land cover class for the studied landscape between 1991 and 2005 was primary forest but after 2010 farmland dominated as land use. A number of significant changes were observed in the area over the 22-year study period. In 1991, primary forest corresponded to 73.3% of the area, which was reduced to 40% by 2010 and to 25.5% by 2013, representing a total PF deforestation of 1237.8 km^2. Forest degradation increased from 5191 ha (2%) in 1991 and affected an area equivalent to 17% (44,072 ha) in 2013. Forest degradation leads to impoverishment of the forest in terms of biodiversity and carbon stocks, and it is thus important that it be evaluated. The area covered by palm oil increased by 11%, while that of farmland increased by 19% (Fig. 2). In 2013, there was a considerable increase in degraded forest and palm oil. This modification of forest cover over time suggests that the palm oil and pasture caused the main changes in the landscape. Secondary forest was relatively stable throughout the study but it can likely hide a dynamic land use; it gets cleared in some areas and regrows in other abandoned ones.

3.2. Trajectories of conversion to oil palm

The four most frequent land-use trajectories of conversion to OP ($>$ 1%) in the study area between 1991 and 2013 were: PF→OP, PF→FA→OP, FA→OP, and OP→OP. The conversion of forest to oil palm plantations, with the PF→OP trajectory, accounted for 12% of the conversion between 2001 and 2013 ($<$ 1% between 1991 and 2001), while the PF→FA→OP trajectory contributed 8% (Table 3). Other prominent trajectories were FA→OP (6%) between 1995 and 2001, and OP→OP (7%), which reflects the presence of oil palm before 1995 and its long-term stability at the landscape level. The highest rates of conversion of PF to all other land uses occurred between 1991 and 2001. Trajectories involving SF and DF contributed 3% and 1%, respectively.

In association with the distinct types of land use trajectories, our results highlight three processes involved in the conversion to oil palm plantations in Moju region (Table 3), starting with the conversion of primary forest (deforestation), and more recent processes involving secondary forests and degraded pastures.

The intensification of oil palm plantations was also observed in areas under consolidated use of this crop and not occupied areas of forest, but there are high rates of conversion of farmland to OP. The FA-OP trajectory generally begins with degraded pasture, which, when not converted immediately to oil palm plantations, leads to the land being put up for sale. An alternative process is initiated by the sale of a family farm not meant for the production of oil palm. This farm is sold to a landowner, who buys several contiguous smaller holdings to form a single large property, which is either planted with oil palm or rented out to an oil palm company. As a result, land ownership becomes limited to few producers or companies. In some cases, companies have contract-regulated arrangements with smallholders, but the ownership of land continues to rest with the smallholders Table 2 Table 3 .

3.3. Landscape structure changes

The largest patch index (LPI) for PF changed significantly between 1991 and 2013 (F = 27,479, $p < 0.001$), with significant differences found between all years ($p < 0.0001$). LPI followed a pattern similar to that of the proportion of land cover (PLAND) of primary forest in the landscape, with a reduction in the size of the largest forest fragments in the period between 1991 (18.4%) and 2013 (15.8%).

Patch Density (PD) changed significantly (F = 52.703, $p < 0.001$) among the study years ($p < 0.001$). This metric follows a trend

Table 1
Description of the main classes of land cover and use in the Moju region in Pará, Brazil.

Class	Description
PF	Primary Forest, including dense broadleaf forest and dense rainforest characterized by abundant species of phanerophytes, lianas, and epiphytes, with relatively thick-stemmed trees, a canopy of 30–40 m, and an emergent stratum. This class included only intact primary forest with no anthropogenic modifications, in a good state of preservation.
DF	Degraded Forest, including selectively-logged areas, an activity facilitated by the construction of logging roads and stockyard clearings. This class also includes forests with a fire-damaged canopy or understory. Alterations of intact forest affect its structure and function, leading to a reduction in its capacity to supply products or services.
SF	Secondary forest, resulting from the succession of clear-cut forest. The principal examples of secondary forest in the Amazon region include fallow areas of swidden farming, abandoned pastures, and regrowth after the harvesting of semi-perennial crops.
OP	The African Oil Palm (*Elaeis guineensis* Jacq.) is one of the world's most productive oilseed species, which is well adapted to the conditions of tropical regions. On average, these palms grow to a height of 8 m, and are highly valued commercially due to their productivity of oil palm.
FA	Farmland (plantations or pasture). Given the difficulty of distinguishing the categories through the interpretation of remote sensing imagery, they were included in a single class. These categories include cattle pastures on ranches, which cover the largest portion of the study area, and plantations of short-term (manioc, maize, rice, etc.) and long-term crops (coconut, orange, rubber, etc).

Note: Adapted from IBGE, 2012; Barlow et al., 2007.

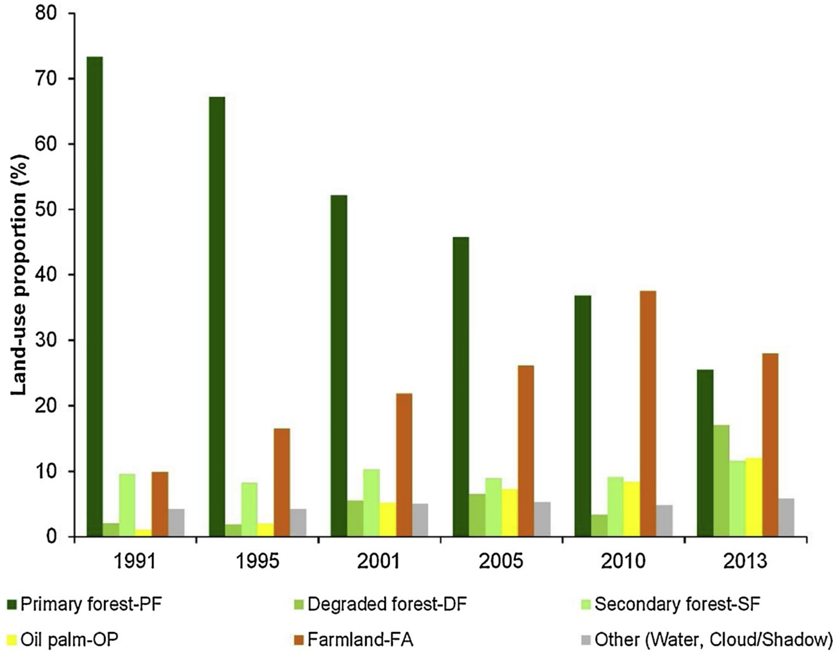

Fig. 2. Land-use proportion from 1991 and 2013 in the Moju river region, Pará State, Brazil.

opposite to that of forest conversion, increasing progressively over the years, reflecting the high levels of fragmentation in the region, from 0.3 to 4.5 fragments per 100 ha. The process has intensified between 2010 and 2013 (Fig. 3a). PROX-MN reduced greatly below 70% of forest, while fragmentation (PD) increases significantly below 40% of forest, which is expected.

Significant changes were also observed in the mean proximity (PROX_MN) among the patches ($F = 12.70$, $p < 0.001$), with significant differences observed across all the study years ($p < 0.001$). In 1991, forest at landscape was less fragmented and isolated (Fig. 3b), occupying with a larger proportion of landscape. As observed at vertical bars, there was a high variation among studied areas, mainly because region 1 started the fragmentation process before 1991. By 2013, the progressive reduction in primary forest resulted in a greater isolation of the fragments.

4. Discussion

4.1. Deforestation and land use changes

The present study provides the first systematic analysis of land-use and land-cover changes in the Moju region of Pará state over a 22-year period, during which large-scale oil palm production operations were established in the area. Our results showed a dramatic increase in cumulative deforestation in the region from 1991 to 2013, with almost 50% forest loss. The loss of 1237.81 km^2 of primary forest in the Moju region – constituting the loss of nearly half the region's primary forests in just two decades – reflects the substitution of this vegetation by expanding oil palm plantations and ranching operations. In addition to this loss of primary forest, our results reveal that 17% of the region's forests were degraded in 2013, an increase of 15% from 1991, due to the ongoing effects of fires and unregulated logging activities. Coupled with the substantial loss of primary forest, this increase in degradation is alarming because the changes in forest structure it induces can have just as deleterious an effect on biodiversity as that caused by deforestation (Barlow et al., 2016). As the Amazon region contains the largest forested area with conditions suitable for palm oil agriculture, the conversion of primary to palm oil in the area before ZEE expanded for primary forest.

By 2013, the annual rate of deforestation in the studied area had fallen to around 659 square kilometers per year, a decline of nearly 48 percent from 1991 and 11% from 2010 (Fig. 2). Despite the rapid

Table 2
Most common trajectories (> 1 %) culminating in oil palm plantations over the 22-year period between 1991 and 2013, involving the primary forest (PF), farmland (FA), and oil palm (OP) classes related to all land conversions to oil palm (295.86 km^2) in the Moju region of the Brazilian state of Pará.

Change Trajectories						LULC Classes	Area (km^2)	%
1991	1995	2001	2005	2010	2013			
PF	PF	OP	OP	OP	OP	Forest conversion to oil palm	37.32	12
PF	PF	FA	OP	OP	OP	Forest conversion to farmland and oil palm	24.88	8
FA	FA	OP	OP	OP	OP	Farmland to oil palm	21.77	7
OP	OP	OP	OP	OP	OP	Stable OP plantation	18.66	6
PF	PF	FA	FA	FA	OP	Forest conversion to farmland and oil palm	8.12	2.3
PF	PF	PF	OP	OP	OP	Forest conversion to oil palm	7.29	2.1
PF	FA	FA	FA	FA	OP	Old forest conversion to farmland and oil palm	3.16	2
PF	PF	SF	FA	FA	OP	Forest conversion to secondary forest, farmland and oil palm	3.12	2
PF	PF	DF	FA	FA	OP	Forest conversion, degradation and OP	1.6	1
PF	SF	OP	OP	OP	OP	Forest conversion to secondary forest and OP	1.3	1

Table 3
Description of trajectories of land use culminating in oil palm plantations over the 22-year period between 1991 and 2013, in the Moju region, Pará state, Brazil.

Trajectories of Land Use	Description
PF → SF → →FA → OP PF → FA → OP PF → OP FA → OP	**Deforestation.** Occurred more intensively in the 1990s, with less direct conversion of PF in recent years. High rates of direct conversion from PF to OP in the past, and more recently, of secondary forests. **Intensification.** Oil palm have expanded throughout the areas under consolidated use of oil palm. In this trajectory, the oil palm does not occupy areas of primary forest, but there are high rates of conversion of farmland (and associated “degraded areas”) to OP. **Concentration of land ownership**. The sale of land for the installation of oil palm operations intensified following the arrival of new industrial oil palm producers, increasing with the arrival of new groups of oil palm planters, motivated by the demands of national and international markets. As a result, land ownership became concentrated in the hands of a small number of companies, which acquire their holdings through purchase, rent and/or working associations with family farmers.

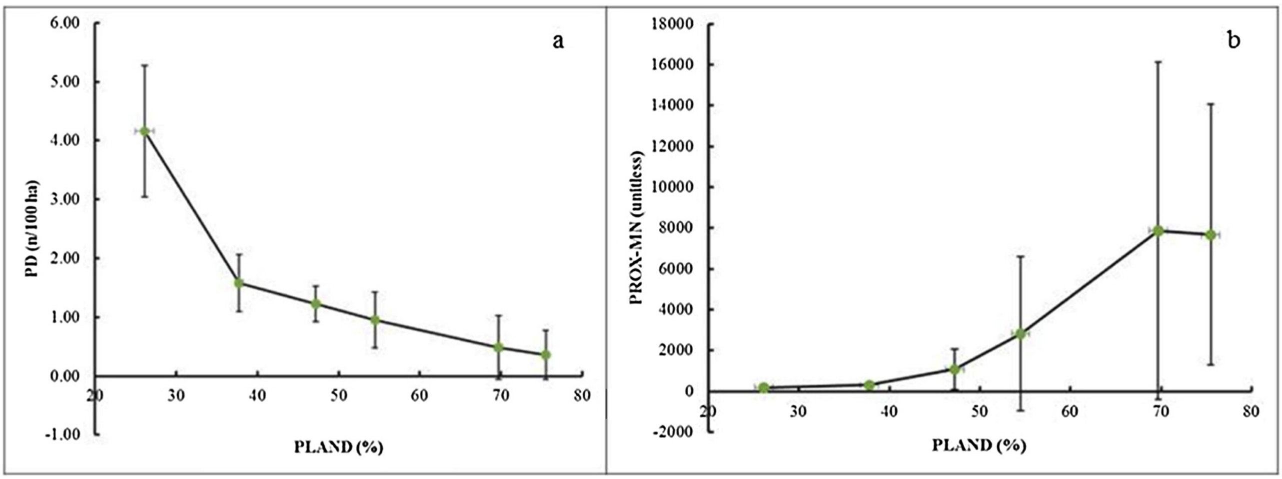

Fig. 3. Landscape structure associated with the primary forest (PF) class between 1991 and 2013 in the Moju region, in the Brazilian state of Pará considering 3 studied areas: (a) Patch Density (PD); (b) Mean Proximity (PROX_MN). Vertical bars on both graphs represent standard deviation values among studied areas.

progress in policies designed to combat deforestation and promote sustainable production in the Amazon, the contribution of oil palm to deforestation is still controversial. Furumo and Aide (2017) showed that a significant amount (284 km^2) of woody vegetation loss (including primary forest) is associated with recent oil palm production in Pará state. Considering the direct conversion of intact forest to oil palm plantations in the palm oil zone of Pará, Benami et al (2018) showed a decline from about 19 km^2 in 2006–2010 to around 8 km^2 between 2010-2014. In the present study, we found that about 87 km^2 (30%) of the oil palm plantations in the study region in 2013 came from areas that were forests in 1991 (Table 2), but after 2005, this conversion rate was 8.2 km^2 (2%) (Appendix 2). There was a tendency that most palm oil plantations are being established on previously cleared lands, particularly cattle pastures. Intensifying production on previously degraded pastures may create a huge opportunity for conservation in this sector. Pastures have long dominated the production landscapes of Para state and open up a zone of the state to expanding palm oil by establishing important infrastructure (i.e. roads), clearing lands for planting, and driving up land prices where large-scale industrial agriculture is more competitive.

The positive response with respect to avoided deforestation can be attributed to a number of factors. The Agroecological zoning of palm oil in the context of SPOPP, offered clear rules on areas designated for production, and restrict credit access for both incompliant companies and smallholders. However, it is clear that oil palm should be included in the long-term deforestation associated with LULC trajectories in this part of the Amazon region.

In Pará, government enforcement of environmental laws and the deforestation moratorium induced by civil society and companies (Assunção et al., 2012) has led to a dramatic reduction in the deforestation rates. Also the strong international pressure to reduce deforestation (Le Tourneau, 2015), the general alignment of the SPOPP with the Forest Code and the constant monitoring and better equipping of the state and municipal environment secretariats meant that the producers did not disrespect environmental legislation. The state secretariat of the environment (SEMAS-PA) has implemented the Rural Environmental Registry-CAR since 2012, which allowed the identification of the progress of palm oil planting at the property level. However, the question remains as to the eventual impact of the expansion of large-scale oil palm plantations on the forest and its fauna, which have already been impacted by severe historical degradation.

4.2. Degradation of the landscape and implications for public policies

Our findings show high rates of forest loss in the long term (1991–2013). However, there was reduced conversion for oil palm production in recent years (2010–2013). Associated with the increase in forest degradation, which raises concerns about the integrity of the forest remnants, the dynamics of land use promoted high fragmentation of the forest cover. By 2013, the progressive reduction in the primary forest cover in the Moju region resulted in a landscape characterized by forest fragments that are structurally isolated by a matrix of pastures and plantations.

With primary forest cover of around a quarter of its original extent, deforestation of Moju region may be nearing, or have already passed, a critical ecological threshold reported by Ochoa-Quintero et al., 2015 in the Rondônia state where landscapes with less than 30–40% forest cover hosted markedly fewer species than those with lower levels of deforestation. Similarly, in the Atlantic Forest, primary forest extent of 30% marks the threshold below which ecological community integrity collapses (Banks-Leite et al., 2014). Moreover, tropical forest landscapes with less than 30% primary forest become progressively less likely to support the recovery of regenerating secondary forest (Arroyo-Rodríguez et al., 2017). As such, any further loss of primary forests in our study area is likely to have disproportionately negative consequences for the conservation of regional biodiversity.

Data from the Moju region also indicate that forest remnants can play an important role in the conservation of its biodiversity (Lees et al., 2015; Mendes-Oliveira et al., 2017) and the integrity of aquatic systems (Cunha et al., 2015). These studies also showed that oil palm plantations have a low value for conservation, similar to that of pastures. In the light of this, the maintenance of forest patches, even degraded habitats, in landscapes dominated by oil palm, can be crucial for conservation planning.

The historical landscape degradation reported here was not only associated with primary forest. The dynamic land use in the studied area led to the conversion of degraded and secondary forests to oil palm plantations (Appendix 2). With the increasing land monopoly of the major oil palm industries in Pará, the term “degraded area” tends to be used in a less conservative sense, including secondary forests as degraded lands (Backhouse, 2016). In fact, secondary forests are considered degraded lands, with little or no economic value, by different actors in the rural area, but are not considered to be degraded forest from a legal perspective. The state of Pará has adopted an explicit definition of second-growth forests, and protected them in the late successional stages (Vieira et al., 2014). Therefore, the law applies to secondary forest only, while degraded forest is left unprotected. This is an opportunity for the expansion of oil palm plantation in areas of degraded pasture, without putting pressure on the existing primary and late secondary forests, which have been shown to hold substantial conservation value in the eastern Amazon (Lennox et al., 2018). In the context of avoiding deforestation in the oil palm landscapes, the SPOPP expects that oil palm should be planted only in deforested and degraded areas (Bertone, 2011). So, specifying levels of land degradation and mapping the available degraded land are crucial to achieving the sustainable expansion of palm oil in the Amazon region (de Carvalho et al., 2015).

In terms of environmental sustainability, there is a great concern about the existence of trajectories of land uses that lead to significant forest fragmentation and loss of biodiversity (Barlow et al., 2016). Thus, the analysis of the landscape considered here is an important component in the discussion of sustainability, insofar as it determines how the expansion oil palm plantations in the region affect the resilience of regional socio-ecological systems. The palm oil producers in the eastern Amazon destroyed large areas of carbon-rich forests to expand plantations, which brought landscape changes such as those reported here. It is known that oil palm adapts to degraded areas and exhibits high productivity under Amazonian conditions (Ramalho Filho et al., 2010). However, in an environment of high biological diversity such as in the Amazon, monocultures cannot be supported at a large scale (Vieira et al., 2008), because it is precisely the biodiversity that ensures the resilience of such region’s forests and guarantees a sustainable landscape.

As land use or landscape change is driven by various underlying proximate factors (Geist and Lambim, 2002) quantitative data like we showed here reflect the linkage between the factors and the process of change and further studies should focus on understanding such relationships in order to potentialize the application of landscape ecology approach in planning and managing land use for palm oil. Also, the ongoing expansion of oil palm in the Amazon region under the SPOPP context must integrate the land uses and stakeholders in a joint planning process (Van Oosten, 2013). This broad approach is increasingly recognized by the industries for conserving large ecologically valuable landscapes, such in the jurisdicional approach of the Roundtable on Sustainable Palm Oil – RSPO. If no appropriate actions under the SPOPP are developed at the landscape level, however, the expansion of oil palm plantations in the Amazon will continue unabated, which would impact the forests, reducing their total area over time, and increasing fragmentation, with subsequent effects on the biophysical environment and ecosystem services.

5. Conclusions

Our findings support the hypothesis that the ongoing degradation of the landscape associated with oil palm cultivation leads to the increasing fragmentation, isolation and reduction in the area of forest remnants. That the loss of nearly half the region’s primary forests in just two decades demonstrates the urgent need for actions to protect the remaining forests and restore degraded and secondary forests, to increase the overall proportion of forests in these oil palm landscapes. Moreover, any sustainable future expansion of palm oil plantations in the state needs to adopt strategies focused not only in the private properties but in the regional landscape, integrating the land uses and stakeholders in a joint planning process. Finally, these data also call for the development of initiatives aimed at the environmental regulation of large areas of monoculture, helping guarantee the region’s environmental sustainability.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2019.104321.

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