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Land use policies and deforestation in Brazilian tropical dry forests between 2000 and 2015

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Abstract

Tropical Dry Forests (TDFs) have been broadly converted into pastures and crops, with direct consequences to biodiversity, ecosystem services, and social welfare. Such land use and cover changes (LUCC) usually are strongly influenced by government environmental and development policies. The present study aimed at analyzing LUCC in Brazilian TDFs between 2000 and 2015, using the north of Minas Gerais state (128 000 km^2) as a case study. We evaluated the potential biophysical and social-economic drivers of TDF loss, natural regeneration and net area change at the county level. Further, we determined the effects of these LUCC variables on socioeconomic indicators. We identified a considerable change in TDF cover, expressed as 9825 km^2 of deforestation and 6523 km^2 of regeneration, which resulted in a net loss of 3302 km^2. The annual rate of TDF cover change was −1.2%, which is extremely high for a vegetation type that is protected as part of the Atlantic Rain Forest biome since 1993. TDF deforestation was directly affected by county area and by the increase in cattle density, and inversely affected by terrain declivity, indicating that land conversion is mostly driven by cattle ranching in flat regions. TDF regeneration was directly affected by county area and inversely affected by the increase in population density and terrain declivity. LUCC variables did not affect welfare indicators, undermining claims from rural sectors that TDF protection would cause a socioeconomic burden for northern Minas Gerais. Our results highlight the importance of naturally regenerating secondary forests to the maintenance of ecosystem integrity and its services, which are frequently neglected in conservation strategies. Hegemonic macroeconomic policies affecting TDFs have been deeply rooted in deforestation for commodities production, and need urgent review because they cause long-term environmental impacts without evidence of welfare gains.

1. Introduction

Tropical dry forests (TDFs) represent 42% of the tropical forests in the world (Murphy and Lugo 1986, Miles *et al* 2006) and are important providers of ecosystem services that support human activities (Calvo-Rodríguez *et al* 2017). Recent estimates indicate the potential existence of approximately 1.6 million km^2 of TDFs in the Americas, of which approximately 1 million km^2 have already been deforested or degraded (Portillo-Quintero and Sánchez-Azofeifa 2010). Conversion into pastures and crops is the main threat to TDFs, which results from a long history of human occupation attracted by flat relief, fertile soils, and appropriate climate for agriculture (Sánchez-Azofeifa *et al* 2005, Miles *et al* 2006). Due to the drastic consequences of forest conversion at multiple scales (Lambin *et al* 2001, Myers *et al* 2013, Portillo-Quintero *et al* 2014, Houghton *et al* 2015), the reduction in deforestation and forest degradation is a growing concern worldwide.

The design and enforcement of public policies to reduce deforestation and promote forest regeneration depend on accurate assessments of the spatial distribution and intensity of these processes (Lambin 1997, Kaimowitz and Angelsen 1998). Many different spatial and non-spatial models can be used to estimate deforestation trends and drivers in tropical regions (see reviews in Lambin 1997, Kaimowitz and Angelsen 1998, Verburg *et al* 2004). In Brazil, most of these models were developed for the Amazon region (e.g. Pfaff 1997, Aguiar *et al* 2007, Dalla-Nora *et al* 2014), with a few studies conducted at the regional scale in other biomes (e.g. Freitas *et al* 2010, Beuchle *et al* 2015, Stan *et al* 2015, Espírito-Santo *et al* 2016). For Brazilian TDFs, although deforestation estimates are available at regional (Bianchi and Haig 2013) and national levels (Portillo-Quintero and Sánchez-Azofeifa 2010, Redo *et al* 2013, Beuchle *et al* 2015), LUCC analyses evaluating drivers of deforestation are still lacking.

Estimates indicate that 52% of the 81 046 km^2 of Brazilian TDFs have already been converted to some sort of human activity (Portillo-Quintero and Sánchez-Azofeifa 2010). Brazilian legislation has two main instruments to decrease the conversion of natural vegetation: are (i) the creation of public PAs (conservation units in Brazilian legislation; SNUC 2000) and (ii) the forest code, which regulates land use change in private rural properties (i.e. outside PAs) (Brancalion *et al* 2016). Only 6.2% of the TDFs in Brazil are located within PAs (Portillo-Quintero and Sánchez-Azofeifa 2010) and, according to the forest code, only 20% of TDFs within rural properties must be protected as 'legal reserves', in contrast to 80% of Amazon Forests (Brancalion *et al* 2016). However, since 1993, Brazilian TDFs have been protected as part of the Atlantic Forest biome (Federal Decree 750, 1993). Later, the Federal Law 11 428, approved in 2006, ratified the protection status of TDFs, only allowing deforestation in cases of public utility and social interest or the conversion of early successional TDF stages (Espírito-Santo *et al* 2011). This protection has led to strong pressures from rural sectors and created a dispute about the classification and land use of TDFs in some parts of Brazil, particularly in the north of Minas Gerais state (Espírito-Santo *et al* 2014).

However, the legal and illegal deforestation of Brazilian TDFs is still high. Legal deforestation is related to public policies that foster the economic activity. As most Brazilian TDFs occur in semi-arid regions (Espírito-Santo *et al* 2009), irrigation governmental projects are considered of public utility and involve the conversion of large extents of TDFs into crops (Espírito-Santo *et al* 2009). Illegal deforestation occurs mainly inside rural properties, due to deficient control and difficulties to recognize TDFs as part of the Atlantic Forest biome. Recent estimates on the Atlantic Forest deforestation indicate that the counties with the highest native vegetation loss occur in areas of TDFs (SOS Mata Atlântica 2015). Hence, the determination of deforestation drivers and policies that influence them is fundamental for the design and implementation of efficient strategies to reduce TDF loss.

The present study aimed at understanding the effect of public policies on LUCC dynamics in Brazilian TDFs from 2000–2015, using the north of Minas Gerais State as a case study. Although our analyses are conducted at the regional level, it is important to highlight the large extent of the study area (128 620 km^2, more than double the size do Costa Rica, for example). We performed non-spatial regional regression models (Kaimowitz and Angelsen 1998) to determine the drivers of LUCC in TDFs, using 89 counties as analytical units. Non-spatial models have limitations such as not accounting for the specific location of forest clearing (i.e. land cover change is calculated by analytical unit) (Kaimowitz and Angelsen 1998) and assuming that the LUCC occurring in a given unit is primarily a function of factors originating within that unit (Lambin 1997). However, we decided to use a non-spatial approach because counties are the smallest administrative units in Brazil, allowing the incorporation of a larger number of independent variables obtained from census data that include human population, welfare indicators, and agricultural variables. Further, the county is the basal level of decision-making in Brazil, which makes county trends and patterns of LUCC very useful for policy design. We also discussed the interplay of local (i.e. county), regional and national processes (state and federal environmental and development policies) on LUCC in the studied area. We aimed at answering the following questions: (i) what is the extent of LUCC (deforestation, natural regeneration, and land cover net change) in TDFs of northern Minas Gerais from 2000–2015? (ii) What are the drivers of these processes and how are they influenced by environmental and economic development policies? (iii) What are the effects of LUCC on human welfare indicators?

2. Material and methods

2.1. Study area

The study area is the north of Minas Gerais State, a politically defined meso-region that encompasses 21% of the state area and comprises 89 counties in São Francisco River Basin (figure 1). The predominant climate in the region is tropical semi-arid (Aw in Köppen's classification), characterized by dry winters (May–September) and rainy summers (November–March), with average rainfall varying from 700 mm to 1200 mm and an average temperature between 21 °C–25 °C (Antunes 1994). Topography is usually flat, with altitudes varying from 400–700 m, except for the Espinhaço Mountains, with altitudes up to 1760 m. With approximately 1.6 million inhabitants (IBGE 2010), the north of Minas Gerais is considered as one of the poorest regions in the state, with a low Human Development Index (HDI = 0.625; Minas Gerais = 0.731; Brazil = 0.727). The region is

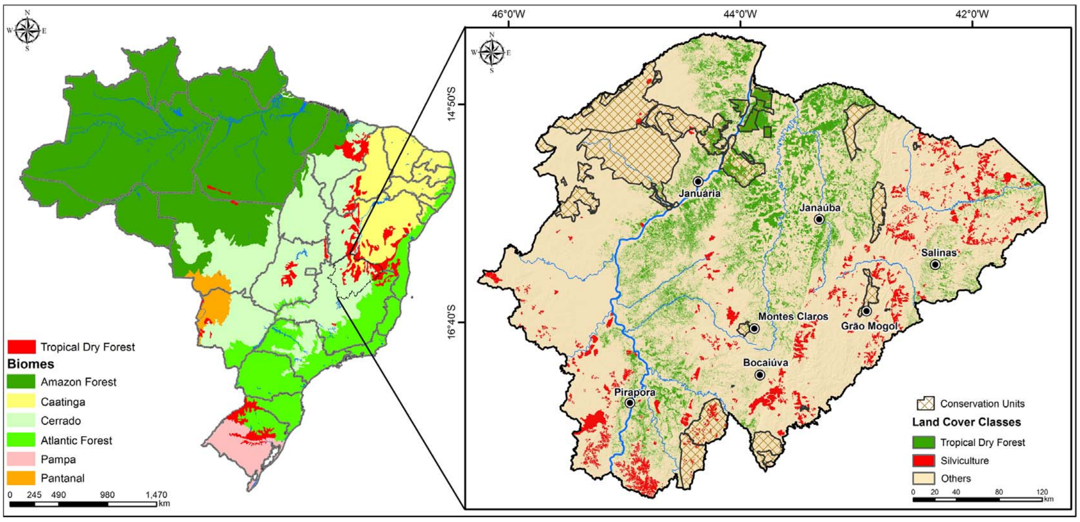

Figure 1. Location of the north (dotted limit) of Minas Gerais State, in southeastern Brazil, with its main cities and protected areas. The insertion of this region in Brazilian main biomes and the country's distribution of tropical dry forests are also shown.

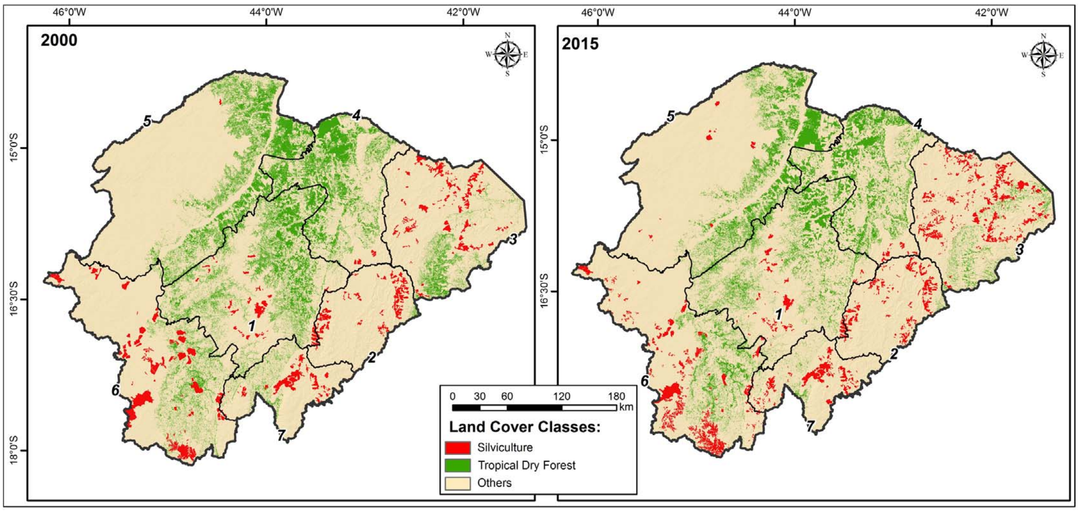

Figure 2. Changes in land cover in each micro-region of the north of Minas Gerais from 2000–2015. Micro-regions are politically defined by the Brazilian IBGE and named as follows: 1 = Montes Claros, 2 = Grão Mogol, 3 = Salinas, 4 = Janaúba, 5 = Januária, 6 = Pirapora and 7 = Bocaiúva.

marked by the presence of three large biomes: Caatinga in the north, Cerrado in the south and west, and Atlantic Forest in the east (figure 1). The Cerrado predominates, followed by TDFs, which currently comprise 14 804.24 km^2 of the region (23.56% of the remaining vegetation cover in the north of Minas Gerais; Scolforo and Carvalho 2006). According to the Brazilian Institute for Geography and Statistics (IBGE), the north of Minas Gerais is sub-divided in seven micro-regions with different biophysical and socioeconomic characteristics, as well as varying extent of PAs and TDF cover (figures 1 and 2).

The main economic activities in the north of Minas Gerais are extensive livestock farming, agriculture, and silviculture (Castillo *et al* 2014). In 1970, the establishment of governmental incentives to promote the regional development triggered a fast human occupation process, which resulted in an economic cycle of deforestation to supply the timber industry and produce charcoal. In regions of flat relief, the deforested areas were predominantly converted into pastures (Espírito-Santo *et al* 2009). TDFs are also frequently encountered in limestone outcrops, where timber extraction and mining activities for the construction industry are common (Espírito-Santo *et al* 2014). However, the Jaíba Irrigation Project has caused one of the highest impacts on TDFs in the north of Minas Gerais. Located on the margins of São Francisco River, this project will reach 107 600 ha when fully implemented. Two out of four phases were executed so far: the first was concluded in 1988, with approximately 24 000 ha destined to irrigation; the second started in 1998 and is still in progress, with a projected extent of 34 700 ha (CODEVASF 2015, RURALMINAS 2015).

To compensate for such great deforestation, approximately 178 000 ha of PAs from two main categories were created (RURALMINAS 2015): 84 000 ha of PAs of restricted use (or integral protection, equivalent to IUCN's category I to IV; IUCN 2003, Rylands and Brandon 2005) and 94 000 ha of PAs of sustainable use (equivalent to IUCN's category V and VI; Chape *et al* 2003, Rylands and Brandon 2005).

2.2. Image acquisition, processing, and classification

To determine the LUCC in the north of Minas Gerais, we obtained images of the satellite Landsat5 for the year 2000 (Thematic Mapper—Sensor TM, at a spatial resolution of 30 m) and Landsat 8 for 2015 (Operational Terra Imager−Sensor OLI, at a spatial resolution of 30 m). Details on image acquisition and processing are described in supplementary material S1 available at stacks.iop.org/ERL/13/035008/mmedia and in Espírito-Santo *et al* (2016). We defined three types of land cover: tropical dry forests (TDFs), silviculture (*Pinus* and *Eucalyptus*) and other (natural vegetation different from TDFs, crops, pastures, urban areas, burned areas, roads, bare soils, and water). The reduced number of land cover classes aims to minimize potential errors that can occur during image classification (Langford *et al* 2006). The separation of pixels into these classes is facilitated the by strong deciduousness of TDFs compared to other vegetation types (such as the semi-deciduous Cerrado and riparian forests) during the dry season. Thus, we used a composite of scenes from the dry season in the years 2000 and 2015, a procedure that also minimizes the incidence of clouds in the Landsat images.

We considered all seasonally dry deciduous woody vegetation in our study area as TDFs, as indicated by the Map of Brazilian Vegetation (IBGE 1993) and the Forest Inventory of Minas Gerais (Scolforo and Carvalho 2006). Most of the TDFs in Minas Gerais are inserted in the Caatinga biome according to the Map of Brazilian biomes (Espírito-Santo *et al* 2011, figure 1). Shrubby formations typically found in Caatinga are rare in our study region (Scolforo and Carvalho 2006) and, due to similar deciduousness levels, these areas were considered as TDFs in our classification. The vectorization of roads, river channels, and *Eucalyptus* and *Pinus* plantations was made through visual interpretation and classification. Validation was conducted with field trips and determination of 42 ground control points in the studied region. To assess the accuracy of our classification, we constructed a confusion matrix comparing our validation points with our land cover map, which was used for the calculation of the kappa coefficient (Congalton and Green 2008). The overall accuracy of the map was estimated to be 91%, with a kappa coefficient of 88.2%.

2.3. Drivers of deforestation and regeneration

We determined the deforestation and natural regeneration rates for TDFs in the entire north of Minas Gerais and for each of its micro-regions (see figure 2). Deforestation was considered the change in land cover from the class 'TDF' to the classes 'Other' (except another type of natural vegetation) and 'silviculture'. Regeneration means natural, spontaneous growth of TDFs (i.e. secondary succession) in areas that were cleared in a previous period. We made no differentiation among successional stages of TDFs or assessed their integrity because such characterization is very difficult at large scales with Landsat images (García-Millán *et al* 2014). We calculated the net area change as the balance between TDF conversion (gross loss in area) and regeneration (gross gain in area). The annual rate of net area change was determined for the entire region using the interest-rate formula (Puyravaud 2003).

We obtained biophysical and socioeconomic variables indicated as important drivers of LUCC in previous studies that also used counties as analytical units (e.g. Pfaff 1997, Andersen *et al* 2002, Aide *et al* 2013). Furthermore, we only included socioeconomic variables that were available for each county and that were more directly affected by policies operating at the county level. Biophysical parameters for the analysis of deforestation drivers were based on land cover maps. We obtained the following variables per county: total area (km^2), average declivity (%), density of rivers (km/km^2), road extent (paved and unpaved together; km), area covered by *Eucalyptus* and *Pinus* plantations (including areas in preparation for plantation—hereafter 'silviculture'), and the TDF area in two different categories of protected areas—restricted use and sustainable use (km^2). Delimitation and year of establishment of the PAs were obtained from the database of the State Forest Institute (IEF 2015). We expected a negative relationship between deforestation (i.e. TDF area loss) and increases in PA extent because we assume that the implementation of PAs in a given county decreases the area available for deforestation in that county. Thus, we ignored possible spillover effects generated by the restrictions imposed by PAs (see Andam *et al* 2008). Conversely, we expected the opposite trend for regeneration (i.e. TDF area gain), because degraded areas inside the farms expropriated for PA implementation would be allowed to regrow to secondary forests. Between 1998 and 2000, several PAs were created in the north of Minas Gerais. These PAs were not accounted into the protected areas calculated for 2000 but for 2015, as their impacts on LUCC occurred in the long-term. Hence, the increase in the protected area resulting from the creation of these PAs was included in the period analyzed (2000−2015).

We also determined the climate class for each county based on a climate map generated for the state of Minas Gerais, using the Thornthwaite Moisture Index (TMI; Carvalho *et al* 2008). There are four climate classes in northern Minas Gerais: Semi-arid (−66.7 to −33.3), Dry Sub-humid (−33.3 to 0), Sub-humid (0–20), and Humid B1 (20–40). Hence, we created an interval variable (humidity index) through the attribution of a proportional value to each climate class (1, 2, 2.6, and 3.2, respectively). When the county area contained more than one climate class, we calculated an average humidity index, using this interval variable.

We obtained socioeconomic parameters for each county from two different census databases carried out by the Brazilian IBGE. We used demographic censuses (fully released in the end of each decade) of the years 2000 and 2010 (IBGE 2010) to obtain the following variables: population density (individuals/km^2) and Gini Index (inequality index). The Human Development Index (HDI) was obtained from the United Nations Development Programme (PNUD 2015). We used the disaggregated version of the index that considers only the income, HDI-I (Human Development Index—Income), as it reflects more directly the economic gains from the conversion of the TDFs at the county level. The complete Human Development Index also considers parameters related to education and life expectancy, which are strongly affected by state and federal development policies. The Gross Domestic Product (GDP; standardized for the year 2000) was also obtained from the IBGE databases for the years 2000 and 2012 (IBGE 2015a). We used agricultural censuses from the IBGE to obtain the size of the cattle herd and crop areas in 2000 and 2014 (IBGE 2015b).

2.4. Statistical analysis

To determine the causes of deforestation and regeneration, we calculated the total area lost and regenerated in TDFs and the net change in TDF area per county between 2000 and 2015 (three response variables). We considered the following 12 explanatory variables: total area per county, TDF area in the beginning of the period, climate type, average declivity, river density, total change in: road extent, silviculture area, TDF area in PAs of restricted use and sustainable use (two different variables), crop area, and percentage variation in population and cattle density. First, we used a paired *t*-test based on permutations to test whether all response and explanatory variables differ between 2000 and 2015, except for county area, climate type, average declivity, and river density. We made the same analyses for human welfare indicators (Gini Index, GDP, and HDI-I; see below). We used a paired *t*-test because the samples were temporally dependent. We tested the effects of the 12 potential deforestation drivers on the three response variables using multiple linear regressions through generalized linear models (GLMs). Details on model construction are given in supplementary material S2.

To determine the effects of LUCC on social welfare, we calculated the percentage change per county in the Gini Index and HDI-I between 2000 and 2010, and in the GDP between 2000 and 2012. Each of these parameters was inserted as a response variable in a GLM containing the total lost and regenerated area in TDFs and the net change in TDF area as explanatory variables. We followed the same procedure previously described for multiple linear regressions through GLMs (see supplementary material S2).

Table 1. Changes in land cover in the north of Minas Gerais state, southeastern Brazil.

Land use class	2000		2015	
	Km^2	%	Km^2	%
Tropical dry forests	18 106.10	14.11%	14 804.24	11.53%
Silviculture	1738.86	1.35%	2247.16	1.75%
Other	108 487.30	85.89%	111 303.45	86.72%

3. Results

In the period from 2000–2015, TDFs in the north of Minas Gerais undergone a considerable change in land cover, expressed as 9825 km^2 of deforestation and 6523 km^2 of natural regeneration, comprising a total net loss of 3302 km^2 (18%) (figure 2; table 1), and annual change of −1.2%. TDFs were unevenly distributed across the seven micro-regions and mostly concentrated in the Januária, Janaúba and Montes Claros in 2015 (table 2). PAs were very concentrated in the micro-region of Januária, where 10 690 km^2 (71.1% of the total area protected in the north of Minas Gerais) are inside 21 PAs of different categories (figures 1 and 2; supplementary table S1). In spite of that, TDF area loss was huge (2433 km^2, 46.6%) and comparable to the micro-region of Janaúba (2128 km^2, 47.7%), which contains only 7.9% of the total area protected in the north of Minas Gerais (supplementary table S1). However, PAs apparently have a slight positive effect on TDF regeneration, since Januária exhibited the highest TDF area gain, strongly reducing the net TDF area change in this micro-region (supplementary table S1). In general, the micro-region of Montes Claros (where the largest city is situated and only 97 km^2 are inside a single PA) had the highest TDF area loss (3020 km^2, 57.7%) and accounted for almost half the net TDF area change (1516 km^2) in the entire study region (supplementary table S1).

During the period analyzed, we observed a moderate increase in population density (7.6%), and a pronounced increase in road density (21%), cattle density (28%), and silviculture areas (18%) (supplementary table S2). However, the areas destined for crops showed a decrease of 11.6% in the same period. As a whole, there was an increase in the area of the two categories of PAs between 1998 and 2015. The PAs of restricted use showed a seven-fold increase in area and the PAs of sustainable use showed an increase of 123.6% (supplementary table S2). It is important to highlight that most of these PAs protected mainly Cerrado. Total TDF extent inside PAs of restricted use increased from 63.5 km^2 in 1998 to 876.7 km^2 in 2015, and from 82.2 km^2 to 486 km^2 inside PAs of sustainable use during the same period (supplementary table S2). The observed change in TDF extent inside PAs

Table 2. Potential drivers of land use and cover change and welfare indicators at regional level for northern Minas Gerais, Brazil, between 2000 and 2015. Significant differences ($p < 0.05$) are shown in bold. The data are given as average ± SD.

Drivers	Year[a]				
	2000	2015	Change (%)	Paired *T*-test	*P*
TDF area (km^2)	235.14 ± 31.02	192.26 ± 24.53	−18.23	2.63	**<0.05**
Potential drivers					
Silviculture (km^2)	48.03 ± 13.89	56.75 ± 15.60	+18.15	−1.49	>0.05
Crop area (km^2)	3554.30 ± 350.37	3143.34 ± 395.28	−11.56	1.37	>0.05
Cattle density (heads/km^2)	21.41 ± 1.38	27.05 ± 1.59	+26.34	−6.64	**<0.001**
Population density (ind/km^2)	14.71 ± 1.70	15.53 ± 1.88	+5.57	−4.28	**<0.001**
Road density (km/km)	0.22 ± 0.008	0.27 ± 0.01	+22.73	−9.46	**<0.001**
PAs of restricted use (km^2)	0.83 ± 7.23	10.71 ± 48.4	+12.9	−0.58	**<0.05**
PAs of sustainable use (km^2)	1.10 ± 6.87	6.31 ± 32.0	+5.73	2.11	**<0.05**
Welfare indicators					
Gini Inequality Index	0.57 ± 0.66	0.49 ± 0.05	−14.03	8.71	**<0.001**
GDP (thousand BRL)	0.50 ± 0.01	0.58 ± 0.01	+13.8	−46.2	**<0.001**
IDH-I	0.49 ± 0.05	0.59 ± 0.04	+17.34	−22.08	**<0.001**

[a] Some variables were collected in years close to 2000 and 2015. See text for details.

was a consequence of both the creation of new PAs and of TDF deforestation and regeneration in formerly existing PAs. In the 77 counties where TDFs occur, the GDP showed a marked three-fold increase between 2000 and 2012, which was below that observed for the entire northern region of Minas Gerais (406%), for the whole state (438%), and Brazil (407%) (PNUD 2015).

The net change in TDF area for the counties of northern Minas Gerais in the period analyzed was consistent with that observed at the regional level: −18.23% (table 2). Of the ten variables compared, only silviculture and crop area did not differ significantly between years (table 2). From 2000–2015, 47 counties (60.3%) showed a net loss in TDF area and 30 (39.3%) showed an increase in TDF area. The number of counties with PAs containing TDF increased from five in 1998 to 23 in 2015, with a high concentration around the Jaíba Project, where two counties (Jaíba and Matias Cardoso) had five CUs. Cattle density decreased in 18 counties of northern Minas Gerais and the population density decreased in 19 counties. Considering the whole period analyzed, 28 counties did not have silviculture (36 had silviculture in 2000 and 33 in 2015), which suggests that this economic activity is also limited to some parts of the region studied (figure 2).

The results of the linear regression analysis indicated that three drivers significantly affected TDF deforestation in the study area between 2000 and 2015: county area, average declivity, and cattle density (figure 3). The area loss in TDFs was positively related to the county area and cattle density and negatively related to average declivity (figure 3). The regenerated area in TDFs was significantly and positively affected by the county area, and negatively affected by average declivity and population density (figure 4). The net change in area was not affected by any of the tested variables.

The GDP and HDI-I increased significantly in the period analyzed (table 2) in all the 77 counties where TDFs occur. The HDI-I increased 17.34%, much above the observed for the state of Minas Gerais (7.35%) and Brazil (6.79%). The Gini Index decreased significantly in the region (−14.3%; table 4), except in seven counties. The decrease in the region was greater than in the state (8.9%) and country (6.6%). The changes observed for these three socioeconomic indicators between 2000 and 2015 were not related to deforestation, regeneration, and net change in TDF area per county in the north of Minas Gerais.

4. Discussion

The TDFs of northern Minas Gerais passed through expressive LUCC between 2000 and 2015, which affected over 16 000 km^2 and correspond to approximately 50% of the original cover of this vegetation type (approximately 32 000 km^2). The extent of TDF deforestation in the region is massive: 9825 km^2, approximately 54% of the extant cover in 2000, which were partially counterbalanced by 6523 km^2 of TDF regeneration (66.3% of the TDF area loss). Our results corroborate other studies that indicate extensive LUCC when both deforestation and regeneration are considered. In a large-scale analysis considering entire Latin America and the Caribbean, Aide *et al* (2013) detected that the regeneration of woody vegetation represented 66.9% of the total deforested area between 2001 and 2010. For Brazil, the same study indicated a total loss of 245 767 km^2 of woody vegetation, which was partially compensated by 146 342 km^2 (59.5%) of regenerated areas. Also in Brazil, Beuchle *et al* (2015) detected a loss of 265 595 km^2 of woodlands in the Cerrado biome between 1990 and 2010, with 143 110 km^2 of regeneration (53.9%); for the Caatinga biome, the authors estimated 89 656 km^2 of woodland loss, with 52 588 km^2 of regeneration (58.7%). Thus, our findings reinforce the importance of natural regeneration for the maintenance of vegetation cover in tropical regions, since this process can reduce the negative net cover change in 50%−70%.

It is important to highlight that, from 2000–2015, most TDF areas in rural properties (except for areas in early natural regeneration stage) were protected by the Federal Decree #750 of 1993, ratified

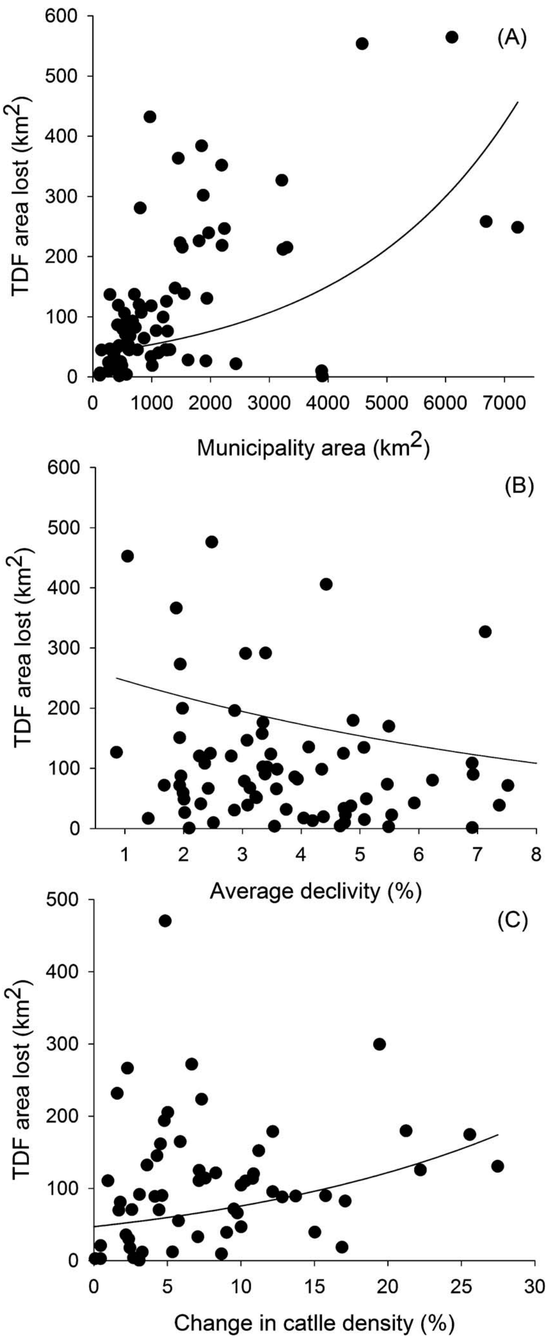

Figure 3. Effects of the (*a*) county area, (*b*) average declivity, and (*c*) changes in cattle density on the deforestation of tropical dry forests in 77 counties of the north of Minas Gerais state. These explanatory variables were retained in minimal adequate models ($p < 0.05$) after stepwise selection.

by the Atlantic Forest Law in 2006. In the period between 2000 and 2006, before the enactment of the Atlantic Forest Law, there were many attempts to regulate the use of TDFs in northern Minas Gerais (Zhouri *et al* 2008), which resulted in legal uncertainty and doubts about their protection status. After 2006, especially after the publication of the Map of Application of the Atlantic Forest Law (Federal Decree #6660), in 2008, the Brazilian TDFs inside rural properties became unequivocally protected (Espírito-Santo *et al* 2011). There are three prominent factors that explain the rampant deforestation observed in the study period: first, there are serious deficiencies in government environmental agencies, due to lack of personnel and structure to prevent illegal deforestation. Second, the correct application of the law depends on the differentiation of successional stages, for which technical criteria were defined based on species composition, forest structure, plant life forms, and even the amount of litterfall (CONAMA Resolution #392/2007). However, this differentiation requires detailed studies and specialized technical knowledge, which are rarely available, making the definition of successional stages by environmental agencies frequently arbitrary, leading to the deforestation of TDFs in advanced successional stages. Finally, it is difficult for the general public,

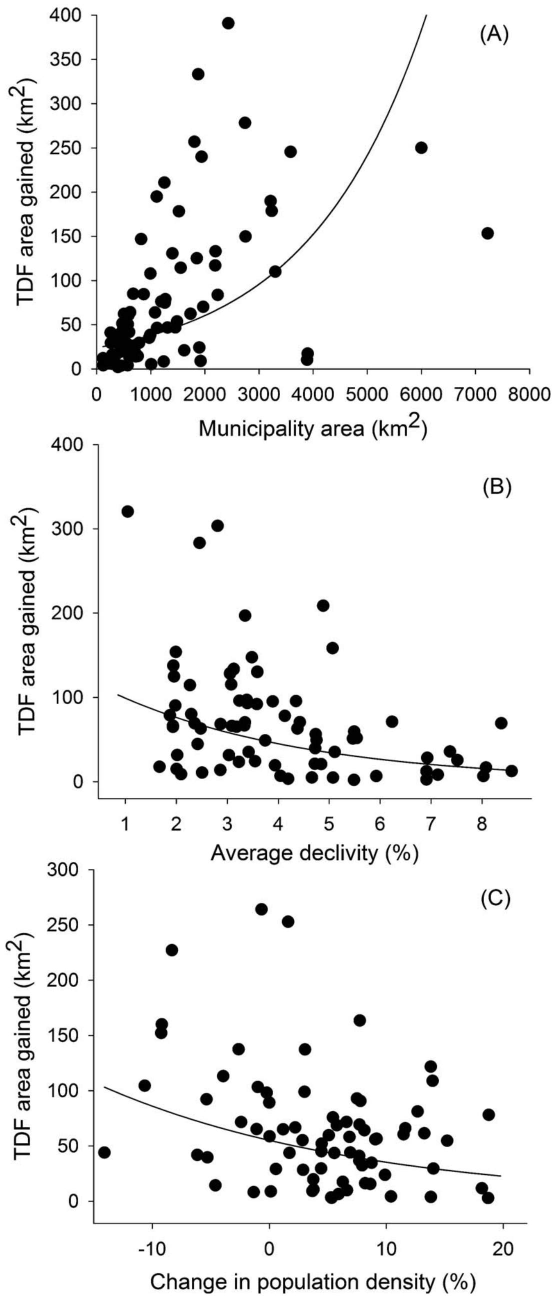

Figure 4. Effects of the (*a*) county area, (*b*) average declivity, and (*c*) change in population density on the regeneration of tropical dry forests in 77 counties of the north of Minas Gerais state. These explanatory variables were retained in Minimum Adequate Models ($p < 0.05$) after stepwise selection.

governmental agencies, and decision-makers to associate TDFs with the Atlantic Forest biome, especially due to the deciduousness and aridity of the regions where they are located. Hence, although there is a map indicating which TDF areas should be protected, they are frequently considered as part of the Caatinga and Cerrado and have their deforestation improperly allowed.

Another factor responsible for the huge deforestation that occurred between 2000 and 2015 was the expansion of the Jaíba Irrigation Project, on the margins of the São Francisco River, in Jaíba and Matias Cardoso. The deforestation in these two counties represented 9.5% of the total observed in the entire northern region. The Jaíba Project was conceived to have four phases, at the end of which 107 600 ha would be destined to irrigated agriculture and its associated infrastructure. During the period analyzed here, the second phase of the project was developed (and still not concluded), with a total deforestation forecast of 34 700 ha. The deforestation within the perimeter of the Jaíba Project comprises different successional stages but is legally allowed, as it is considered a project of public utility and social interest. However, an enterprise of such magnitude is also a deforestation driver, as it promotes the expansion of the agroindustry and service sectors, and also increases population density. The counties of Jaíba and Matias Cardoso, where the Jaíba Project is implemented, showed a population increase of 23% and 16%, respectively, markedly above the average value observed for the whole northern region of Minas Gerais (5.83%).

The analysis of LUCC drivers at the county level provided important information that can set the ground for human occupation and sustainable use policies for TDFs in the region studied. The size of counties was one of the main drivers of the deforestation intensity, but this is an expected relationship, as counties that harbor a larger extent of natural vegetation are more subject to lose a larger amount of its cover (Aide *et al* 2013). The analysis of other drivers is important to identify which biophysical and socioeconomic factors cause deforestation. The declivity and cattle density affected deforestation, indicating that TDF clearing results predominantly from the livestock farming in flat areas, where the establishment of pastures for the cattle is facilitated by mechanization (Jasinski *et al* 2005). In the region, the most important economic activity is extensive cattle ranching (59% of the rural areas; Espírito-Santo *et al* 2009), which comprised approximately 2.8 million heads of cattle in 2014, followed by agriculture (21.6%), and silviculture (11.7%) (Rodrigues 2000). Indeed, the cattle ranching is amongst the main causes of deforestation in Brazil (Barona *et al* 2010, Aide *et al* 2013) and in the world, and it is frequently encouraged by governmental programs and policies (Morán and Galletti 2002).

It is important to highlight the fundamental role of natural regeneration for the maintenance of TDFs (Stoner and Sánchez-Azofeifa 2009), which reduced the net loss of this vegetation type to 3302 km^2 in the study period. The natural regeneration of TDFs occurs through ecological succession in abandoned areas, after inadequate soil management and its resulting degradation (Espírito-Santo *et al* 2014). The management practices usually applied in extensive pastures are extremely impacting (Espírito-Santo *et al* 2009), such as the use of annual fires for the resprouting of grasses (Barreda-Bautista *et al* 2011) and the massive application of pesticides and fertilizers (Tilman *et al* 2001). Besides, the large extent of regenerated TDFs can result from the enactment of the Atlantic Forest Law in 2006, which may have discouraged the agricultural production in TDFs, leading to the abandonment of pastures and crop areas.

The importance of secondary forests for biodiversity conservation and maintenance of ecosystem services has been progressively acknowledged (Poorter *et al* 2016). Our LUCC analysis did not separate the different successional stages of TDFs, which is fairly difficult through remote sensing. According to Frolking *et al* (2009), there are many technical hurdles in classifying forests under different disturbance regimes, such as unclear definitions of successional stages, the development of robust algorithms that generalize across a region, and the difficulty of detecting small-scale changes. The use of hyperspectral, multi-angular images such as the CHRIS/PROBA sensor is promising, although topography can interfere with the spectral separation of successional stages in TDFs (García-Millán *et al* 2014). It is also difficult to determine the integrity of regenerated TDFs, but studies carried out in the region indicate that intermediate stages of succession (30–40 years after logging) already harbor richness and species composition similar to those of forests at late stage for several groups of organisms, as well as similar functional characteristics (Espírito-Santo *et al* 2014). The higher protective status of Brazilian TDFs under the umbrella of the Atlantic Rain Forest law generates a huge potential for the application of REDD+ in this vegetation type, a strategy that should be evaluated for its possible contribution to biodiversity conservation and reduction in carbon emissions.

The analysis of drivers revealed that the extent of the county area was also an important factor for the regeneration of TDFs in northern Minas Gerais, for the same reasons related to deforestation. The regeneration was also higher in flat areas because they are more deforested and used for cattle ranching, and consequently, there is a higher extent of flat areas subject to abandonment. The gain in TDF areas was higher in counties with lower population density, which indicates that anthropogenic pressures certainly have a negative impact on regeneration. However, TDFs regeneration was not affected by the increment in PAs in the study region. Some counties that showed considerable regenerated areas, such as Januária (280.7 km^2), Jaíba (246.6 km^2), Manga (218.1 km^2), and Matias Cardoso (196.4 km^2), which together summed 14% of the TDF gain in the entire region, possessed a large extent of PAs. A substantial part of the PAs are Areas of Environmental Protection (Áreas de Proteção Ambiental—APAs), composed of a set of public and private areas that allow cattle ranching and agriculture, and therefore, may not effectively permit TDF natural regeneration.

It is also important to mention that our study did not consider the likely occurrence of spatial spillovers, i.e. a response to PA implementation by changing land uses in neighboring locations (Andam *et al* 2008). Thus, deforestation can increase (due to agricultural displacement) or decrease (due to enhanced law enforcement) in the surroundings of PAs (Andam *et al* 2008), generating biased estimates of the effects of PAs at the county level. Thus, LUCC models exclusively designed to evaluate the role of PAs to avoided deforestation are necessary for TDF regions. Because PAs are not randomly distributed across the landscape, it is necessary to set-up a quasi-experimental design and to use matching methods that formally develop a counterfactual control group (Andam *et al* 2008, Ferraro *et al* 2011). Such approach eliminates the bias inherent to the non-random location of PAs by randomly distributing observation points or pixels across the entire study area to get an untreated observation with biophysical and socioeconomic features that match each treated observation (i.e. the counterfactual), and then compare pixels in protected and unprotected areas (Pfaff *et al* 2015).

Our results confirm an improvement in the economic scenario of each county, indicating a decrease in social inequality, which was evident in the three-fold increase in GDP and decrease in income concentration (−14.03%) and the increase in HDI-I (17.34%). In spite of the regional improvement in all human welfare indicators between 2000 and 2015, none of these variables was affected by deforestation, regeneration, or net change in TDF area at the municipal scale. Hence, the statement by rural sectors that TDF protection would cause a socioeconomic onus for northern Minas Gerais has no statistical support. Anyway, the improvement in human welfare at a regional level should be analyzed with caution. It also reflects a substantial improvement in socioeconomic conditions in Brazil between 2004 and 2014, as a result of the economic growth and development policies created by the federal government, such as the income transference programs and the considerable increase in the minimum wage.

5. Conclusions

The TDFs of northern Minas Gerais underwent considerable land use changes, which affected approximately 16 000 km^2 of this vegetation between 2000 and 2015. TDF deforestation is directly related to cattle ranching, the main economic activity in the region, and public policies for the development of irrigated areas, such as the Jaíba Project. As a federal law unequivocally protects TDF fragments within rural properties in the region since 2006, the deforestation rate observed can be considered extremely high. Although better law enforcement by government environmental agencies is urgent, such level of deforestation suggests that command-and-control strategies have not been effective for TDF conservation, and indicates the need of proactive approaches such as dissemination and education regarding the role of TDFs as providers of ecosystem services. If deforestation is high in northern Minas Gerais, where the repercussion of the TDF legal protection reached all sectors of the society, it is possible that TDF clearing is even higher in regions where a broad public debate did not occur.

However, the natural regeneration is an important process to compensate the conversion of TDFs. Therefore, the relevance of secondary forests must be strongly considered in conservation strategies, as this vegetation type is fundamental for the maintenance of biodiversity and ecosystem services. In addition, specific policies should be developed to promote the natural regeneration of abandoned pastures, as the resulting carbon sequestration can contribute to the Brazilian goal of reduction in carbon emissions and encourage the development of REDD+ projects in TDFs, which are still neglected in favor of rainforests. Finally, macroeconomic policies that encourage the hegemonic development model in TDF areas must be reviewed. These policies are rooted in deforestation and in the production and exportation of agricultural and livestock commodities, causing long-term environmental impacts without evidence of welfare gains.

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