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Authors:

Julien BLANCO[1,*], Beatriz BELLÓN[2,3], Liane BARTHELEMY[4], Baptiste CAMUS[4], Aurélie DE PALMAS[4], Inès FILLON[4], Louise JAFFRE[4], Anne-Sophie MASSON[4], Alix MASURE[4], Fabio DE O. ROQUE[5,6], Franco L. SOUZA[5], Fabio BOLZAN[5], Isabel MELO[5], Guilherme DALPONTI[5], Aline GIROUX[5], Dinah MADRUGA[5], Michel VAILLANT[4], Pierre-Cyril RENAUD[2,7]

Author affiliations:

[1] SENS, IRD, CIRAD, Univ Paul Valery Montpellier 3, Univ Montpellier, Site St Charles, Route de Mende, 34199 Montpellier Cedex 5, France

[2] Univ Angers, BiodivAG-IRL REHABS, F-49000 Angers, France

[3] Department of Environmental Science, Rhodes University, Makhanda, 6140, South Africa

[4] UR ADI-Suds (Agrodéveloppement et innovation aux Suds), Istom, College of International Agro-Development, 4 rue Joseph Lakanal, 49000 Angers, France

[5] Instituto de Biociências, Universidade Federal de Mato Grosso do Sul, Cidade Universitária, Caixa Postal 549, CEP 79070-900, Campo Grande, MS, Brazil

[6] Centre for Tropical Environmental and Sustainability Science (TESS) and College of Science and Engineering, James Cook University, Cairns, QLD 4878, Australia

[7] Sustainability Research Unit, Faculty of Science, George Campus, Nelson Mandela University, George, South Africa

E-mail addresses:

Julien BLANCO: julien.blanco@ird.fr

Beatriz BELLÓN: bellon.beatriz@gmail.com

Liane BARTHELEMY: l.barthelemy@istom.fr

Baptiste CAMUS: b.camus@istom.fr

Aurélie DE PALMAS: a.depalmas@istom.fr

Inès FILLON: i.fillon@istom.fr

Louise JAFFRE: l.jaffre@istom.fr

Anne-Sophie MASSON: a.masson@istom.fr

Alix MASURE: alixmasure@turcat.com

Fabio DE O. ROQUE: roque.eco@gmail.com

Franco L. SOUZA: cariama007@gmail.com

Fabio BOLZAN: fabiobolzan@gmail.com

Isabel MELO: imelov@gmail.com

Guilherme DALPONTI: guilhermedalponti@gmail.com

Aline GIROUX: aline.giroux@gmail.com

Dinah MADRUGA: dvdmadruga@gmail.com

Michel VAILLANT: m.vaillant@istom.fr

Pierre-Cyril RENAUD: pierre-cyril.renaud@univ-angers.fr

*Corresponding author:

Julien Blanco

Postal address: Université Paul-Valéry, UMR SENS - St Charles, Route de Mende, 34199 Montpellier Cedex 5

Phone : +33 (0) 6 87 90 11 10

Email address: julien.blanco@ird.fr

1. Introduction

The conversion of natural habitats to agricultural land is a primary driver of terrestrial ecosystem degradation and species extinction risk worldwide, threatening both biodiversity and human well-being (IPBES, 2019). To combat this threat, two main strategies currently exist: (i) creating protected areas (PAs) by delimiting a territory where biodiversity conservation is a priority and human activities are restricted to differing degrees (McDonald & Boucher, 2011); and (ii) promoting 'working landscape conservation', which involves managing productive landscapes so they maintain biodiversity, provide goods and services for humanity, and support the abiotic conditions necessary for sustainability and resilience (Kremen & Merenlender, 2018).

These two strategies are increasingly considered complementary, allowing conservationists to move beyond the archetypal land sharing/sparing debate (Fischer et al., 2017). If surrounded by 'biodiversity-unfriendly' landscapes, PAs become ecologically isolated and some of the species inhabiting them may disappear (Newmark, 2008); conservation practices in working landscapes must therefore complement PAs. Conversely, working landscapes might not guarantee the conservation of species particularly sensitive to human activities (Venter et al., 2014); PAs are thus required in addition to sustainable working landscapes. Furthermore, research has shown that the effectiveness of biodiversity conservation in PAs is influenced by their interactions with the landscapes surrounding them (Blanco et al., 2020; DeFries et al., 2010). As a consequence, focusing on working landscapes in the vicinity of PAs appears a sound priority: improving the conservation status of these working landscapes might also contribute to biodiversity conservation within PAs.

Addressing this challenge is particularly critical in Brazil. The country hosts a high level of species diversity and endemism in biomes currently experiencing a dramatic reduction in native vegetation due to agricultural expansion: this is the case in the Amazon, the Atlantic Forest, the Pantanal, and the Cerrado biomes (Klink & Machado, 2005; Ribeiro et al., 2009; Roque et al., 2016). While over 18% of the country is now covered by PAs (MMA, 2020), deforestation and landscape transformation are occurring inside and around PAs (Bellón et al., 2020), threatening biodiversity as well as indigenous land rights (Walker et al., 2020). To limit forest clearance, since 2012 the new

Brazilian Forest Code has required rural landowners to maintain natural vegetation in 'Legal Reserves' on 20% to 80% of their property (depending on the biome), and to preserve sensitive ecosystems by delimiting 'Areas of Permanent Protection' (Machado, 2016; Soares-filho et al., 2014). Yet the code's effectiveness has been questioned in many studies (Azevedo et al., 2017; Brancalion et al., 2016; Vieira et al., 2018): Brazil records the highest net loss of natural forest area in the world (-11.5% between 1990 and 2015 [FAO, 2014]). After several decades of slowdown, there has been a rise in deforestation in Brazil since 2012 (Escobar, 2019).

In this context of increasing tension between agricultural expansion and natural habitats, it is critical to understand how types of farming systems in Brazil affect the capacity of working landscapes, in particular around PAs, to effectively maintain biodiversity and its associated goods and services. Aiming to contribute to this general research goal, this study focuses on an agricultural region bordering Brazil's Serra da Bodoquena National Park, which is a good model for investigating the complex trade-offs between agriculture and biodiversity conservation. While deforestation rates have decreased in this region since 2001 (INPE, 2019), recent infrastructure investments such as the multi-national *Corredor-Bioceánico* "bi-oceanic corridor" road project might further drive soybean expansion dynamics in the region (Henderson et al., 2021). As a consequence, current and envisioned crop expansion dynamics around the park might alter the region's capacity to sustain forests and biodiversity in the future (Ribeiro, 2017; Roque et al., 2018), and thus its capacity to act as a landscape that serves both people and biodiversity.

The aim of the study was to explore whether farming systems and their recent evolution in this region were resulting in substantial changes in farm-scale vegetation patterns. We hypothesized that the more a farm is involved in crop cultivation, the more spatially segregated the agricultural and forested areas, with larger and less patchy vegetation areas within the farm estate. Conversely, we posited that the more a farm uses low-intensity livestock production systems, the more spatially integrated the agricultural and forested areas, with smaller and patchier vegetation areas within the farm estate. In a caricatural way, our overall hypothesis was that more intensive crop cultivation would foster 'land sparing' types of landscapes, whereas lower intensity pastoral activities would contribute to 'land sharing' types of landscapes. Consequently, we assumed that ongoing soy expansion in the region, which seems to occur at the expense of both pastoral and forested areas (Blanco et al., 2022), would result in more contrasted, less biodiversity-friendly landscapes. To investigate this, we used a mixed approach combining comprehensive interviews of farmers from 40 farms and landscape analyses based on MapBiomas land cover maps. The interviews allowed us to collect detailed data on cropping and ranching activities, as well as how farming systems have evolved over the last ten years. The landscape analyses allowed us to assess (i) farm-scale vegetation patterns and dynamics between 2009 and 2019 through the calculation of a set of seven landscape metrics, and (ii) changes in intensity in crop cultivation over this same period through the calculation of the proportion of cropland and pastureland. We then combined these two approaches to explore the relationship between farming systems and vegetation patterns, and the implications of ongoing agricultural dynamics for forest and biodiversity conservation in the region.

2. Methods

2.1. Study site and local conservation strategies

The study took place in the state of Mato Grosso do Sul, in six rural municipalities mainly bordering the east side of the Serra da Bodoquena National Park (SBNP) (Fig. 1). The region lies within the Cerrado biome, but includes remnants of Atlantic Forest. It is characterized by a savanna climate with humid sub-tropical influences, with a dry season from April to September, a wet season from October to March, and annual rainfall of around 1500 mm.

Created in 2000 as an IUCN (International Union for Conservation of Nature) category II protected area, the SBNP is the cornerstone of biodiversity conservation in the state (Lacerda et al., 2007). It extends over a surface area of >77,000 ha, mainly on private land, and encompasses a variety of vegetation formations (e.g. Cerrado sensu stricto, Cerradão, Altantic Forest). The buffer zone around the park is spatially limited, and currently only the use of genetically modified crops is regulated in this zone. The Brazilian Forest Code is the main legal instrument used to enforce conservation by landowners around the SBNP. In the Cerrado, this code requires rural properties to maintain a 'Legal Reserve' of native vegetation on at least 20% of the land. Furthermore, 'Areas of

Permanent Protection' must be defined in environmentally sensitive areas, including mountains and steep grades (altitude of >1800 m or a slope of >45°), hilltops or ridges (altitude of ≥100 m and a slope of >25°), and areas bordering watercourses and reservoirs (for further details, see Machado, 2016). To enforce the code, since 2012 landowners have been obliged to geo-reference their property boundaries, Legal Reserves, Areas of Permanent Protection, and forest remnants in the Rural Environmental Registry (CAR) (Azevedo et al., 2017). In 2019, more than 90% of the rural properties in our study area were registered in the CAR (Table S1).

2.2. Local agricultural practices and dynamics

In the study area, annual deforestation has drastically decreased since 2001, reflecting the general trend in Mato Grosso do Sul (Fig. S1; INPE, 2019). Clearing for extensive rangelands occurred long ago in this consolidated agricultural region, so most productive lands may already have been deforested (Franco, 2001).

The dominant farming system in the region is ranching, in which zebu cattle are raised on extensive planted pastures. The livestock production cycle is divided into three phases: (i) *cria*, when mothers and calves are kept in barns until weaning at around 8 months; (ii) *recria*, when animals graze in pasturelands; and (iii) *engorda*, the fattening phase in which animals are fed in full or semi-containment, before being sold for slaughter. In addition to cattle-raising, soybean cultivation has recently experienced a rebound in the region, as in the Bonito municipality, where the proportion of cropped areas increased from 2.46% to 6.98% between 1987 and 2016 (Ribeiro, 2017). As a consequence, an increasing number of farms cultivate crops, sometimes through leasing a part of their land, typically for soybean/maize double-cropping systems.

2.3. Interview-based data collection

To collect farm-scale data on cropping and ranching activities and changes in these, we conducted semi-structured interviews on 40 farms between June and July 2019, including eight farms with land inside the SBNP and seven family farms (Fig. 1). We used a purposive sampling method to select farms, according to three criteria: (i) farms had to be located in relatively close vicinity to the SBNP; (ii) the overall sample had to represent the diversity of farming systems in the region; (iii) one person with enough knowledge about the farm (i.e. preferably the landowner or manager) had to be available and agree to be interviewed. Apart from these criteria, farms were selected as randomly as possible with the help of a local driver and the co-authors who knew the area well.

A set of closed and open-ended questions allowed us to collect data on current cropping and ranching activities, farm ownership and human resources (see SI Interview guide). For each farm, we also extracted pasture and cropland proportions from the 2019 MapBiomas land cover maps (see Section 2.4). This allowed us to populate a dataset with 30 quantitative and qualitative variables describing current (2019) farming systems and farm characteristics (Table S2). As some interviewees were not able to answer all the questions, the initial dataset had 1.4% missing values (17 from a total of 40x30 values). As a preprocessing step, we imputed missing values with the 'missForest' method (Stekhoven & Buhlmann, 2012), which provides low rates of imputation errors for mixed-type data (Misztal, 2019).

Data on recent changes in farming systems, in particular on recent and envisaged land conversions and the reasons behind these, was obtained through questions about farms' history (see SI Interview guide). This data was analyzed through qualitative techniques, which allowed us to identify the main factors – socio-economic, legislative or ecological – that influenced farmers to operate (or not) certain changes on their farms (also see Blanco et al., 2022). This qualitative analysis of land-use changes was complemented by a quantitative analysis from MapBiomas maps (see Section 2.4).

The interviews were conducted in Portuguese by groups of three to four undergraduate students from France and Brazil. This research was approved by the ethics committee of the Federal University of Mato Grosso do Sul (CAAE: 87336418.6.0000.0021; approval number: 3.587.104).

2.4. Landscape and vegetation pattern analyses

To evaluate landscape patterns and dynamics, we used the 2009 to 2019 MapBiomas Land Cover and Use Collection 5.0 Map Series of the MapBiomas project (Project MapBiomass, 2021) and computed all statistics in the R environment (R Core Team, 2021).

First, we retrieved the spatial boundaries of the 40 farms from four different databases: the Rural Environment Registry (CAR) (SFB, 2019), the National Institute of Colonization and Agrarian Reform's Land Management System (SIGEF), the National System of Real Estate Certification (SNCI), and the Settlement Projects (*Projetos de Assentamentos*) (INCRA, 2019). Second, we retrieved the 2009 to 2019 MapBiomas land cover maps of Mato Grosso do Sul at 30-m spatial resolution from the Google Earth Engine MapBiomas Toolkit (Project MapBiomas, 2021), and projected all spatial data to EPSG: 31981 (SIRGAS 2000/UTM21S).

From the 2009–2019 MapBiomas time series, we merged all natural vegetation classes together and discriminated pasture and cropland classes over the total surface area covered by the 40 farms. For each farm, we assessed vegetation patterns and dynamics from these land cover maps by calculating seven landscape metrics from the Natural Vegetation class (Table 1) using the Quantum GIS Landscape ecology analysis (LecoS) plugin (v.2.0.7) (Jung, 2016; QGIS Development Team, 2019). We also calculated for each the evolution in the respective proportions of pastures and cropland, as additional indicators of recent farming system changes (complementing the interview-based data).

2.5. Relationship between farming systems and vegetation patterns

We explored the relationship between farming systems and vegetation patterns in three steps: (i) analyzing the variability in current farming systems; (ii) exploring the correlations between current farming systems and vegetation patterns, as well as their respective dynamics between 2009 and 2019; (iii) checking for the respective influence of biophysical factors and farming systems by including them in the same model.

In order to investigate variability in current farming systems, we used a multiple factor analysis (MFA) as this has the capacity to jointly integrate the qualitative and quantitative variables collected during interviews, without requiring the conversion of quantitative variables into ordinated or categorial variables (Abdi et al., 2013; Pagès, 2014). In the MFA, we included a set of 13 active variables that were relative to farming systems (variables about land-use types and cropping and ranching activities), as well as seven supplementary variables that were relative to landscape patterns (see Table S3 for further details). The MFA was followed by a hierarchical clustering on principal components (HCPC) that allowed us to formally differentiate farm clusters based on farming systems. Both the MFA and the HPCP were computed in the R environment with the *FactoMineR* R package (Lê et al., 2008).

To analyze the correlations between current farming systems and vegetation patterns, we then used linear regressions and Pearson's correlation tests between, on the one hand, the farm coordinates in the first two axes of the MFA – which depicted cropping and ranching practices, respectively (see Section 3.1) – and, on the other hand, the seven landscape metrics.

Similarly, to analyze the correlations between changes in farming systems and vegetation patterns, we explored the correlations between the 2009–2019 evolution in the proportions of farm-scale cropland and pastureland and the 2009–2019 evolution in farm-scale landscape metrics.

Finally, we conducted a pixel-wise analysis to explore the relationship between a set of biophysical factors (including elevation, slope, distance to water, and soil type), and the probability of natural vegetation being present, and assessed the related links to farming systems (thus to farm coordinates in the MFA). To calculate elevation and slope, we used the centroids of the SRTM 90-m resolution data as sampling locations (149,703 in total). The centroids were used to sample the soil type based on the soil map 'Mapa de Solo do Estado de Mato Grosso do Sul' (Mato Grosso do Sul, 2016) and the land cover type ('Natural vegetation' or 'Other LULC types') from the MapBiomas 2019 land cover map. To calculate distance to water bodies, we first used the 'Channel Network and Drainage Basins' module from SAGA-GIS (Conrad et al., 2015) to extract the channels with Strahler order ≥ 3 from the SRTM elevation data. We calculated the distance to the channels from each centroid, using the nearest neighbor distance. We computed several binary logistic models for the year 2019, applying the generic equation:

$$logit(Y) = a + b\sum_{i=1}^{n} X_i$$

where *logit(Y)* was the probability of natural vegetation being present in one pixel and X_i the different predictors tested (see SI Methods). All models were trained on a 25% sample of pixels and tested on another 25% sample of pixels, which allowed us to avoid spatial autocorrelation issues. To judge the quality of prediction of the different models, we relied on the Akaike Information Criterion.

3. Results

3.1. Characteristics and variability of farming systems

Based on the interviews, the 40 farms we visited covered 117,963 ha, which was congruent with the total surface area assessed from the spatial boundaries of the farms: overall, the two assessments differed by 3.7% (4403 ha). There was also good correspondence for individual farms, except for two smallholder farms and four larger farms (Fig. S2). The average farm size was 2949 ha, but the size was highly variable (SD=3480): the smallest was 12 ha and the largest 17,000 ha.

The MFA highlighted that both cropping and ranching activities contributed to explaining variability in farming systems between the 40 farms (Fig. 2). The first differentiating factor was farm land-use types, as showed by the strong correlation of the first MFA axis with the respective proportions of cropland and pastures, and with the proportions of soy and maize crops (Fig. 2a, Table S4, Fig. S3). The second axis of differentiation was linked to ranching activities, and more precisely to their quantitative descriptors such as cattle density and the number of breeding races, and to a lesser extent to farm involvement in animal fattening (Fig. 2b, Table S4, Fig. S3). Finally, the third and fourth MFA axes were mostly related to the qualitative descriptors of ranching activities (Figs S3 and S4), in particular the livestock production phases in which farms were involved (i.e. *cria*, *recria* and/or *engorda*), the insemination method used (natural vs. artificial), and the type of containment practiced (semi vs. full containment).

Based on this diversity of cropping and ranching activities, the HCPC identified five farm clusters (Fig. 2c; Table 2):

- **Cluster 1 ('Specialized ranching'; 12 farms):** contained farms characterized by a high proportion of pastures (62.5% ± 18.9 SD) and a low proportion of cropland (0.5% ± 0.2 SD), as well as by their specialization in *engorda* (i.e. animal fattening). None of these farms were involved in calf reproduction and nursing (*cria*), while 8 were involved in animal growing (*recria*) and 11 were involved in *engorda*, mostly relying on a semi-containment method (*N*=8). This cluster contained farms that did not have any land in the Serra da Bodoquena national park, and included two family farms and 10 non-family farms. Farms had an intermediate surface area (1894 ha ± 1711 SD) and relatively high cattle density (1.75 ± 0.7 heads of cattle/ha).

- **Cluster 2 ('Small-scale ranching'; 11 farms)**: contained farms with high proportions of pastures (52.6% ± 13.95 SD) and low proportions of cropland (0.6% ± 0.2 SD) that were all involved in *cria*, mostly relying on natural insemination techniques (except for two farms). Out of these 11 farms, 7 were involved in *recria* and 6 were also involved in *engorda* (through a semi-containment method). This cluster contained 5 family farms (out of the 7 included in our sample) and was characterized by the fact that farm owners lived locally, either on the farm (*N*=6) or in nearby municipalities (*N*=4). These were the smallest farms of our sample (1283 ha ± 2288 SD), working with a limited number of breeding races (1.18 ± 0.40 SD).
- **Cluster 3 ('Intensive ranching'; 5 farms):** contained farms characterized by their large size (6108 ha ± 3823 SD) and intermediate proportions of pastures and cropland (Table 2). A key distinctive factor was relative to their use of full containment methods and artificial insemination, which allowed them to work with a higher diversity of breeding races than other farms (2.2 ± 0.4 SD). Farms were all owned by people not living locally but elsewhere in Mato Grosso do Sul (generally in Campo Grande, the main State's city).
- **Cluster 4 ('Mixed system'; 7 farms)**: contained farms characterized by a relatively high proportion of cropland (25.0% ± 16.9 SD) and involved in *engorda*. Farms in this cluster were therefore characterized by their involvement in both ranching and crop cultivation, with a certain degree of specialization for the former activity: all farms were involved in *engorda* while only one of them was involved in the three livestock production phases.
- **Cluster 5 ('Cropping system'; 5 farms):** contained large farms (5913 ha ± 6569 SD) characterized by a high proportion of cropland (40.4% ± 16.4 SD) and a low proportion of pastures (14.4% ± 4.5 SD). This cluster had an absence of farms involved in *engorda*, while two farms were specialized in *cria*. It harbored particularly low herd density (0.33 ± 0.54 heads of

cattle/ha) and a low number of breeding races (0.4± 0.5) compared to the other two clusters (Table 2). Three of these farms had land within the national park.

In sum, the clustering analysis depicted a gradient of farm involvement in crop cultivation as well as a diversity of ranching systems that harbored contrasting insemination and containment methods, but also different degrees of involvement in *cria*, *recria* and *engorda*. Cluster 3 and 5 tended to be the largest farms in surface area (Table 2) and to belong to non-local wealthy owners who, according to our interviews, had the financial capacity to intensify farming systems, through either artificial insemination and full containment (cluster 3) or crop cultivation (clusters 5). Furthermore, and consistently with the MFA outputs (Table S4), cluster description evidenced that ranching activities varied according to involvement in crop cultivation: farms involved in crop cultivation (clusters 4 and 5) tended to be specialized in one or two phases of the livestock production cycle. These results reflected that crop expansion was part of an overall intensification process of farming systems, as was pointed out by interviewed farmers: "*Our goal is to have 3000 ha of cropland in three years. Currently, we have 2000 ha. [In the meantime,] we are decreasing the surface area in pastures but increasing the number of animals. This number has already increased. We aim to halve the pasture area while doubling the number of cattle*" (an interviewed farmer).

3.2. Relationship between farming systems and vegetation patterns

Our analysis revealed that, independent of farming systems, forest conservation levels within the 40 farms were above the minimum threshold imposed by the Brazilian Forest Code. According to landscape analyses, farms had an average 45.7% (± 17.9 SD) of their land covered in natural vegetation, and all farms but five had natural vegetation covering > 20% of their land (Fig. 3a). The proportion of natural vegetation within farms was independent of farm clusters (Table 2). Furthermore, the proportion of forest declared in interviews (30.4% ± 15.4 SD) was generally lower than the proportion of natural vegetation obtained from the land cover map (Fig. 3b), suggesting that beyond 'proper forests' as declared by farmers, farms contained many complementary areas of natural vegetation such as groves and isolated tree patches.

We found a limited correlation between farming systems (assessed through farm coordinates along the MFA axes) and vegetation patterns, as evidenced by Pearson's (Fig. 4) as well as Spearman's correlation coefficients (Fig. S5). Firstly, farm coordinates on the first and second axes were only correlated with farm surface area (Fig. 4). Secondly, farm coordinates on the third axis (which was linked to insemination methods and farm involvement in *cria*, Fig. S3) were positively correlated with mean vegetation patch area (r=0.47; p<0.01) and farm surface area (r=0.45; p<0.01), and negatively correlated with edge density (r=-0.32; p<0.05). Thirdly, farm coordinates on the fourth axis (which was linked to cattle density and insemination methods, Fig. S3) were positively correlated with natural vegetation proportion (r=0.44; p<0.01) and edge density (r=0.43; p<0.01). Contrary to our hypothesis, the intensity of current cropping vs. ranching activities within farms appeared to have little effect on natural vegetation patterns at this scale of analysis. However, breeding activities such as farm involvement in calf nursing, insemination techniques and livestock density were correlated with some key landscape metrics depicting vegetation amount and fragmentation.

Binary logistic regression models further corroborated these results by showing that the intensity of cropping activities had no significant influence on the likelihood of presence of natural vegetation at pixel scale, and that breeding activities had a weak, yet significant, predictive power (Table S5). Based on the AIC, the best model was the multiple predictor model that combined both biophysical (i.e. slope, distance to watercourses, elevation and soil type) and farming-system-related variables (Kappa=0.43; Sensitivity=0.77; Specificity=0.65; see Table S6), demonstrating the interplay between these two types of variables on vegetation patterns.

3.3. Temporal dynamics in farming systems and vegetation patterns

Our results found that there has been little deforestation in the area between 2009 and 2019, and that crop expansion mainly involved the conversion of pastures into cropland rather than increased deforestation. At landscape level (i.e. over the whole area comprising the 40 farms), the proportion of forest remained stable, at 46.8% in 2009 and 46.2% in 2019. In contrast, the proportion of pasture decreased from 45.2% to 36.8%, while the proportion of cropland increased from 8.0% to 16.9% (Fig. S6). At farm level, we found that the change in the proportion of crops was negatively correlated with the change in the proportion of pastures (r=-0.95; p<0.001), but not with the change in the proportion of forests (p=0.77) (Fig. 5). While not linked to crop expansion, the change in the proportion of forests was positively correlated with the change in mean patch area (r=0.54; p<0.001) and negatively with the change in landscape division (r=-0.89; p<0.001). Interviews corroborated these results, indicating that cropland was implemented in old pastures: only one interviewee declared having directly converted forest into cropland during the last decade (on ca. 2000 ha), while four interviewees reported converting pastures into cropland (on ca. 4500 ha). For farmers, this conversion was seen as a way to regenerate old pastures and to improve farm profitability: *"[The farm] used to be a ranch, but the soil was degrading so we had to find another solution. […] Ranching activities were no longer profitable. We had to regenerate the soil, which I did by starting crop cultivation with direct sowing"* (an interviewed farmer).

In addition, we found that crop expansion was highly variable between farms for the 2009–2019 period, and was not correlated with any farm-scale landscape metric (Fig. 5). Information collected in our interviews suggested that crop expansion was conditioned by topographical and other biophysical features, as well as by environmental legislation restrictions. Of the 40 farms, between 2009 and 2019 crop expansion occurred in only 15, where it increased on average from 8.5% (± 16.2 SD) in 2009 to 28.2% (± 18.0 SD) in 2019, independent of farm size (Fig. 5). According to interviewees, most remaining forested and pasture areas in this consolidated agricultural region were effectively not suited to crop cultivation due to either low soil fertility, steep slopes, the presence of rocks, or frequent floods: *"There are not many areas left that can be farmed with machines. The rest of the farm has a lot of rocks. Perhaps another 200–300 ha could be converted to cultivation, but not much more"* (an interviewed farmer). As a consequence, only the flattest and most fertile pastures seemed to be prone to conversion to cropland: "*Here, there are a lot of rocks and hills, which is good for ranching. We maintain rocky areas as pastures, and in areas without rocks, we cultivate crops"* (an interviewed farmer). Yet the availability of such arable areas seemed to be limited, in particular when taking into consideration the restrictions of the Brazilian Forest Code: *"I have riverbanks that I can't touch and hillsides that I can't deforest because they're protected by law. I have declared these in the [required] 20% of reserves and protected areas, but I also have forest that I cannot clear. I have a lot of Cerrado* *[land], which is too rocky and steep to be suitable for grazing – the soil is not good for planting pasture"* (an interviewed farmer).

4. Discussion

Using semi-structured interviews and landscape analyses in the agricultural region bordering the Serra da Bodoquena National Park in Brazil, this study identified five main types of farming systems in a region that was historically dedicated to extensive ranching and where cultivated areas have been expanding since the late 2000s (Ribeiro, 2017). For farmers, investing in crop cultivation appeared a strategy to both diversify and increase the profitability of a farm, resulting in changes in their overall farming system. Contrary to our hypotheses, we found that these changes have had little impact on farm-scale vegetation patterns to date, and have not led to a measurable increase in the spatial separation between agricultural and forested areas. Our interviews with farmers suggested that crop expansion in the region has been constrained by farms' biophysical characteristics as well as legislative constraints, corroborating that anti-deforestation policies can be effective under certain conditions (Nolte et al., 2017). Reversely, we found some differences in vegetation patterns according to breeding activities, such as farm involvement in calf nursing and insemination techniques.

Our temporal analyses allowed us to identify two plausible explanations for this relatively low linkage between ongoing changes in farming systems and vegetation patterns. First, as crop expansion has mainly occurred at the expense of old pastures rather than forests, this may have induced subtle changes in vegetation patterns that are not detectable with 30-m resolution MapBiomas land cover maps, such as the removal of isolated trees within a pasture. Second, crop expansion remained limited in terms of both number of farms and surface area. As a consequence, farm-scale analyses might not be able to reveal the early effects of this expansion on vegetation patterns, as the signal is too weak. Both explanations point to the need to conduct landscape analyses at a finer spatial resolution in order to detect the influence of early-stage crop expansion on agricultural landscapes. These results are discussed in detail below, emphasizing the implications for future research and biodiversity conservation practices in the area.

4.1. Characteristics and evolution of farming systems around the national park

Our study revealed different farm management strategies, in particular with regards to farmers' choices to either invest in crop cultivation or in ranching. According to multi-factorial analyses, soybean-based cropping systems were the main factor differentiating farms. The recent expansion of soybean crops in the region, as elsewhere in the Brazilian Cerrado (Rausch et al., 2019), is likely to contribute to further segregation between farms. We found that farmers who cultivate crops generally maintain a ranching activity, some practicing crop–livestock rotation in order to valorize old and degraded pastures, which should limit the clearing of remaining natural vegetation (Nepstad et al., 2019).

This mixed-system strategy can have varying rationales. As soy is initially expanded on the most fertile and flat lands (see Eloy et al., 2016, for a historical perspective in the Brazilian Cerrado), mixed systems reflect farmers' strategies given the biophysical constraints of a hilly and mountainous region. Another reason revealed by our interviewees was related to risk management, as crop cultivation generates less stable income than livestock raising: *"Crop cultivation is more profitable [than ranching], but it is riskier – ranching is safer. As there are bad years and good years, livestock raising is more stable"* (an interviewed farmer). Additionally, several farmers mentioned the long administrative procedure required to obtain a license to convert pastureland into cropland, which might further slow the crop expansion process and contribute to maintaining mixed systems. Nonetheless, several farmers we interviewed decided to entirely dedicate their farm to crop cultivation, separating crops and livestock, as occurred during the modernization of agriculture in Europe, for instance (Schott et al., 2010). In Mato Grosso do Sul, this tendency might be further reinforced by the opening of transoceanic roads, which are expected to foster soy expansion (Henderson et al., 2021; Tomas et al., 2019), or by sugarcane development, as the region appears particularly suitable for this crop (Alkimim et al., 2015; Defante et al., 2018).

We found that only the largest farms, generally owned by wealthy landowners living in São Paulo or other major cities, developed crop cultivation. This is doubtless because crop cultivation is particularly costly, requiring large investments in machinery, infrastructure, labor and know-how, which only the biggest farms can afford. To cope with these expenses, leasing part of a farm (with 5–10 years leasing contracts) to another farmer with experience in cultivation was a frequent strategy, allowing landowners to transfer the costs and risks of crop cultivation, while making more profit than with ranching. As a consequence, crop cultivation is expanding through diverse strategies: sometimes leading to a clear separation between cropping and ranching activities and sometimes to their close integration. These results are in line with other studies showing the existence of a diversity of soy cultivation practices (e.g. Vander Vennet et al., 2016).

Ranching activities were the second differentiating factor between farms, and were particularly diverse. Some farms were specialized in producing calves, others in raising and fattening livestock, while a few had a full-cycle livestock production system. Based on our interviews, producing grown livestock to sell directly to slaughterhouses was more profitable than solely producing calves to be sold to other farms to raise and fatten, which echoes with risk and profitability assessments conducted for cattle production systems in the upper Pantanal region (Peixoto Simões et al., 2015). Yet the husbandry system chosen by farmers was chiefly influenced by the quality of the farm's pastures and its economic situation, explaining the diversity of practices. While it is uncertain how ranching systems in the area will evolve, our results suggest that crop expansion is fostering mixed-system farms that specialize in one or two phases of the livestock production cycle, and the use of crossbreeds that allow more intensive containment methods.

Although we took into account 13 variables to characterize farming systems, our multi-factorial analysis did not allow a full overview of farming system diversity, so further research would be valuable. For example, some of the information obtained from interviews may be relevant but was not analyzed, such as a farm's involvement in ecotourism, which is a key diversification strategy in the region (Sabino & Andrade, 2003). While such farms remain marginal in terms of number and land area, they are not in terms of socio-economic benefits. Due to the low number of agrotourism farms in our sample (N=3), we did not integrate an 'ecotourism' variable in the analysis. However, our interviews suggest that landowners and managers of agrotourism farms might have a more positive attitude toward forest and biodiversity conservation than other farms, which has also been observed in other contexts (Mastronardi et al., 2015). Further research could be of great interest to explore to what extent ecotourism, or other types of farm activities that are not widespread, might influence farm landscapes and associated biodiversity.

4.2. Dynamics of natural vegetation areas in a changing working landscape

Our joint analysis of farm-scale vegetation patterns, biophysical variables and farming systems allowed us to reach important conclusions on the current state and potential evolution of natural vegetation areas around the SBNP. Our choice to conduct in-depth qualitative interviews with farmers limited our final sample size (N=40 farms), so a larger sample could be relevant to confirm our results. Nonetheless, this approach allowed an in-depth understanding of farming practices that enriched our overall analysis. Furthermore, as the 40 farms investigated cover a sizeable area around the SBNP (Fig. 1), we argue that our results can be considered as representative of the area surrounding this national park.

Consistent with previous studies (Azevedo et al., 2017; Vieira et al., 2018), we found that the average proportion of natural vegetation within farms (>45%) largely exceeds the minimum 20% required as Legal Reserve by the Forest Code. This was independent of the farming systems in place, which might relate to the fact that the Forest Code applies this indicator identically to all rural properties, independent of the nature of their activities. As a result, even at farm scale, native vegetation is currently slightly above the 40% threshold, the crossing of which might cause abrupt biodiversity loss (Arroyo-Rodríguez et al., 2020; Rodrigues et al., 2016; Roque et al., 2018). However, as the current level is now very close to this threshold or has been already crossed on several farms, this merits close monitoring in the future.

In contrast to Stefanes et al. (2018), we found no influence of farm size on the level of compliance with the code, indicating potentially important regional differences regarding compliance (Vieira et al., 2018). In our case, it appeared that the conservation of natural vegetation was highly dependent on slope and soil type (Table S6), and therefore that biophysical constraints limited the risk of large-scale forest clearing. Many farmers corroborated this conclusion during interviews, highlighting that the most accessible areas had already been deforested for pastureland in the past, and that the most accessible pastures had already been converted into cropland. This may imply that large-scale pasture or forest conversion is unlikely, and that only the flattest and most fertile areas are currently prone to cropland conversion. Yet considering the proximity to the forementioned 40% threshold and the key role of wooded pastures for biodiversity (e.g. Fernandes Seixas & Mourão, 2002), preventing the conversion of these areas should not be disregarded. There should be a particular focus on farms with land within the SBNP, as these farms tend to be larger and more involved in crop cultivation than others (Table S7).

4.3. Impact of early-stage crop expansion on vegetation patterns

Lastly, our study highlights some of the key research challenges in understanding the complex changes in vegetation patterns induced by crop expansion, in particular in its early stages. Indeed, at farm scale and using 30-m resolution land cover maps, we were not able to detect any relationship between the evolution in farming systems and the evolution in natural vegetation patterns. We did find that the farms practicing calf nursing tented to have larger vegetation patches than farms involved in animal fattening, and that cattle density tended to be positively correlated with natural vegetation proportion and edge density. However, further research would be necessary to determine whether these farms conserve more forests because of the characteristics of their activities or whether biophysical or legislative constraints condition their activities.

One possible explanation for the absence of a relationship between vegetation patterns and farming systems in our study may be the resolution of the land cover maps we used. As shown in our temporal analyses (Fig. 5 and Fig. S4), crop expansion has mainly occurred on old pastures rather than forests, which was also evidenced in a recent study focusing on Cerrado biome protected areas and their buffer zones (Bellón et al., 2020). As our respondents explained, pasture conversion into cropland only affects small groves and isolated trees: *"To improve pastures, we have to do crop–livestock integration. But to cultivate crops, we need to remove most of the trees, conserving only one or two"* (an interviewed farmer). The 30-m resolution MapBiomas land cover maps we used are not suited to detect such small-scale tree removals. While this resolution is prevalent in current research to assess pasture dynamics in Brazil (e.g. Gosch et al., 2021; Souza et al., 2020), images with higher spatial resolution should be used in future to detect the influence of pasture conversion on trees outside forests, and thus to understand the early effects of crop expansion on vegetation patterns in the region.

Our results also showed that crop expansion concerned a limited number of farms in the region, and only 15 of the 40 farms we analyzed. Moreover, in terms of land use, crop expansion occurred on a limited proportion of the total surface area investigated (Fig. S4). These results suggest that crop expansion is to date (at least up to 2019, the end of our study) a weak signal in the region, with effects that are not yet visible. This stresses the need for future research at a more local scale and with a narrower focus on the areas where crop expansion has already occurred or is likely to occur (i.e. the flattest and most fertile areas), as a way to anticipate and monitor the vegetation changes induced by the future expansion of soy and sugarcane expected to occur in Brazilian landscapes (Alkimim et al., 2015; Rausch et al., 2019).

In terms of spatial planning, our results showed that ranches specialized in calf nursing and maintaining a high cattle density tended to have a higher proportion of natural vegetation and bigger vegetation patches than other farms, contributing to the preservation of a ‘land sharing’ type of landscape. Interviewees and economic studies pointed to the fact that calf nursing was less profitable than fattening grown animals in the region (Peixoto Simões et al., 2015). Thus, although the mechanisms that explain this result are unresolved by this study, we might assume that farmers specialized in calf nursing have more limited investment capacity, which limits their forest-clearing potential. Furthermore, and as suggested by the correlation between cattle density and vegetation proportion, calf nursing might be less demanding in grazing areas than cattle rearing and fattening, and thus more compatible with high forest proportions within farms. If this is true, promoting ranches specialized in calf nursing in the periphery of the SBNP could be a sound strategy for improving biodiversity conservation. These ranches could be assumed to host higher levels of biodiversity due to their greater forest cover (see the habitat amount hypothesis; Fahrig, 2013) and to their extensive pastures with scattered trees and shrubs, all assets for ecological connectivity and farmland biodiversity (Fernandes Seixas & Mourão, 2002; Godoi et al., 2018). In contrast, crop cultivation should be discouraged at the periphery of the SBNP, which does not presently seem to be the case (Table S7).

Although more research is required to study the actual and site-specific links between vegetation patterns and biodiversity, the ongoing crop expansion on former pastureland around the SBNP and, more generally, around many PAs in the Brazilian Cerrado (Bellón et al., 2020), raises concerns about the subtle impacts this may have on vegetation patterns. Considering that cropland and pasture dynamics in Brazil are intimately linked to forest conservation restrictions and broader supply chain development, demand from the international market will surely play an important role in the future trajectory of the region and should be urgently monitored and anticipated.

5. Conclusion

While deforestation resulting from agricultural expansion is a major threat to biodiversity conservation in tropical countries, and in Brazil in particular, changes in farming systems can also be key drivers of biodiversity loss. In our analysis of the relationship between farming systems and vegetation patterns around the Serra da Bodoquena National Park in the Cerrado biodiversity hotspot, we found a diversity of cropping and ranching systems, and an ongoing expansion of crop cultivation at the expense of extensive pastureland. This early-stage dynamic mainly concerned the largest farms owned by the wealthiest landowners, including in the close vicinity of the park. Yet crop expansion has had little impact on the current proportion of natural vegetation within farms, mainly because crops are expanding in areas that already have a low amount of natural vegetation, i.e. the flattest and most fertile pastures.

Nonetheless, the conversion of pastures into cropland could have a major detrimental impact on the unique biodiversity of the SBNP. In order to better monitor the subtle influence of such early-stage crop expansion processes on vegetation patterns and biodiversity, we recommend the use of higher resolution images, which could be instrumental to detect the small-scale tree removals occurring when wooded pastures are converted into cropland. To ensure conservation of the biodiversity in the SBNP, fine-scale monitoring of the occupancy patterns of species in both forested and agricultural areas should be implemented. Ultimately, the implications of our findings are that conservation strategies such as the Brazilian Forest Code should not focus strictly on forested areas, but should also consider wooded pastures, which are crucial in building more ‘biodiversity-friendly’ agricultural landscapes. This would require an approach at a finer spatial scale, based on high-resolution satellite imagery.

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Tables

Table 1. Description of the seven landscape metrics used to characterize farm-scale landscape patterns (LecoS = Landscape Ecology Statistics plugin).

Type of estimate	Name of metric in LecoS	Name used in this study	Description*	Equivalent FRAGSTATS index
Area and edge	Landscape proportion	Vegetation proportion (*VegPro*)	Proportion of a farm's total area covered by natural vegetation.	Percentage of landscape (PLAND)
	Edge density	Edge density (*EdgDen*)	Edge length of natural vegetation divided by a farm's total area. Higher values correspond to higher vegetation fragmentation.	Edge density (ED)
	Mean patch area	Mean patch area (*MeaPatAre*)	Average area of the natural vegetation patches in a farm.	Mean patch size (AREA_MN)
Shape	Fractal dimension index	Fractal dimension index (*FraDimInd*)	Measure of the degree of complexity of the shape of natural vegetation patches using their perimeter/area ratio.	Fractal dimension index (FRAC)
	Mean patch shape ratio	Mean patch shape (*MeaPatSha*)	Average Shape Index of the natural vegetation patches in a farm.	Mean patch shape index (SHAPE_MN), calculated from the Shape Index (SHAPE)
Aggregation	Number of patches	Number of patches (*NumOfPat*)	Number of patches of natural vegetation in a farm.	Number of patches (NP)
	Landscape division	Landscape division (*LanDiv*)	Probability that two random places in a farm are not situated in the same patch. Values close to 1 mean that the natural vegetation is very patchy (divided) and 0 means that the whole farm is covered by natural vegetation.	Landscape Division Index (DIVISION)

* For the metric calculation details, the equivalent indices in FRAGSTATS are available in (McGarigal, 2015).

Table 2: Average and standard deviation values of quantitative farm characteristics and landscape metrics for the five farm clusters and p-values (Kruskal-Wallis test).

	Cluster 1 *Specialized ranching* *N*=12	Cluster 2 *Small-scale ranching* *N*=11	Cluster 3 *Intensive ranching* *N*=5	Cluster 4 *Mixed systems* *N*=7	Cluster 5 *Cropping systems* *N*=5	p-value
Farm characteristics						
Property size (ha)	1894 ± 1711	1283 ± 2288	6108 ± 3823	3002 ± 1772	5913 ± 6569	p<0.05
% of pastures	62.5 ± 18.9	52.6 ± 13.5	47.5 ± 31.1	32.7 ± 13.6	14.4 ± 4.5	p<0.001
% of cropland	0.5 ± 1.7	0.6 ± 1.8	5.3 ± 7.8	25.0 ± 16.9	40.4 ± 16.4	p<0.001
Herd density (/ha)	1.75 ± 0.66	1.58 ± 0.44	1.41 ± 0.66	1.76 ± 0.77	0.33 ± 0.54	p<0.05
No. of breeding races	1.6 ± 0.8	1.2 ± 0.4	2.2 ± 0.4	1.4 ± 0.8	0.4 ± 0.5	p<0.01
Landscape metrics						
% of natural vegetation	35.5 ± 19.5	45.3 ± 13.2	45.3 ± 26.8	40.1 ± 7.5	43.0 ± 16.9	p=0.66
Patch density	2.81 ± 2.71	2.20 ± 1.04	0.82 ± 0.34	2.22 ± 2.66	1.08 ± 0.49	p<0.05
Mean patch area	24.5 ± 21.6	24.3 ± 11.9	60.5 ± 37.4	31.6 ± 17.2	49.6 ± 32.7	p=0.12
Edge density	47.6 ± 23.1	55.7 ± 19.4	28.8 ± 8.7	42.0 ± 19.4	36.6 ± 13.5	p=0.09
Mean patch shape	1.89 ± 0.60	1.77 ± 0.35	1.56 ± 0.49	1.76 ± 0.39	1.63 ± 0.22	p=0.89
Landscape division	0.91 ± 0.11	0.88 ± 0.09	0.78 ± 0.23	0.91 ± 0.07	0.87 ± 0.11	p=0.61
Fractal dimension index	1.07 ± 0.02	1.08 ± 0.01	1.07 ± 0.01	1.07 ± 0.01	1.08 ± 0.01	p=0.54

Figures

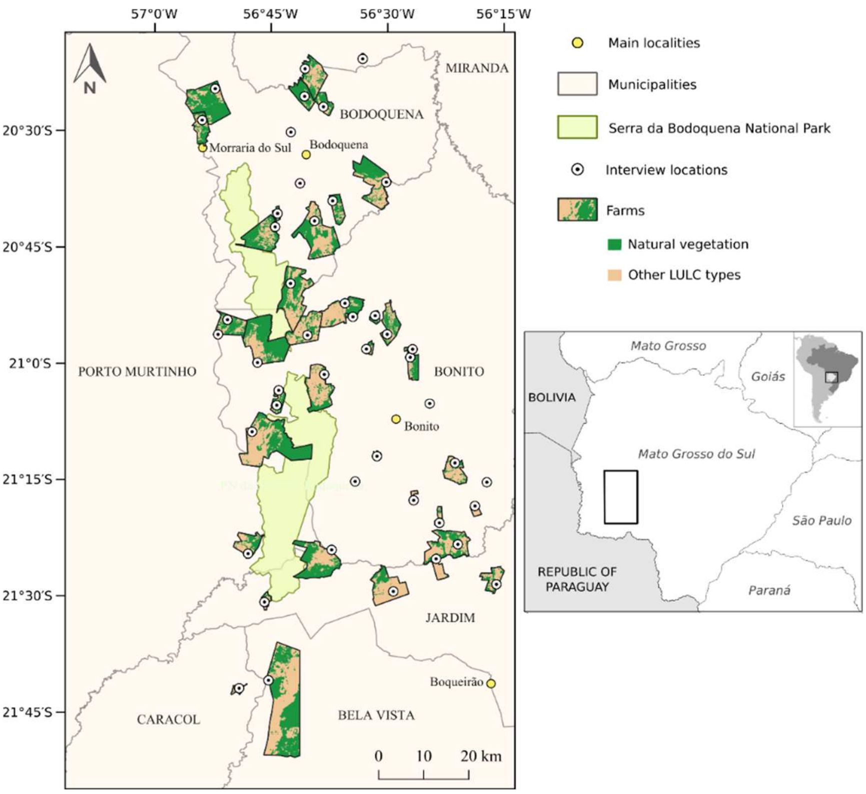
Figure 1: The location of the 40 farms investigated around the national park and the interview sites, plus the land cover (natural vegetation and other land use and land cover [LULC] types).

Figure 2: Representation of farm diversity and associated variables depicting farming systems and landscape metrics highlighted by a multiple factor analysis (MFA). (a) Correlation graph for the quantitative variables, colored according to their contribution to the first two axes. (b) Graph of the active categories along the first two axes, colored according to their contribution. (c) Plot of the individual farms (N=40) along the two first axes of the MFA and colored according to the clusters identified by the hierarchical clustering on principal components (HCPC). (d) Correlation graph of the supplementary variables (i.e. landscape metrics) with the first two axes of the MFA.

Figure 3: Proportion of natural vegetation at farm scale assessed from land cover data and interviews according to the five farm clusters. (a) Proportion of natural vegetation derived from land cover data in the 40 farms assessed. (b) Proportion of natural vegetation proportion derived from land cover data compared to proportion of forest declared by interviewees.

Figure 4: Relationship between farm-scale landscape metrics and farm coordinates in the multiple factor analysis. In red, plots for the first axis, which depicts a farm's cropping activities; in blue, plots for the second axis, which depicts a farm's breeding practices. Regression lines correspond to linear models with a 0.95 confidence interval. Pearson's correlation coefficients are provided, and statistically significant correlations are denoted by asterisks.

Figure 5: Heatmap showing Pearson's correlation coefficients between farm area and the evolution in land use and landscape metrics between 2009 and 2019 on the 40 farms. Blue tones represent positive correlations and red tones represent negative correlations. Asterisks indicate the p-value of significant Pearson's correlation tests: * for $p < 0.05$; ** for $p < 0.01$; *** for $p < 0.001$.



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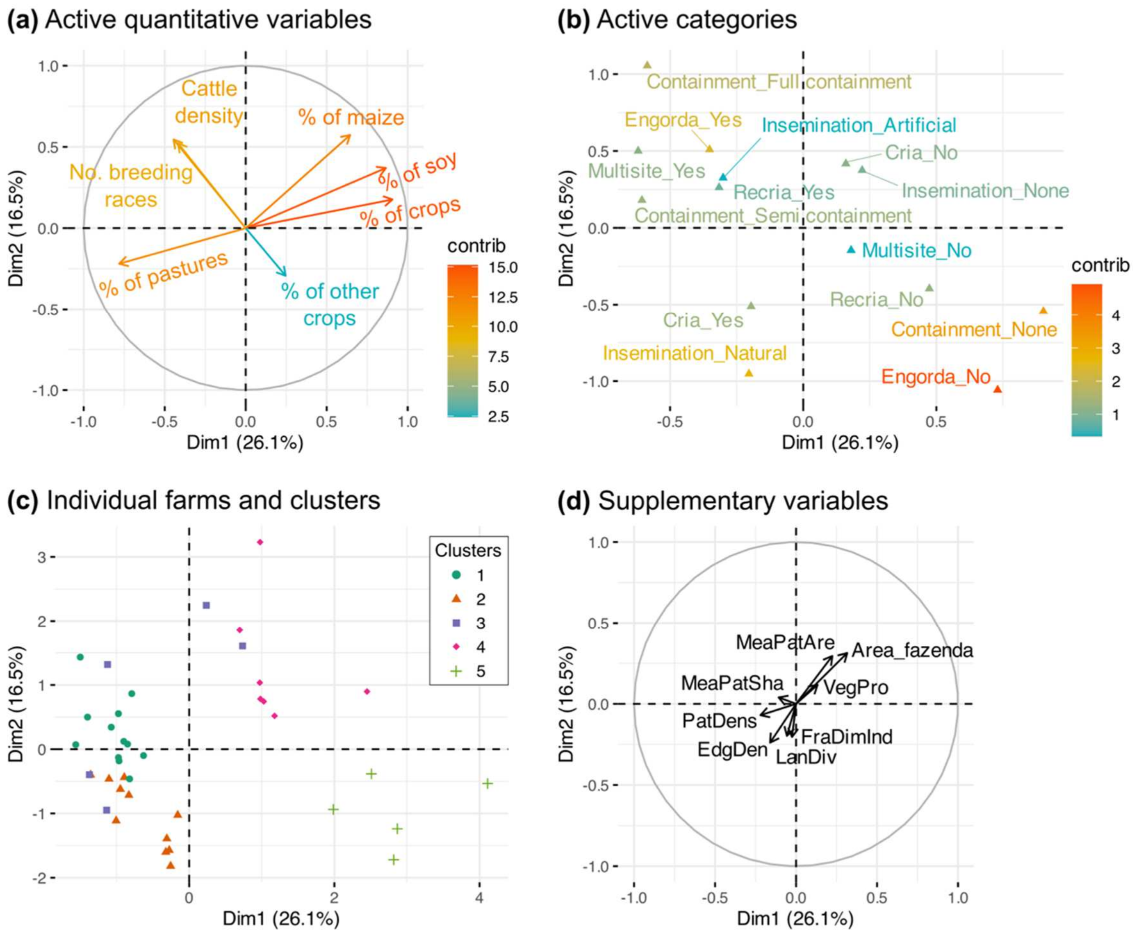

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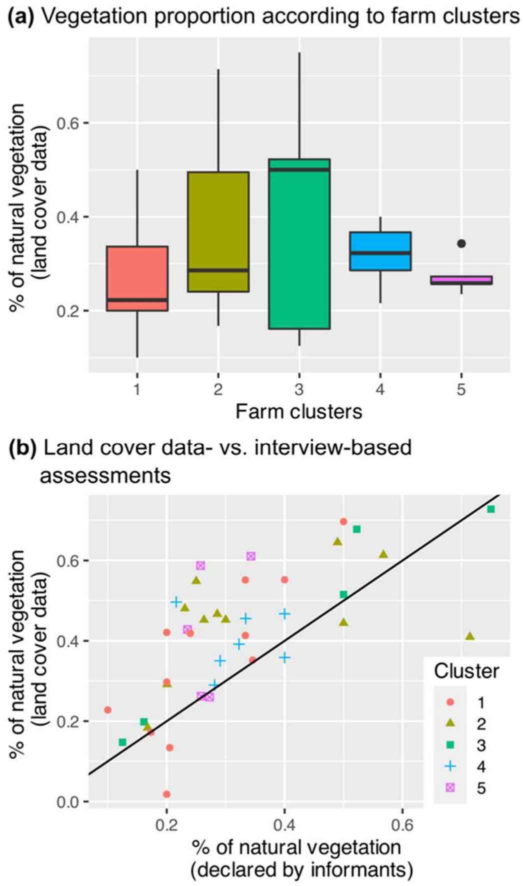

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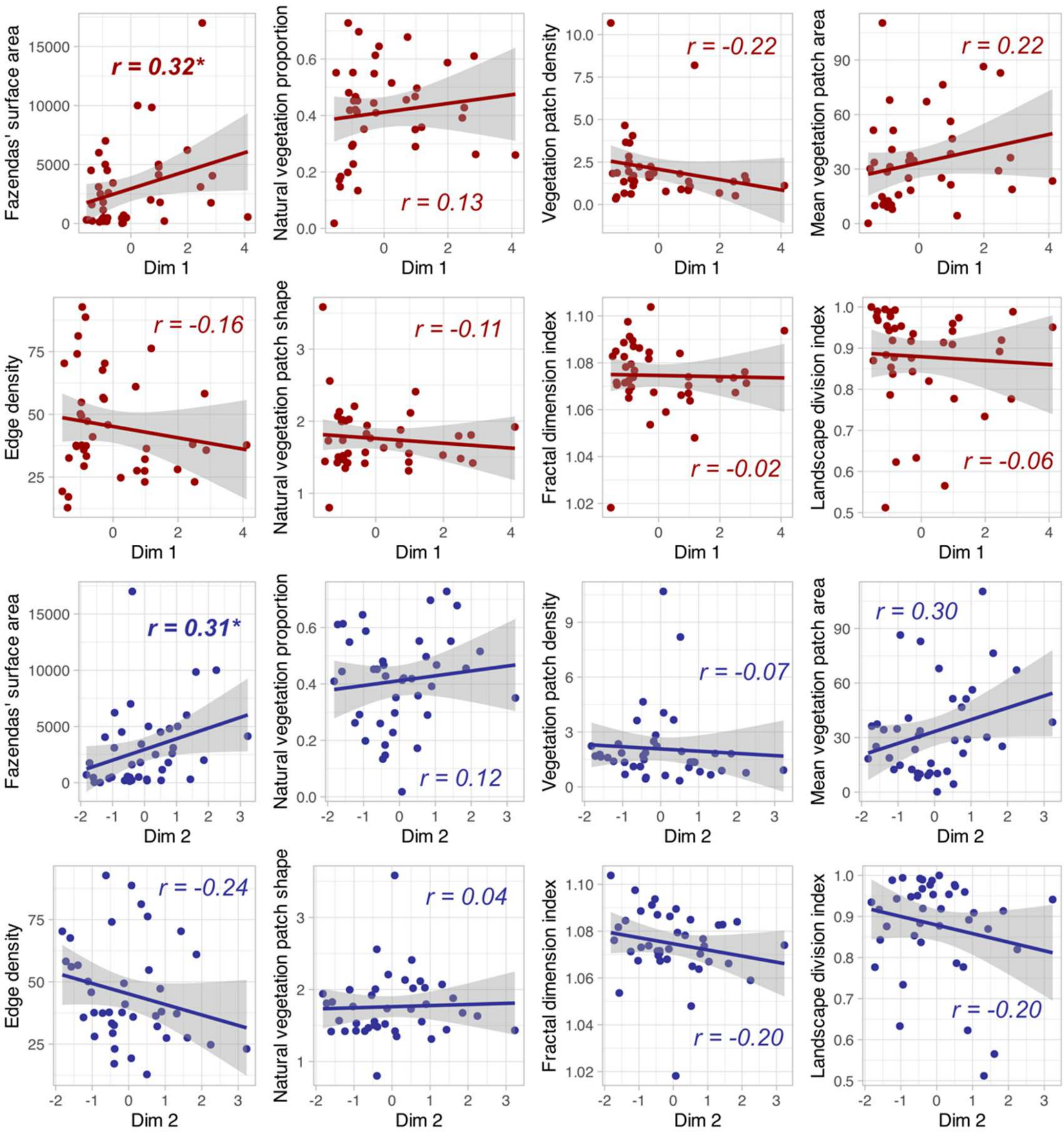

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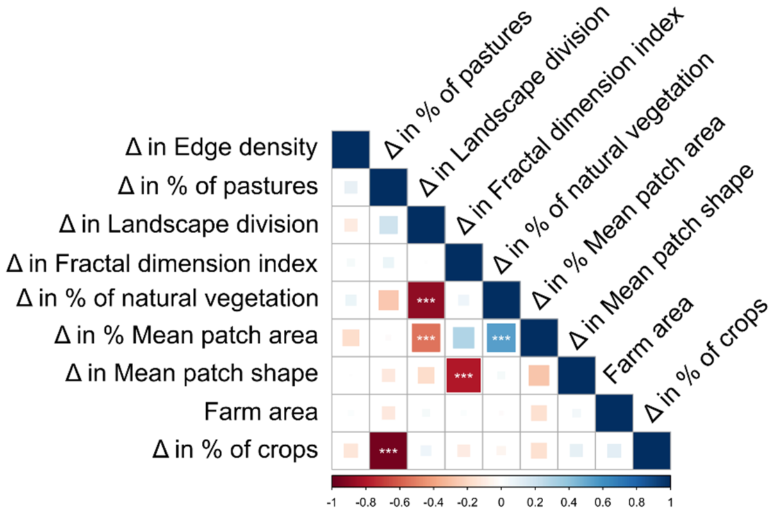

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