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Understanding patterns of land-cover change in the Brazilian Cerrado from 2000 to 2015

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Clearing tropical vegetation impacts biodiversity, the provision of ecosystem services, and thus ultimately human welfare. We quantified changes in land cover from 2000 to 2015 across the Cerrado biome of northern Minas Gerais state, Brazil. We assessed the potential biophysical and socio-economic drivers of the loss of Cerrado, natural regeneration and net cover change at the municipality level. Further, we evaluated correlations between these land change variables and indicators of human welfare. We detected extensive land-cover changes in the study area, with the conversion of 23 446 km^2 and the natural regeneration of 13 926 km^2, resulting in a net loss of 9520 km^2. The annual net loss (−1.2% per year) of the cover of Cerrado is higher than that reported for the whole biome in similar periods. We argue that environmental and economic variables interact to underpin rates of conversion of Cerrado, most severely affecting more humid Cerrado lowlands. While rates of Cerrado regeneration are important for conservation strategies of the remaining biome, their integrity must be investigated given the likelihood of encroachment. Given the high frequency of land abandonment in tropical regions, secondary vegetation is fundamental to maintain biodiversity and ecosystem services. Finally, the impacts of Cerrado conversion on human welfare likely vary from local to regional scales, making it difficult to elaborate land-use policies based solely on socio-economic indicators.

This article is part of the themed issue 'Tropical grassy biomes: linking ecology, human use and conservation'.

1. Introduction

Land-use and -cover changes (LUCC) are among the most pervasive of human impacts on ecosystems, with complex direct and indirect consequences across spatial and temporal scales [1,2]. In tropical regions, the most important land-cover change is the agricultural conversion and consequent degradation of natural ecosystems [3,4], with drastic impacts for biodiversity and ecosystem function, in turn affecting the provision of ecosystem services that support human well-being [2,5]. On the other hand, clearing of natural vegetation can be, to a degree, mitigated by natural regeneration, a process frequently neglected in LUCC studies [6], and conservation research and policies [3,7]. However, specific programmes and funds to both protect biodiversity and promote ecosystem recovery are usually focused or even restricted to tropical forests with higher carbon stocks [8,9].

The intensity of tropical land conversion and rates of regeneration varies both spatially and temporally as influenced by a range of biophysical and human drivers, from local soil properties, density of paved roads and management practices [10–12] to the global demand for commodities [13,14]. Although

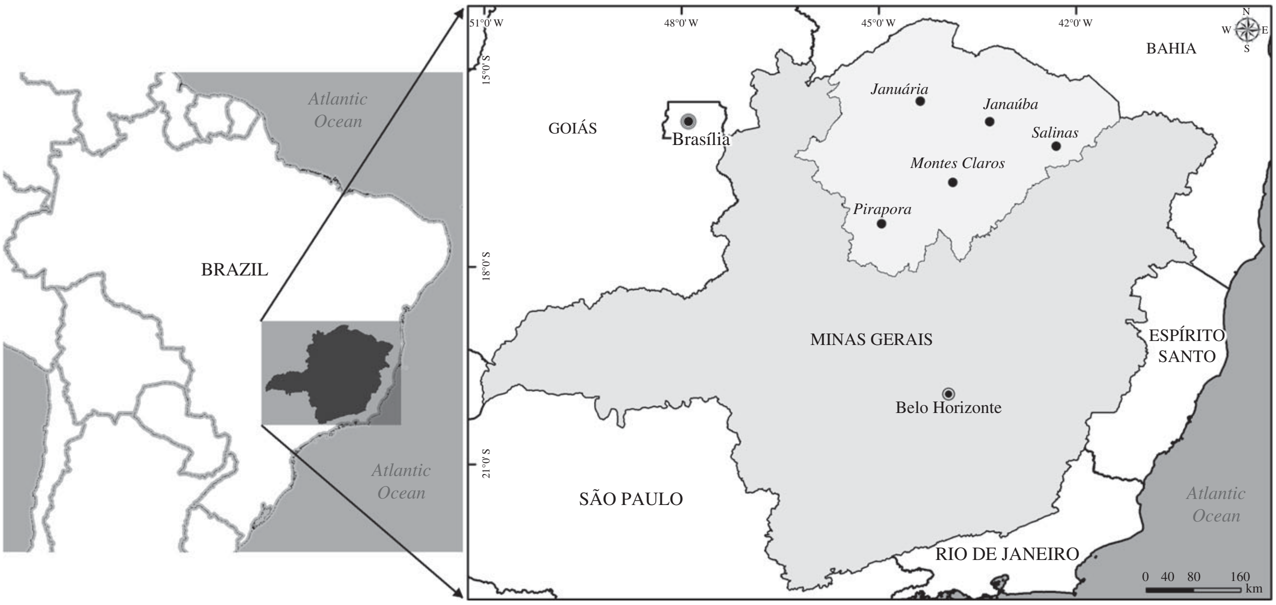

Figure 1. Limits of the north of the Minas Gerais state, Brazil, with its most important cities.

LUCC in the tropics is frequently related to population growth [5,15], the underlying causes of this process are mainly political and socio-economic [1,15,16]. Indeed, government development and environmental policies are crucial determinants of rates of LUCC in tropical countries [15,17], and, in turn, such policies are strongly influenced by national and international economic factors [13,14]. In Latin America, rates of land conversion currently track the international markets for soya bean and meat products [3,18]. In Brazil, over the recent decades, rates of LUCC have been strongly influenced by China's economic growth and high demand for mineral and agricultural commodities [19], and internal and European demand for biofuels [13,20].

One common argument to support decision-making towards land conversion to agriculture is that the resulting economic activity will generate jobs, taxes and productive chains that ultimately increase population income and welfare [21,22]. Although there are examples of increase in the gross domestic product (GDP) of some counties or regions at the expense of natural vegetation [17,23], deforestation was demonstrated to increase income concentration correlated with social inequalities [24,25], and to exacerbate social–environmental conflicts [26,27]. Also, land clearing has been related to the outbreak of disease vectors and epidemics [28]. In Brazil, this 'developmentalist' discourse has been frequently used to justify the relaxation of environmental laws, such as the forest code [29]. The relationship between land clearing and poverty alleviation is context-dependent [17,25] and should be analysed at the appropriate scale in order to inform sustainable government land-use policies.

While much attention has been placed on the Brazilian Amazon, the land-conversion pressure in the Cerrado is higher [9]. The Cerrado covers approximately 2 million km^2, forming a mosaic of many physiognomies including grasslands, woodlands, rupestrian fields and riparian forests [30], which comprise a complex and heterogeneous landscape. According to the Brazilian Ministry of the Environment, until 2010 the accumulated clearing of the Cerrado was approximately 990 000 km^2, almost 50% of total area, mainly due to agricultural expansion for crops, such as soya bean, and pasturelands for beef production [16,31,32]. In 2009 alone, the Cerrado lost 0.32% of its cover, more than twice the rate observed in the Amazon (0.14%) in the same year [33]. The Cerrado harbours 30% of the Brazilian species richness [34], with high levels of endemism, being considered one of the world's hotspots of biodiversity [35]. However, the legal protection under the Brazilian environmental legislation is low compared with forest biomes, as well as the area protected by conservation units [9,31,34].

We sought to understand LUCC in the Brazilian Cerrado between 2000 and 2015, using the northern Minas Gerais state as a case study. This large region, approximately 128 000 km^2, represents the colonization and socio-economic processes characteristic of the broader Cerrado biome. This region experiences high rates of LUCC caused by cattle ranching, agriculture, charcoal production and silviculture. The north of Minas Gerais is a large transitional zone between the Cerrado, the Caatinga and the Atlantic Rain Forest, harbouring a rich but understudied biodiversity [36]. We examined the following questions: (i) how has the Cerrado extent changed from 2000 to 2015 and how has this been influenced by government policies? (ii) What are the main biophysical and socio-economic drivers of the clearing of Cerrado and also of regeneration? (iii) Do land-cover changes correlate with metrics of human welfare in the Cerrado region?

2. Material and methods

(a) Study area

The north of Minas Gerais state is a politically defined meso-region constituting 89 municipalities [37], situated in the Sao Francisco River Basin (figure 1). This region is in the confluence of three large Brazilian biomes: the Cerrado to the south and west, the Caatinga to the north and the Atlantic Rain Forest to the east (figure 1). The predominant climate is tropical semiarid, with dry winters (May–September) and rainy summers (November–March; Aw in Koppen's classification), with average annual precipitation ranging from 700 to 1200 mm and average temperature between 21°C and 25°C [38]. The Cerrado biome dominates this region, originally covering approximately 113 500 km^2 (88%). Topography is generally flat, with altitudes ranging from 400 to 700 m, with the exception of the Espinhaço mountain

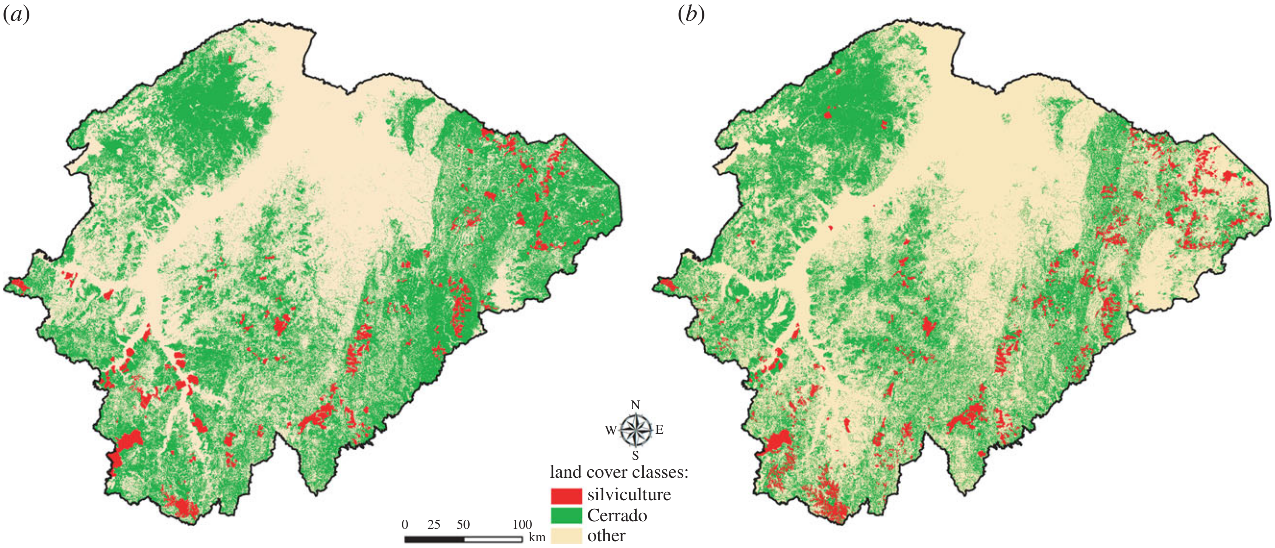

Figure 2. Land-cover change in the north of the Minas Gerais state, Brazil, from (*a*) 2000 to (*b*) 2015.

chain at the east, with altitudes up to 1760 m (figure 1). Cerrado soils are usually Oxisols with low fertility, high aluminium levels and acidity [39]. The population of the north of Minas Gerais state is 1.5 million people, and is one the poorest regions of the state, with a low Human Development Index (HDI = 0.625; the whole state = 0.731; Brazil = 0.727) [37].

(b) Image acquisition and processing

For the determination of LUCC, we obtained Landsat 5 (Thematic Mapper—TM sensor, 30-m spatial resolution) imagery for the North of Minas Gerais for the year 2000, and Landsat 8 (Operational Land Imager—OLI sensor, 30-m spatial resolution) for 2015 (figure 2). We used images from the dry period (June–August) because it is easier to distinguish the Cerrado from the neighbouring deciduous forests, and cloud cover is usually absent or sparse. These images were obtained from the Instituto Nacional de Pesquisas Espaciais—INPE (http://www.dgi.inpe.br/CDSR/) and the United States Geological Survey—USGS (http://earthexplorer.usgs.gov/). The scenes were reprojected to Geographic Coordinate System (GCS) Datum SAD 1969, in order to keep compatibility with the shapefiles from the Brazilian Institute for Geography and Statistics (IBGE) that were used in this study to obtain environmental and socio-economic parameters. The band composite of 2000 and 2015 images was performed, and this mosaic construction used 10 orbit/point compositions from each reference year, observing that the scenes from 2000 were first submitted to geometric correction, because they were not obtained with geometric distortions already corrected as in the case of Landsat 8 [40]. Then, following the protocol proposed by Kennedy *et al.* [41], the mosaic for the year 2000 was performed, using the mosaic from 2015 as reference. Finally, nine ground control points (GCPs) were collected and second-degree polynomial transformation was carried out, resulting in a RMSE below 30 m. All these procedures were conducted with ArcGIS v. 10.2.1 (ESRI Inc., USA).

(c) Image classification

The method adopted for land-cover classification was the supervised algorithm Decision Tree [42], using the software ENVI 4.5 [43]. The Digital Elevation Model from Shuttle Radar Topographic Mission—SRTM (1 : 250.000 scale) was employed for deriving slope and for height control as an input dataset in the decision tree. In addition, the following indices were also used as variables for the classification: Normalized Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI) and Leaf Area Index (LAI). We defined three land-cover classes: Cerrado *lato sensu* (with no differentiation between physiognomies), silviculture (pinus and eucalyptus plantations) and other (natural vegetation other than Cerrado, croplands, pasturelands, urban and burned areas, roads, bare soils and water). The Cerrado *lato sensu* included grassland formations with sparse shrubs and trees, such as 'campos sujos' and 'veredas'. However, we decided to merge natural open grasslands (i.e. 'campo limpo') and planted pastures (mostly exotic grasses) into the class 'other' for two reasons: first, they are difficult to reliably spectrally separate using Landsat images [44]; and second, natural grasslands in the Cerrado are predominantly used for cattle raising outside protected areas (all PAs were included in the Cerrado class). According to Scolforo & Carvalho [45], 'campo limpo' formations constitute approximately 8.7% of the Cerrado remnants in the north of Minas Gerais. For these reasons, we consider that this procedure does not undermine our conclusions, given that the ultimate goal of the study is to determine drivers of land-cover change to support policy decisions. Although fire is a natural phenomenon in the Cerrado, we did not quantify burned areas in the study region, including them in the 'other' class. We performed a visual interpretation and classification for the vectorization of roads, river channels, and eucalyptus and pinus plantations. Validation was conducted with field trips and determination of 42 GCPs in the studied region.

(d) Drivers of land-cover change

The biophysical parameters used in the analyses of LUCC in the Cerrado were determined from land-use maps. The following variables were obtained per municipality: total area (km^2), average declivity (%), river density ($km\,km^{-2}$), road extension (paved and non-paved together; km), area covered by eucalyptus and pinus plantations (including areas under preparation for plantation—hereafter 'silviculture') and the area protected by two different categories of PAs—integral protection and sustainable use (km^2). Delimitations of PAs and the year of their establishment were obtained from the State Forestry Institute [46]. We also determined the climate for each municipality based on climate data generated for the Minas Gerais state using the Thornthwaite's Moisture Index (TMI) [47]. Four climate classes occur in the north of Minas Gerais, with increasing TMI: semiarid (−66.7 to −33.3), dry sub humid (−33.3 to 0), sub humid (0–20) and humid B1 (20–40). Thus, we created an interval variable (a humidity index) by assigning a proportional value to each climate class (1, 2, 2.6, 3.2, respectively). When a municipality area was covered by more than one climate class, we calculated the average humidity index using this interval variable.

We determined conversion and regeneration rates for the Cerrado biome in the north of Minas Gerais with no discrimination between its constituent physiognomies. Semi-deciduous (including riparian vegetation) or deciduous forests (i.e. tropical dry forests) that occur in the middle of the Cerrado were excluded from the analyses. Conversion was considered as the change in land cover from Cerrado to the classes 'other' (except natural vegetation) and 'silviculture'. Regeneration means the natural regrowth of Cerrado vegetation in areas where it was destroyed in a previous period. In terms of image classification, these are Cerrado areas (forest ecosystems excluded) that had a LAI < 7 in 2000 and LAI ≥ 7 in 2015. No further details on the ecological integrity of such secondary stands were obtained. In this case, the possible colonization of natural grasslands (campo limpo) by shrubs and trees was also considered as regeneration, although we recognize that this encroachment process may have negative impacts on grassland biodiversity and ecosystem services [48]. We calculated the net area change as the balance between conversion (area loss) and regeneration (area gained), and the annual rate of net area change was determined for the whole region using the interest-rate formula [49].

Socio-economic parameters were obtained for each municipality from two censuses conducted by the IBGE. We used the demographic censuses (fully released at the end of each decade) for the years 2000 and 2010 [37] to obtain population density (people km^{-2}) and the Gini Inequality Index. The HDI was obtained from the United Nations Development Programme [50]. We used a disaggregated version that considers income, the IDH-R ('Índice de Desenvolvimento Humano-Renda' in Portuguese), because it more directly reflects the economic gains at the municipality level. The complete HDI also considers education and life expectancy, parameters strongly affected by federal and state development policies. The GDP (standardized for the year 2000) for 2000 and 2012 were also obtained from the IBGE databases [50]. The agricultural censuses of IBGE were used to obtain size of the cattle herd, crop area and charcoal production for the years 2000 and 2014 [51].

(e) Statistical analyses

To determine the drivers of land clearing and regeneration, we calculated the total Cerrado area lost and gained, and the net area change per municipality between 2000 and 2015 (three response variables). Thirteen explanatory variables were considered: we expect that the total municipality area (i) and Cerrado area in the beginning of the period (ii) would be directly related to Cerrado loss, as the greater the area available, the greater the conversion. The same trend is expected for humidity index (iii) and the opposite for average declivity (iv), due to more favourable conditions for agriculture. River density (v) would also correlate positively with rates of Cerrado conversion, as water availability facilitates both human settlements and the establishment of irrigated agriculture. The total change in road extension (vi), area of silviculture (vii), crop area (viii) and the per cent change in population (ix) and livestock density (x) and charcoal production (xi) generally expand at the expense of natural vegetation. Finally, we expect that the total change in PAs of integral protection (xii) and sustainable use (xiii) (two different variables) would decrease rates of Cerrado conversion. The opposite trends are expected for Cerrado area gained and net area change.

First, we used the paired *t*-test based on permutations to test whether the above response and explanatory variables differed between 2000 and 2015, with the exception of total municipality area, humidity index, average declivity and river density. We undertook the same analyses for the human welfare indicators (Gini Inequality Index, GDP and IDH-R; discussed later). We used a paired *t*-test because sampling was temporally dependent, thus we separated the treatment effect (i.e. the variable tested) and the spatial autocorrelation (SAC) effect [52]. The SAC was estimated using spatial filters (MEMs, Moran's eigenvector maps; [53]) that were selected progressively. For this analysis, we followed the R code by Eisenlohr [54].

We tested for significance in the data of 13 potential correlates of LUCC on the three response variables using multiple linear regressions through generalized linear models (separate GLM for each response variable). The variance inflation factor (VIF) was used as measure of multicollinearity, where a VIF > 5 can indicate strong collinearity [54]. Our data indicate VIF-tolerant values (below 2.5 for all variables), thus all predictor variables were maintained in the complete models. The complete GLM models with Gaussian error distribution were built (i.e. adjusted for log-link function whenever necessary), followed by stepwise comparisons (backward selection), with the removal of non-significant variables. The models were adjusted for orthogonal partitioning of variance (type III sum of squares), to verify the proportion of variance explained attributed to each variable regardless of sequential order of the explanatory variables in the models. The minimal adequate models were submitted to residual analysis to verify the adequacy of the error distribution. These GLM models were performed using the software R v. 2.15 [55]. We checked for spatial independence in the residuals of both the complete and minimal adequate GLMs using correlograms, with Moran's *I* coefficient as an indicator of SAC. The correlograms were constructed in SAM 4.0 [56], and the number and size of distance classes followed the defaults for SAM. The significance of SAC for each correlogram was verified by sequential Bonferroni criteria [57]. We tested the spatial independence of the residuals of the minimal adequate GLMs and no SAC was detected.

To evaluate the correlations between land-cover change and human welfare, we calculated the per cent change in the Gini Inequality Index and IDH-R per municipality between 2000 and 2010, and in the GDP between 2000 and 2012. Each parameter was considered as a response variable in a GLM containing the total Cerrado area lost and gained and the net area change as explanatory variables. We followed the same procedures described previously for multiple linear regressions through GLMs.

Table 1. Land-cover change in northern Minas Gerais from 2000 to 2015.

land-use class	2000		2015	
	km^2	%	km^2	%
Cerrado	55 256.05	43.17	45 732.04	35.73
silviculture	4652.84	3.63	5715.11	4.46
other	68 091.11	53.20	76 552.85	59.81

3. Results

(a) Regional-level changes

The Cerrado in the north of Minas Gerais experienced extensive land-cover change between 2000 and 2015, with conversion of 23 446 km^2 to other cover types and the natural regeneration of 13 926 km^2, resulting in a net loss of 9520 km^2. All subregions were cleared, especially the northeastern and the south. On the other hand, the northwest sub-region showed the greatest extension of Cerrado regeneration (figure 2). There was a slight increase in the silviculture area, especially in the northeastern sub-region, whereas conversion to other land-cover types was more intense in all the north of Minas Gerais (figure 2 and table 1).

Table 2. Cerrado area, drivers of land-cover change and welfare indicators in the north of Minas Gerais state, Brazil, for the years 2000 and 2015. Statistically significant differences ($p < 0.05$) are in Italic. Average values for 89 municipalities were calculated for each variable (±s.e.) and values at regional level are given in parentheses. The Gini Inequality Index and the Human Development Index (for income only; IDH-R) are not available at the regional level.

	year[a]				
source	2000	2015	change (%)	paired *t*-test	*p*-value
Cerrado area (km^2)	620.85 ± 73.65	513.84 ± 67.08	−17.24	4.07	*<0.001*
potential drivers					
silviculture (km^2)	52.28 ± 12.58	64.22 ± 14.51	+22.83	−1.98	*<0.05*
crop area (km^2)	35.22 ± 3.34 (3135)	33.50 ± 4.19 (2981)	−4.88	0.61	>0.05
livestock density (cattle km^{-2})	19.4 ± 1.34 (16.43)	24.70 ± 1.55 (21.32)	+27.31	−6.14	*<0.001*
population density (people km^{-2})	13.36 ± 1.52 (11.9)	14.15 ± 1.67 (12.6)	+5.91	−4.92	*<0.05*
charcoal production (t)	1912.26 ± 335.35 (170 191)	370.10 ± 55.78 (32 939)	−80.64	6.11	*<0.001*
road density (km km^{-2})	0.21 ± 0.01 (27 432)[b]	0.25 ± 0.01 (28 729)[b]	+19.04	−10.67	*<0.005*
CUs of integral protection (km^2)	24.17 ± 9.0 (2151)	45.98 ± 11.25 (4093)	+90.23	−3.50	*<0.05*
CUs of sustainable use (km^2)	69.75 ± 35.65 (6207)	133.75 ± 60.24 (11 904)	+91.75	−2.55	*<0.05*
welfare indicators					
Gini Inequality Index	0.57 ± 0.01	0.49 ± 0.01	−14.03	9.63	*<0.05*
GDP (thousand BRL)	45.50 ± 16.58 (4050)	184.90 ± 16.16 (16 456)	+406.37	−50.54	*<0.001*
IDH-R[c]	0.50 ± 0.01	0.58 ± 0.01	+16.0	−24.02	*<0.001*

[a]Some variables were collected in years close to 2000 and 2015. See text for details.
[b]Regional values represent total road extension and are given in kilometres.
[c]IDH-R is a disaggregated version of the HDI that only considers the *per capita* income. See text for details.

There was a slight increase in population density (5.8%) between 2000 and 2015, and in road density between 1996 and 2010 (4.7%), whereas livestock density showed a more pronounced increase (29.8%) (table 2). On the other hand, the area of crops decreased 4.9%, but the most remarkable change during the studied period was in charcoal production, which decreased 80.6%. The area under integral protection is much smaller than that in PAs of sustainable use, but both almost doubled in expanse during the period (90.26% and 91.76%, respectively) (table 2). As a whole, the economic activity in the north of Minas Gerais increased substantially, as shown by a fourfold increase in the GDP from 2000 to 2012, which is similar to that observed for the whole state (438%) and for Brazil (407%) in the same period [50].

(b) Municipality level change

All 89 municipalities from the north of Minas Gerais had some Cerrado area in 2000, although a few of these municipalities are embedded in areas dominated by tropical dry forest. Only eight municipalities had less than 50 km^2 of Cerrado in 2000. On average, the net change in the Cerrado area for the municipalities of the north of Minas Gerais was −17.24% between 2000 and 2015 (table 2). All variables changed significantly over the time period, with the exception of crop area. The trends at the municipality level were consistent with those observed at the regional level (table 2). As a whole, 32 municipalities (35.9%) had an increase in the Cerrado area and 57 (64.1%) had net area loss from 2000 to 2015. Silviculture was not recorded in 28 municipalities during the time period (38 municipalities did not have silviculture in 2000 and 33 in 2015), indicating that this economic activity is concentrated in some parts of the region (see also figure 2). PAs are spatially concentrated: only 17 municipalities had some protected area in 2000, increasing to 34 in 2015. Population density decreased in 21 municipalities, the same occurring with livestock density in 18 municipalities.

The stepwise linear regression analysis indicated that six variables significantly correlated with Cerrado clearing between 2000 and 2015. These were, in decreasing order of relevance (i.e. based on deviance explained): initial cerrado area, humidity index, declivity and changes in cattle density, silviculture area and road extension (table 3). Except for the declivity, the Cerrado area lost was positively related to the other five above-listed variables (figure 3). Cerrado regeneration was affected only by the municipality area (figure 4*a*), and the net area change was affected only by the original area of Cerrado remnants (figure 4*b*). Municipalities with larger area showed higher regeneration, and those with larger Cerrado extent showed higher net area change during the analysed period (table 3 and figure 4).

Regarding the welfare indicators, IDH-R increased 16% during the study period, more than that observed for the state of Minas Gerais (7.35%) and for Brazil (6.79%), and it occurred in all 89 municipalities (table 2). GDP also increased significantly in all municipalities but at a rate comparable with that observed at the state and country levels, as mentioned before (table 2). The Gini Inequality Index decreased 14% (table 2), more than that observed for the state (8.9%) and for the whole country (6.6%), although no change was observed across 10 municipalities. These results indicate that the improvement in the economic activity of the municipalities was followed by a reduction in social inequality. However, none of these welfare indicators were related to Cerrado conversion, regeneration

Table 3. Analyses of deviance of the generalized linear models (GLMs, type III sum of squares) showing the effects of multiple drivers on total Cerrado area lost and gained, and on the net area change per municipality between 2000 and 2015 ($n = 89$ for each model). We used a log-link function for the Cerrado area lost and gained models, and a Gaussian-link function for net area change. Asterisks indicate significant variables retained in the minimal adequate model after stepwise selection (backward). *$p < 0.05$; **$p < 0.01$; *** $p < 0.001$.

	land-cover change					
	area lost (km²)		area gained (km²)		net area change (km²)	
potential drivers	estimate	deviance	estimate	deviance	estimate	deviance
average declivity (%)	−0.070	12.78***	+1.493	0.001	−26.469	296 742
humidity index	+1.835	20.94***	−0.190	11.488	+70.71	117 504
municipality area (km²)	+0.001	1.43	+1.339	23.421***	+0.095	633 054
initial Cerrado area (km²)	+0.001	21.73***	+0.001	0.3203	−0.0005	944 902***
river density (km² km⁻²)	+0.030	0.97	+0.0001	0.002	+5.678	1975
change in road extension (km)	+0.019	2.59*	+0.095	4.963	−3.240	76 480
change in population density (%)	+0.021	0.12	−0.028	2.030	+4.657	106 191
change in PAs—integral protection (km²)	−0.003	0.80	+0.034	0.403	−0.176	1264
change in PAs—sustainable use (km²)	+0.007	1.20	+0.0002	2.057	+0.173	7344
change in crop area (km²)	+0.005	1.47	−0.002	2.695	+0.615	19 050
change in cattle density (%)	+0.238	4.72**	+0.007	1.407	+2.748	43 625
change in silviculture area (km²)	−0.010	4.48**	+0.012	5.390	−1.106	70 980
change in charcoal production (%)	−0.001	0.31	−0.010	0.649	+0.014	19 081

and net area change per municipality between 2000 and 2015 (electronic supplementary material, table S1).

4. Discussion

(a) Change in land use and land cover

We detected extensive land-cover changes in the Cerrado at the north of Minas Gerais state, affecting more than 37 300 km^2 of this vegetation (almost 33% of the original cover in that region). Most studies addressing LUCC in the Cerrado quantify land clearing using the net change in total cover [32,33,58], and estimates of Cerrado natural regeneration are seldom directly informed (e.g. [59]). Examination of net change alone can underestimate the extent of land clearing in the Cerrado. In our study region, the net change in Cerrado cover was 9520 km^2, representing a loss of 17.2% of this biome in that region in 15 years. However, the area deforested was much larger: 23 446 km^2, which accounts for 42.4% of the original extent in the year 2000. This result highlights the importance of natural regeneration for the preservation of the integrity of the Cerrado, as more than half the deforested area (13 926 km^2 –25.2% of the total extent in 2000) was regenerating as secondary savannah in the same period.

Our quantification of the extent of Cerrado regeneration may be slightly overestimated, as our classification considered the transition from natural grasslands to other Cerrado phytophysiognomies (i.e. encroachment) as regeneration. However, our estimates corroborate that of other studies that have detected similar levels of regeneration in other parts of the Cerrado. A recent assessment by Beuchle *et al.* [59] estimated that 72 170 km^2 of Cerrado recovered from 2000 to 2010 (see also [3,60]). Jepson [6] detected that, between 1986 and 1999, 50% of the previously converted Cerrado in Mato Grosso state regenerated, indicating the need for accurately assessing this process in land-use and climate-change policies. However, frequently, secondary savannah does not fully recover original vegetation structure and ecosystem function. The importance of secondary habitats to biodiversity conservation has increasing recognition [7], although investigation of the ecosystem health and diversity of secondary savannahs are few (see [61]). In any case, LUCC analyses of the Cerrado would benefit from improved assessment of both the processes driving encroachment and its extent, which usually results from fire suppression and has raised serious conservation concerns [48].

The annual net loss (−1.2%) of Cerrado cover in the study region is higher than that reported for the Cerrado as a whole over a similar period. Beuchle *et al.* [59] reported an annual cover change of −0.60% from 2000 to 2010 for the Cerrado, a value which is similar to that detected by the Brazilian Ministry of the Environment (−0.69% per year) from 2002 to 2008 [33]. Thus, the north of Minas Gerais experienced intensive clearing of the Cerrado over the last 15 years. Indeed, this region concentrates most of the preserved Cerrado in the state, and is an agricultural frontier as evidenced by the change in livestock over the time period. In addition, although the proportion of the Cerrado contained within PAs has increased substantially in the north of Minas Gerais during the study period, PAs of integral protection account for only 4.8% of the region's area (higher than the 3.1% in the Cerrado in the whole country), and most of them lack effective management, being 'paper parks' in practice [62].

On the other hand, the extent of Cerrado regeneration observed during the study period is high. It is likely that the majority of regenerating areas are abandoned pasturelands

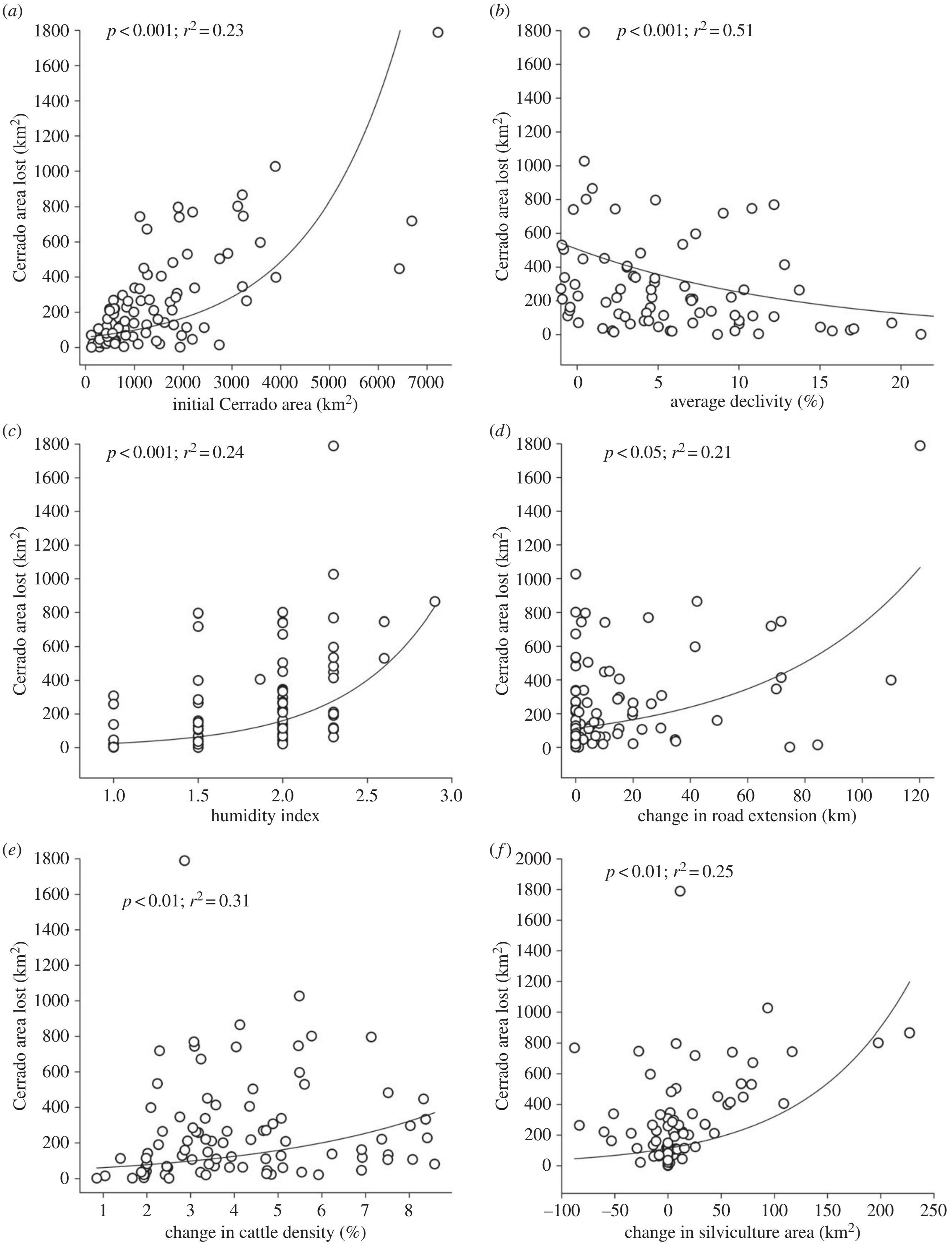

Figure 3. Relationship between the Cerrado area loss in 89 municipalities of Minas Gerais state, Brazil, and the following drivers: (*a*) initial area of Cerrado remnants, (*b*) average declivity, (*c*) humidity index, and changes in (*d*) road extension, (*e*) cattle density and (*f*) silviculture area. These explanatory variables were retained in the minimal adequate model ($p < 0.05$) after stepwise selection ($n = 89$). Humidity index reflects the following climate types: semiarid (1), dry sub humid (2), sub humid (2.6) and humid B1 (3.2). See text for details.

and former plantations. Recent studies indicate that up to 60% of Cerrado pasturelands are degraded [63], reaching 87.6% under the drier conditions of the north of Minas Gerais [64]. According to the IBGE [65], the extension of pasturelands in the region decreased 27.6% from 1996 to 2006, from 37 712 to 27 318 km^2. Degraded pasturelands are usually abandoned and frequently regenerate naturally. However, depending on the degree of degradation, these areas can suffer desertification processes, an increasing problem in the Brazilian semiarid regions [66].

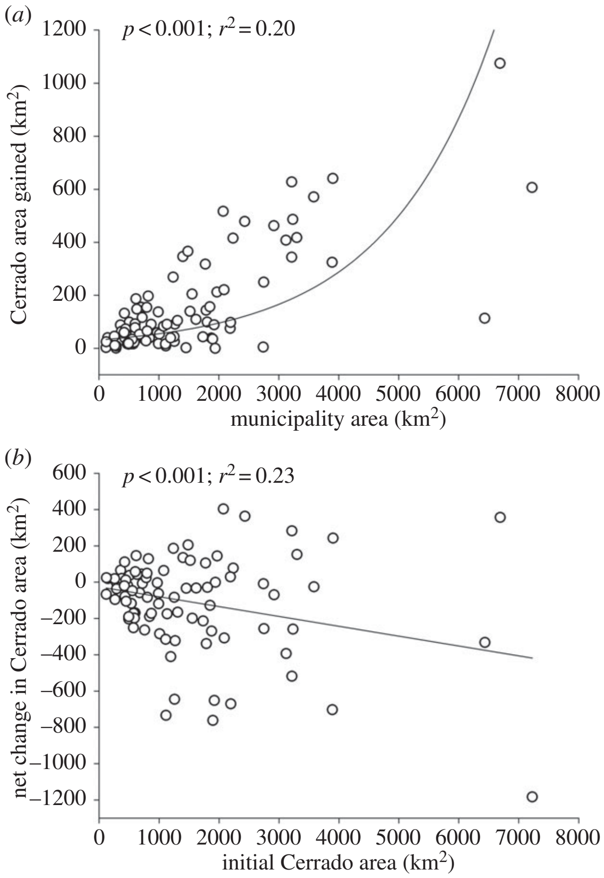

Figure 4. Relationship between (*a*) the Cerrado area gain and municipality area, and (*b*) the Cerrado net area change and the initial area of Cerrado remnants, between 2000 and 2015 ($n = 89$).

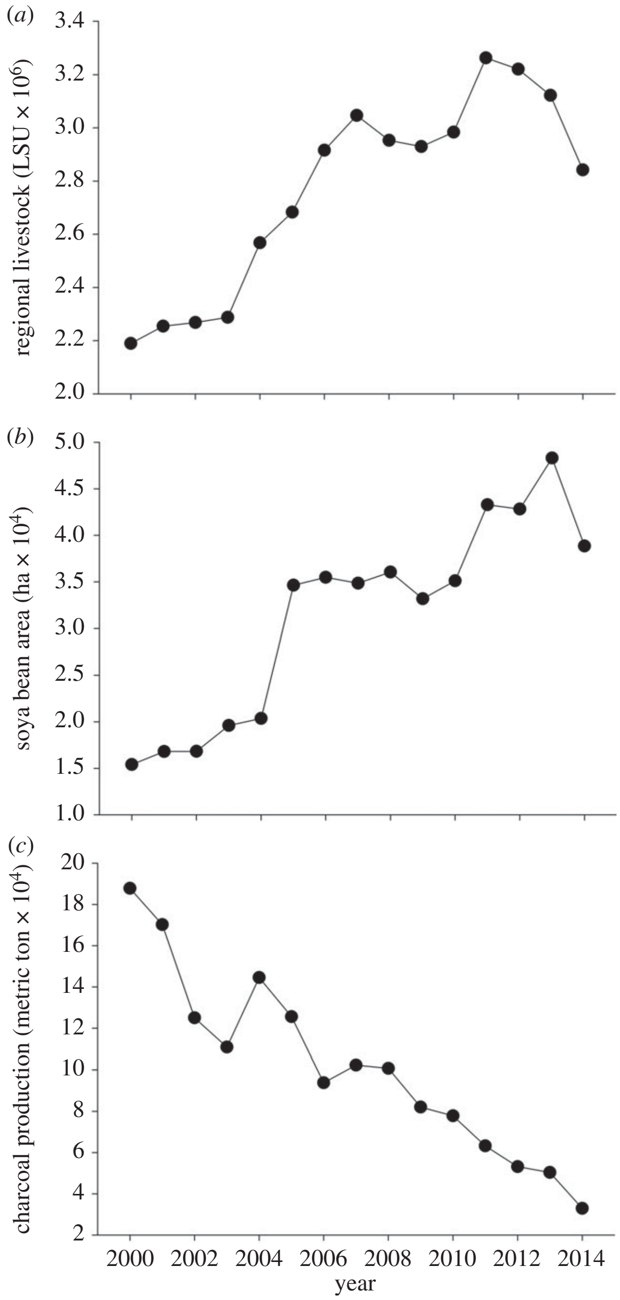

Figure 5. Economic activities in the study region (north of Minas Gerais state, Brazil) over the period 2000–2015. (*a*) Cattle herd; (*b*) soya bean area and (*c*) charcoal production.

(b) Drivers of change in Cerrado extent

Multiple drivers have impacted the rate of gross area loss in the Cerrado across the north of Minas Gerais. We found that municipalities with a greater extent of Cerrado in the year 2000 were most likely to experience both gross area loss and net area change. Aide *et al.* [3] made a similar finding in an assessment of drivers of land-cover change across biomes in Latin America. These authors point out that this is an expected relationship, given that municipalities with a large land area of Cerrado are prone to land transformation. However, this does not clarify the underlying causes of land-use change in a given municipality. Four of the other drivers that significantly affected gross area loss are directly related to agricultural potential, and in particular to cattle ranching: humidity index, declivity and changes in livestock density and silviculture area (figure 3). Thus, our results demonstrate that land clearing occurs predominantly in lowlands with higher humidity index and is mainly caused by increasing cattle herd and plantation forestry. A key driver of conversion in the Cerrado biome at the national scale, soya bean production has increased in the study region, but affected only a relatively small area (figure 5). However, the opposite trend is observed for charcoal production, one of the most important drivers of Cerrado clearing in the north of Minas Gerais (figure 5), and we link this to the observed extent of Cerrado regeneration.

Cattle raising for beef production is the main economic activity in the north of Minas Gerais state and the size of the cattle herd increased from 2.2 to 2.8 million head of cattle from 2000 to 2014, peaking at 3.3 millions in 2011 (figure 5). This activity is most intensively experienced in flat areas, where mechanized clearing and sowing of productive exotic grasses is facilitated, and in municipalities with a more humid climate. Indeed, at a broader scale, cattle ranching is well recognized as responsible for high rates of LUCC across Brazilian biomes, mainly due to the poor management of pasturelands [67]. In our semiarid study region, where most municipalities have 800–1100 mm of rain per year [38], poor management quickly causes pasture degradation and abandonment, followed by the clearing of new areas of Cerrado.

Finally, we also found that of the extent of Cerrado gross area loss was correlated with an increase in the number and types of roads. Over the period of observation, the expansion of the road network was fostered by two state government programmes ('ProAcesso', launched in 2004; and 'Caminhos de Minas', launched in 2010) aimed at constructing and paving state roads. Road construction has direct impacts on LUCC, but important effects are indirect, specifically by permitting ease of access to remote areas where vegetation has been historically preserved [10], and this in turn correlates with changes in other drivers of LUCC. For example, Rada [16] found that a 1% improvement in paved-road density in the Cerrado region led to an increase of more than 1% in both livestock and crop production. Thus, it is highly likely that environmental and economic factors interact to determine rates of Cerrado clearing in Minas Gerais.

Cerrado regeneration (i.e. gross area gained) was correlated only with municipality area, most likely because, as we outline above, larger municipalities have converted greater areas, and that this in turn leads to larger areas to regenerate after abandonment. Surprisingly, we found no correlation between an increase in PAs and Cerrado regeneration at a municipality level. The concentration of PAs in only a few municipalities in the northwestern sub-region likely underpins this trend. Indeed, three municipalities (Januária, Bonito de Minas and Chapada Gaúcha) that contain several PAs of sustainable use accounted for approximately 2300 km^2 of the total regeneration observed. Cerrado conversion is also concentrated in a limited number of municipalities (12 municipalities lost greater than 500 km^2 of Cerrado in 15 years). We suggest that investigating regeneration and conversion processes in these highly dynamic municipalities is important to gain insight to the underlying drivers of LUCC and to improve policies addressing sustainable land use.

(c) Socio-economic consequences

From 2000 to 2015, there was a positive trend of change in human welfare indicators, including income distribution. At the municipality level, we found no correlation between welfare indicators and the rates of Cerrado clearing, regeneration or net area change. Indeed, the nexus between environmental degradation and human welfare is controversial, with contrasting results depending on socio-economic and historical factors, environmental setting and public policies. The relationship between degradation and welfare is frequently explained using a Kuznets environmental (inverted U-shaped) curve, which describes an increase in *per capita* income with increasing vegetation loss, until a turning point is reached. After that, further increases in income are associated with reductions in land clearing and even with an increase in reforestation [25,68]. In the case of the north of Minas Gerais (and likely the Cerrado biome as a whole), the relationship between the loss of Cerrado over time and human welfare seems scale-dependent. Although none of the land-cover change variables were correlated with socio-economic indicators at the municipality level, substantial improvement in welfare was observed at a regional scale (table 2), despite high levels of gross area loss. However, these results should be interpreted with caution, as regional-level indicators also reflect a marked improvement in Brazilian socio-economic conditions from 2004 to 2014. This improvement was a consequence of a period of high economic growth and of federal government development policies, which substantially increased the minimum wage and invested in programmes of income transfer [69]. A longer time-series analysis with regional scale replicates is needed to understand the development trajectory of the Cerrado region and any relationship between changes in welfare and rates of LUCC.

5. Conclusion

Recent land-cover changes in the Brazilian Cerrado have been extensive. The case study of the north of Minas Gerais demonstrates this, where 37 327 km^2 of the Cerrado have been impacted by LUCC from 2000 to 2015. Our results highlight the importance of secondary savannah to counterbalance intensive rates of Cerrado clearing, especially to pastureland. Sustainable land-use policies in this region must involve a reduction in rates of land conversion rates, which are twice that observed across the Cerrado as a whole, and promoting regeneration. Given the high frequency of land abandonment in tropical regions, allowing vegetation regrowth and protecting secondary ecosystems is a fundamental strategy to maintain biodiversity and ecosystem services in such dynamic, human-modified landscapes. Low-impact cattle ranching techniques and increasing agricultural productivity through sustainable intensification (where possible given social and biophysical constraints) [67], and avoiding pasture degradation will reduce rates of land-use conversion. Given that lowlands with higher humidity levels are more severely affected, these areas must be prioritized in land-use planning. Policies should be considered to promote the natural regeneration of abandoned pasturelands, but the ecological success of such initiatives depends on: (i) assessing the quality of regenerated areas; and (ii) accurate mapping and determination of the previous natural cover of the region to be recovered, to avoid woody encroachment and the loss of natural grasslands. Finally, the relationship between conversion of the Cerrado and human welfare vary from local to regional scales, making it difficult to elaborate conservation strategies based solely on its consequences to socio-economic indicators. Land-use policies should also consider the ethical and cultural reasons to preserve the Cerrado's biodiversity, along with ecosystem services such as water provision, soil quality and food production, which may not be directly and readily translated into measurable indicators.

Data accessibility. Data on land-cover changes are available in the Dryad Digital Repository: http://dx.doi.org/10.5061/dryad.53h16 [70].

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