Department of
BIOLOGY

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Contents

Abstract

Brazilian beef farming is the leading driver of tropical deforestation globally. Though environmental impacts are known to vary widely between otherwise similar farms, Brazilian beef farming's impacts on habitat have rarely been studied at the farm level. I investigated the associations among forest configuration, cattle's access to forest, and forest quality, as well as among farm agrochemical use, productivity, and conservation performance, on a sample of beef farms in and around Aparecida do Taboado, Mato Grosso do Sul. I found that forests with a greater perimeter-to-area ratio had canopies that were lower, more open (lower image homogeneity), and less green (lower NDVI), and that cattle access to forests greatly reduces understorey. Farms using agrochemicals had higher pasture quality, but pasture quality and farm productivity were not associated, and neither were farm productivity and conservation performance. My findings suggest that impacts on fragmented forest can be minimised by conserving it in simpler configurations and excluding cattle, and that beef farms can conserve local biodiversity and store carbon regardless of their productivity.

1. Introduction

Farming is the leading driver of tropical deforestation (Pendrill *et al.*, 2022). Consequently, farming contributes significantly to global biodiversity loss and greenhouse gas emissions. Tropical forests are home to more than half of the world's vertebrate species (Pillay *et al.*, 2022), and tropical deforestation released an estimated 2.6 gigatonnes of carbon dioxide annually between 2010 and 2014 (Pendrill *et al.*, 2019). The country with the highest rate of tropical deforestation is Brazil, with 33% of global tropical deforestation, 72% of which is driven by beef farming (Pendrill *et al.*, 2022). Brazil is the world's second highest beef producer and the world's highest beef exporter (FAOSTAT). Demand for beef is expected to keep increasing with world population growth and the economic development of developing countries (OECD & FAO, 2023), which may drive substantial further deforestation in Brazil. To meet climate and biodiversity targets, it is imperative to find ways of producing beef in Brazil that meet future demand with the least environmental impact.

Two farm-level approaches exist to address farming-driven deforestation while meeting a given level of demand. The first is to increase farm productivity (intensification) and the second is to protect or restore on-farm biodiversity. The former approach assumes that more efficient farms contribute less to deforestation by requiring less land per unit production, though evidence supporting the link between increasing productivity and reduced land use is mixed. Within the Brazilian Amazon, findings range from municipalities in which deforestation was strongly disincentivised having more productive beef farming than other municipalities (Koch *et al.*, 2019) to more intensive beef farming systems being associated with higher deforestation (Carvalho *et al.*, 2020). Current analyses are limited to the municipal level. This makes it impossible to understand farm-level heterogeneity, which can often be substantial – farms producing the same product in the same region can vary 50-fold in their environmental impacts (Poore & Nemecek, 2018).

The Brazilian government is trying to address deforestation through both agricultural intensification and habitat protection. Firstly, the Brazilian government's current Low Carbon Agriculture plan – the ABC+ plan for 2020–2030, replacing 2010–2020's ABC plan – seeks to intensify beef farming by improving underproductive pastures, among other aims (MAPA, 2021). Secondly, the Native Vegetation Protection Law (Law 12.651) of 2012, replacing the earlier Brazilian Forest Code of 1965 (Metzger *et al.*, 2019), requires the protection of "legal reserves" and "areas of permanent protection" (APPs). Legal reserves are mandatory protected areas that all private landowners must keep, covering a certain proportion of their land depending on the region: 20% outside the Amazon, 80% in the Amazon, and 35% in transitional areas (Metzger *et al.*, 2019). APPs are mandatory protected areas along natural watercourses, on steep slopes, and in other unstable areas, and can form part of legal reserves. Though Law 12.651 requires conservation of local biodiversity across Brazil, making it globally leading environmental legislation, habitat protected by this law is left fragmented.

Remote sensing has been the main tool used to quantify habitat loss and fragmentation in Brazil, enabling researchers to collect data without travelling into the field. The effects of fragmentation on forests at a local scale have been studied in the field (e.g. Santo-Silva *et al.*, 2016), while remotely sensed data have been overwhelmingly used to study fragmentation at a landscape scale (e.g. (Palmeirim *et al.* 2019)). There is also a bias in the literature both towards Brazil's Atlantic Forest ecoregion, which has suffered the most historic deforestation among Brazil's ecoregions and is the most populated, and towards the Amazon, Brazil's most intact ecoregion which is currently threatened by expanding agriculture. Meanwhile, the Cerrado, Brazil's tropical savanna ecoregion recognised as a biodiversity hotspot (Myers *et al.*, 2000), surpassed the Amazon in 2023 as the most deforested ecoregion in Brazil (Del Lama *et al.*, 2024), but receives less attention. Most agricultural production in Brazil, including beef production, is in the Cerrado, with farming having replaced 41% of the Cerrado's original area of natural vegetation by 2015 (Rausch *et al.*, 2019) and leaving the surviving Cerrado mostly greatly fragmented (Carvalho *et al.*, 2009; Reynolds *et al.*, 2016).

Though remote sensing studies in Brazil have explored a range of agents of forest change, one that has largely escaped investigation is cattle entering forests. Much of Brazil's forest exists within a cattle ranching matrix due to Law 12.651. Because forests are a useful resource for cattle, providing food and shade, cattle entering forests is probably common. The effects of cattle on savannas and forests in South America have been analysed in the field (Durigan *et al.*, 2022; Mazzini *et al.*, 2018; Vieira *et al.*, 2007), but have not been explored using remote sensing, probably because of the difficulty of getting cattle access data for large samples of sites. In a 2024 review of remote sensing studies of forest degradation in the Amazon, cattle are never mentioned among the agents of forest degradation discussed by the authors (Oliveira *et al.*, 2024).

To address these issues in the sustainable intensification and forest impacts of Brazilian beef production at a farm level, I analysed the productivity and legal reserve quality of 22 Brazilian beef farms at the Cerrado–Atlantic Forest border. I tested four groups of hypotheses:

Hypothesis 1: Farms with more fragmented forests have lower remotely sensed forest quality.

This hypothesis was based on Santo-Silva *et al.*'s (2016) finding that light-demanding pioneer tree species are more common in small forest fragments than in mature forest in the Brazilian Atlantic Forest.

Hypothesis 2: Forests to which cattle have access have lower forest quality, both observed on-site and remotely sensed.

This hypothesis was based on findings reviewed by Mazzini *et al.* (2018) that cattle have negative effects on vegetation quality elsewhere in South America.

Hypothesis 3a: Farms that regularly use agrochemicals have higher pasture quality.

Hypothesis 3b: Farms with higher pasture quality have higher productivity.

I tested this pair of hypotheses to assess the possibility of intensifying beef farms in my study region.

Hypothesis 4: Farms with higher productivity have better forest conservation performance.

This hypothesis was based on Koch *et al.* (2019) finding a negative association between deforestation and beef farm productivity in the Brazilian Amazon in municipalities with enforced reductions in deforestation. This finding is likely applicable to my sample of farms as the region from which I sampled has negligible ongoing deforestation.

These hypotheses and their relationships to each other are summarised below in Figure 1.

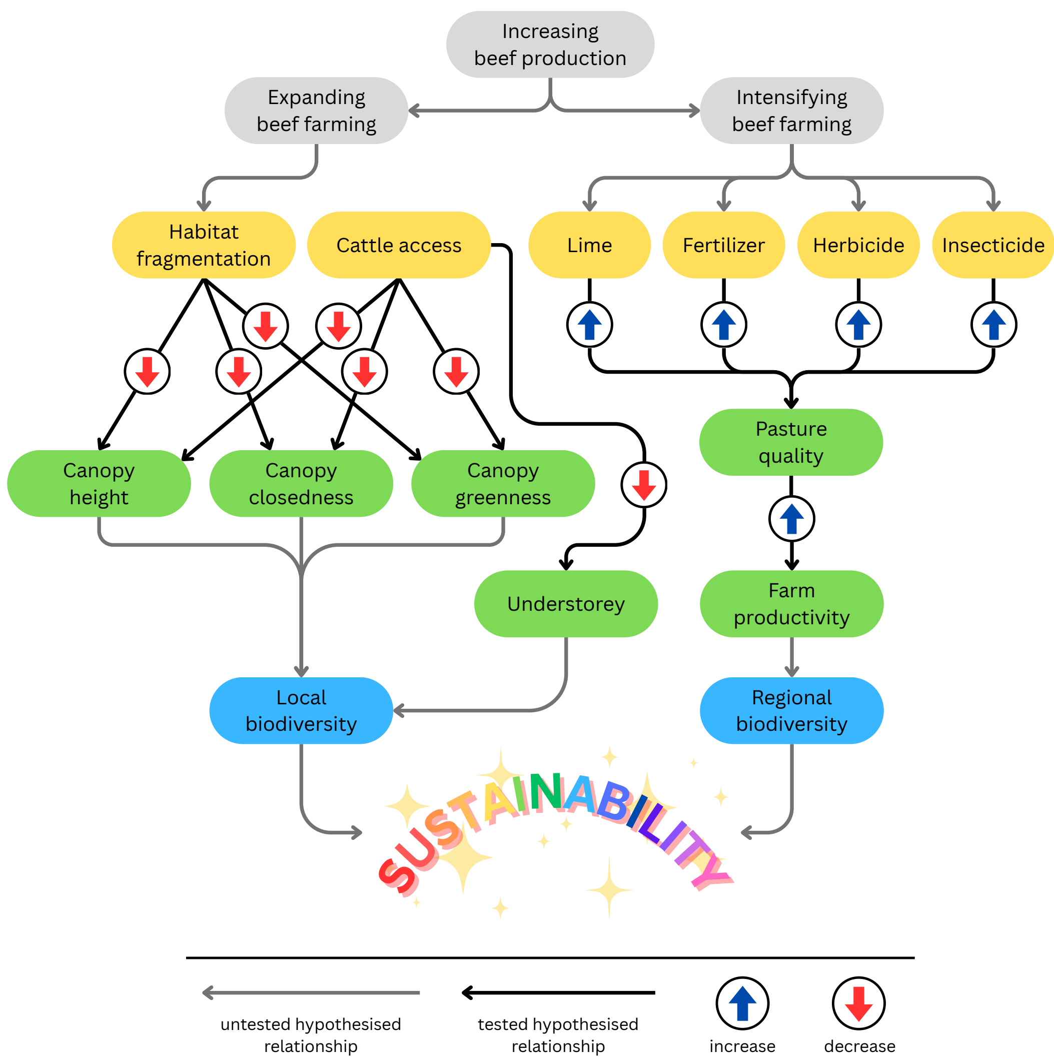

Figure 1. A flowchart describing the conceptual relationship between this study's hypotheses, excluding hypothesis 4. Grey boxes represent economic drivers of the negative effects of Brazilian beef farming on biodiversity. Yellow boxes represent independent variables I measured. Green boxes represent dependent variables I measured. Blue boxes represent the biodiversity outcomes influenced by beef farming.

2. Methods

Overview

To understand how fragmentation and cattle entering legal reserves affect forest quality on Brazilian beef farms, I tested the associations among three forest quality metrics and forest configuration and cattle access. The forest quality metrics were canopy height, image homogeneity, and normalised difference vegetation index (NDVI). All were remotely sensed from farm legal reserves. To assess the possibility of intensifying Brazilian beef farms, I tested the associations between agrochemical use and farm pasture quality, and between pasture quality and farm productivity. Pasture quality was remotely sensed, and agrochemical use and productivity were sampled with an in-person questionnaire. To see whether there was an association between farms' productivity and their conservation performance, I tested for an association between productivity and a conservation performance index. I constructed this index from three conservation performance metrics: total woodland volume, legal reserve area-to-perimeter ratio, and proportion legal reserve cover of the farms.

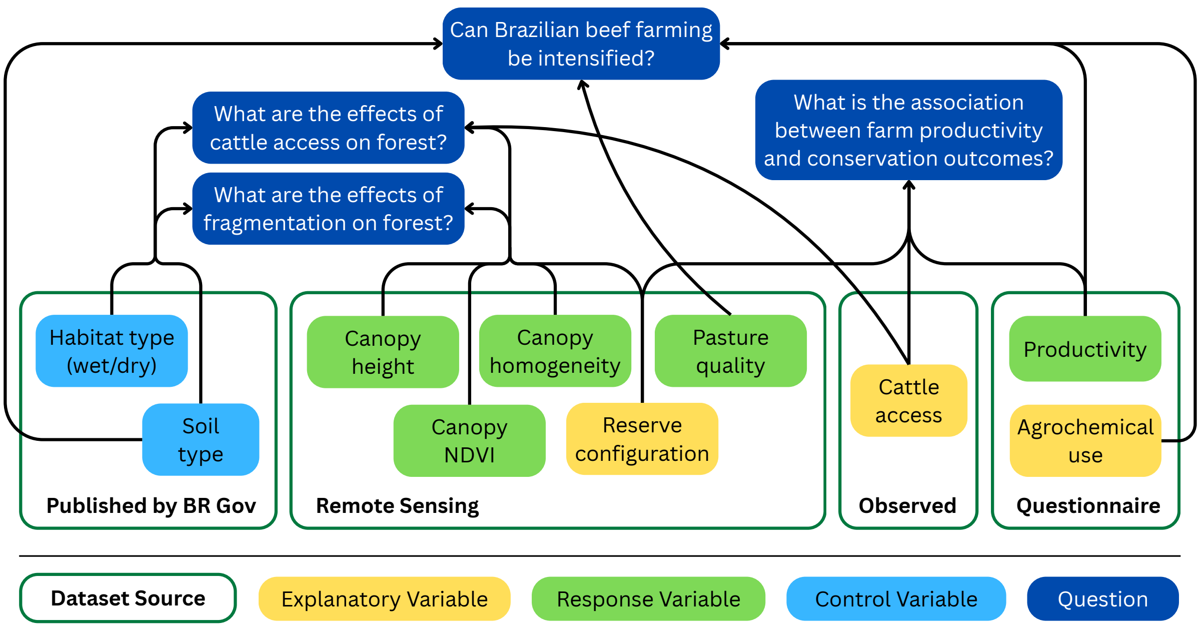

Figure 2. A flowchart summarising the variables measured in this study by which research question they were used for and by how the data were collected.

2.1. Farms Sampled and Study Region

22 beef farms were sampled on an expedition I participated in as part of a collaborative project between the University of Oxford and the University of São Paulo. 18 were in the municipality of Aparecida do Taboado, Mato Grosso do Sul, and 4 were in neighbouring municipalities in the states of Mato Grosso do Sul, São Paulo, and Minas Gerais. The mean declared area of the farms I sampled was 506 hectares; for context, this is 6 times the average UK farm size of 82 hectares (Defra, 2024). None of the farms sampled were smaller than 100 hectares, and the largest were around 1300 hectares (over 15 times the average UK farm).

The study region straddles the boundary between the Atlantic Forest and Cerrado ecoregions and has correspondingly transitional and variable natural vegetation. Consequently, farm legal reserves were almost all forest, ranging from wet evergreen forest along streams to dry semideciduous forest, and marshland rather than savanna or grassland. The primary landcover of the region is pasture for beef production, with *Eucalyptus*, rubber, and sugarcane also being common.

The region was settled in 1948 (IBGE, n.d.) and largely deforested for cattle ranching by at least 40 years ago (MapBiomas, 2024). Deforestation in the region is therefore relatively historic, making it useful for studying the advanced effects of fragmentation on forests.

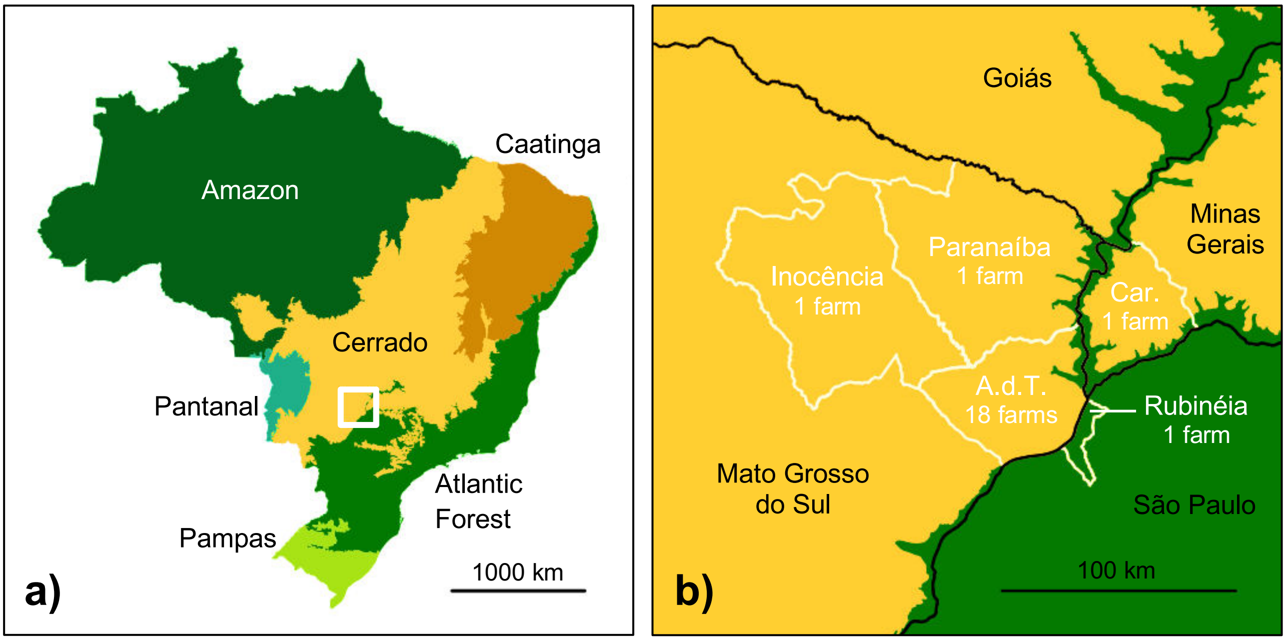

Figure 3. Maps of the study region. (a) is a map of Brazil's ecoregions with a white square around the study region. (b) is a map of the area within the white square in (a), shaded by ecoregion as in (a). In (b), boundaries and names of states are in black, and those of municipalities containing study farms are in white. 1 study farm was in the municipality of Carneirinho (Car.) in Minas Gerais; 1 study farm was in the municipality of Rubinéia in São Paulo; 20 study farms were in Mato Grosso do Sul – 1 in the municipality of Inocência, 1 in the municipality of Paranaíba, and 18 in the municipality of Aparecida do Taboado (A.d.T.). No study farms were in Goiás. To retain anonymity, farm locations are not shown. Ecoregion and political division boundaries are from IBGE.

2.2. Data Collection

2.2.1. Questionnaire and On-Site Observation

Farm agrochemical use data and data to calculate farm productivity were collected with a questionnaire. Questionnaires were filled out in-person with either the farm owner or a farmworker from May to August 2024. The data were collected with the consent of the farm owner, and the questionnaire was approved beforehand by the University of Oxford's Central University Research Ethics Committee (CUREC, reference: SOGE CIA23 18) and by the Brazilian government's Commission of Public Ethics (CEP) and National Commission of Ethics in Research (CONEP) via Plataforma Brasil. A collaborating veterinarian who worked in the region recruited a diverse and representative sample of farms and assisted with questionnaire data collection.

The use of four types of agrochemicals was recorded – lime, fertiliser, herbicide, and insecticide – as well as whether the agrochemical was used recurrently (annually or more frequently) or in a one-off application within the last 12 months (for example, for isolated insect pest outbreaks or resowing pastures). I only analysed recurrent agrochemical use, as the period of recorded one-off uses did not cover all of 2023, the latest year for which pasture quality data was available.

I calculated farm productivity as total cattle liveweight gain per hectare of pasture per year. A farm's yield of beef – the final product – cannot be easily calculated, as most farms form part of a complex supply chain involving three stages of raising cattle: (1) breeding, where cows and bulls have calves which are raised until weaned; (2) rearing, where weaned cattle are raised until either sexual maturity, if they are to be used for breeding, or until fattening, if they are to be slaughtered; and (3) fattening, where cattle are fed to gain weight quickly over a short period before slaughter (see Figure 4). Different farms host different combinations of breeding, rearing, and fattening, relying on other farms for the stages they do not host. Farms might rear cattle for breeding, fattening, or both in a ratio that varies between farms, and farms might rear or fatten only males, only females, or both in a ratio that varies between farms. This complexity, alongside the variability of who trades with whom, for example in auctions, makes it difficult to quantify most farms' relative contribution to some final amount of beef.

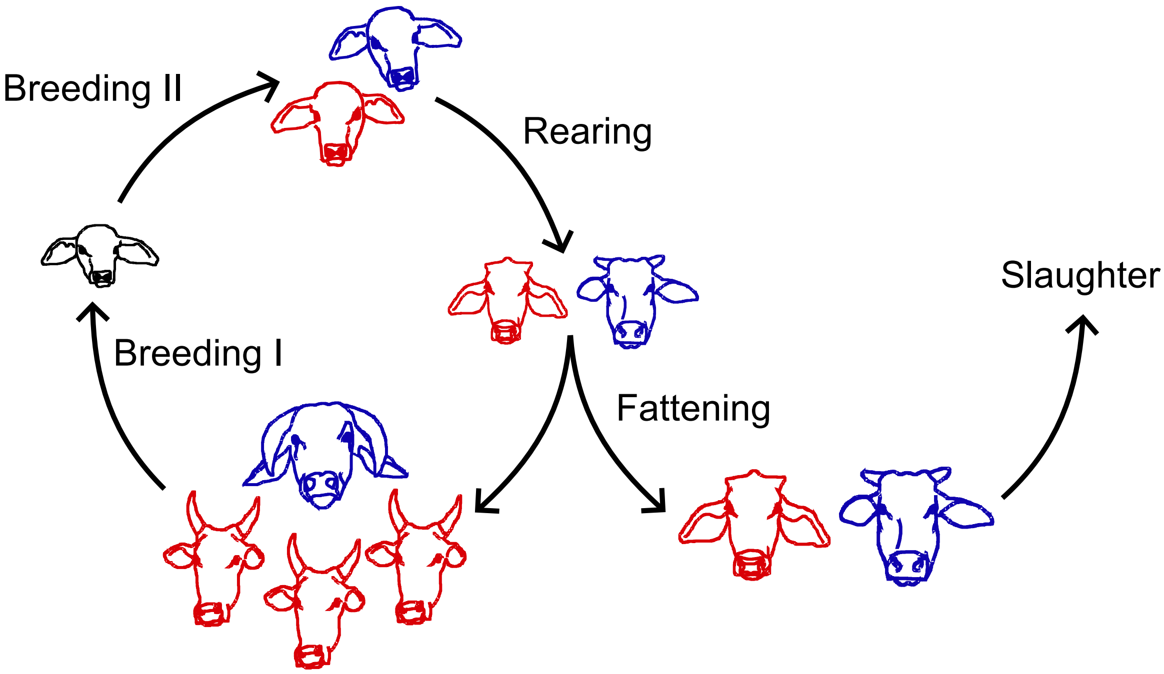

Figure 4. A diagram of the full beef production cycle up to slaughter. Breeding I – cows and bulls reproduce; breeding II – calves are raised until they are weaned; rearing – weaned cattle are raised either until sexual maturity to be used in breeding or until fattening to be slaughtered; fattening – cattle are fattened for slaughter.

To calculate farm productivity, the questionnaire asked for data describing farms' current cattle populations and cattle inputs and outputs in the last year. This data consisted of groupings of cattle by sex and age, with the number of head and average liveweight per head of each grouping. Farmers also declared the area of their farm and the area of pasture on their farm in the questionnaire, as well as cow pregnancy rate and calf survival rate on breeding farms. This is the formula used for liveweight gain per hectare per year (productivity):

$$P_i = \sum_{j \in C_i} \frac{G_j N_j}{A_i T_j}$$

where:

P_i = annual productivity of farm i (kg liveweight ha^{-1} yr^{-1})

C_i = set of beef production cycles on farm i

G_j = mean liveweight gain per animal over cycle j (kg liveweight)

N_j = number of animals in cycle j

A_i = pasture area of farm i (ha)

T_j = length of cycle j (yr)

Cycles here are the production stages hosted on a farm (see Figure 4), differentiated between males and females for rearing and fattening. I assumed cycles happened back-to-back, and if the cycle parameters were not obvious from the input and output data, I assumed the current animal population represented a steady state. For breeding cycles, the current number of calves cannot be taken as representative of a steady state, as there may still be unborn calves in their pregnant mothers, and calves may die before being weaned. Instead, I used the following formula:

$$\text{Final no. weaned calves} = \text{No. breeding cows} \times \text{Pregnancy rate} \times \text{Calf survival rate}$$

Breeding cows and bulls gain negligible weight once full-grown (Goldberg & Ravagnolo, 2015), so I assumed cows' and bulls' liveweight gain per cycle to be 0.

Cattle access data was collected by on-site observation by recording for each farm whether its legal reserves were or were not fenced off from cattle as a binary variable.

2.2.2. Remote Sensing

Variables and Datasets

I acquired canopy height data from a global 1 metre resolution canopy height map made by Tolan *et al.* (2024) and published on Google Earth Engine. The map was produced with a model trained on several sources of LiDAR (laser scanning) imagery from 2009 to 2020. I used canopy height as a forest quality metric because of its association with biodiversity and carbon storage. Canopy height has been found to have a positive association with the diversity of several animal taxa (Davies & Asner, 2014) as well as with aboveground biomass of forests (Fischer *et al.*, 2019), and therefore with carbon storage and sequestration. In the Cerrado, belowground carbon stocks are estimated to be 6.6 times greater than aboveground stocks (Terra *et al.*, 2023), but unfortunately, I was not able to measure or proxy belowground carbon storage for the farms I sampled.

Homogeneity calculated with the grey level co-occurrence matrix (GLCM) was used as a measure of canopy closedness. The GLCM is a matrix that describes the texture of a greyscale image by describing the spatial relationship of pixels with the same value (Haralick, 1979). Different image texture statistics can be calculated from the GLCM, including homogeneity, a measure of the similarity of neighbouring pixels' values. Forest is much darker than grassland in a greyscale panchromatic (full spectrum of visible colour) image from above, so points within an area of contiguous forest or grassland will have high homogeneity, whereas points along the interface of forest and grassland, and points in discontinuous or patchy forest, will have low homogeneity (see Figure 5). GLCM statistics of satellite images have been found to be significant predictors bird species diversity across a range of habitats in North America (Farwell *et al.*, 2021; St-Louis *et al.*, 2006). The images I used to calculate homogeneity were taken by the Landsat 8 satellite. I used

Landsat 8's panchromatic band – band 8 – which has the advantage of having a higher resolution than the satellite's other image bands, at 15 m instead of 30 m. To calculated homogeneity, I used the "GLCMTextures" R package, quantising the satellite image pixel values to 16 levels and using a 3 by 3 pixel window around each pixel to calculate pixel homogeneity values.

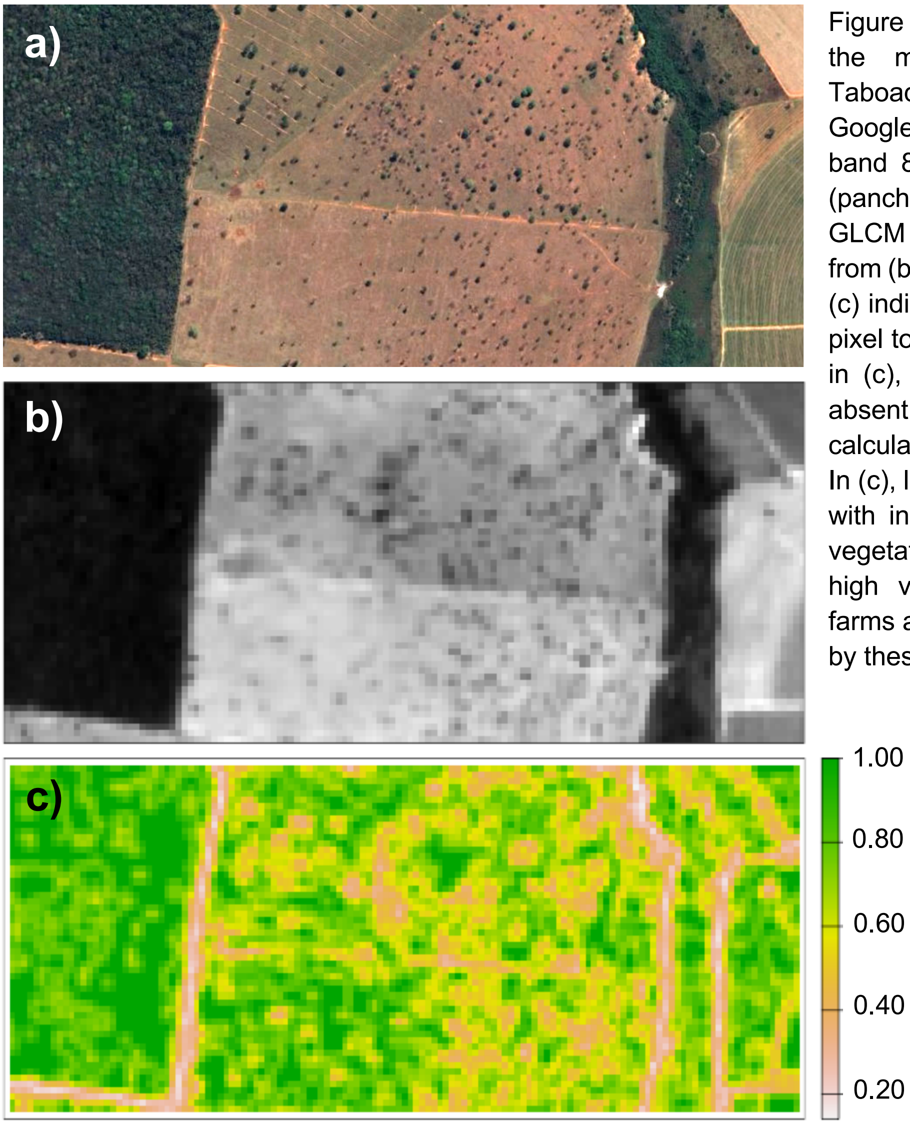

Figure 5. 3 images of the same place in the municipality of Aparecida do Taboado, Mato Grosso do Sul. (a) is a Google Earth image. (b) is a Landsat 8 band 8 image from 8th January 2024 (panchromatic, 15 m resolution). (c) is a GLCM homogeneity image calculated from (b). Greater homogeneity values in (c) indicate greater similarity of a given pixel to adjacent pixels in (b). Note that in (c), the outermost line of pixels is absent, as adjacent pixels with which to calculate homogeneity are out of frame. In (c), low homogeneity values coincide with interfaces between low and high vegetation and areas of mixed low and high vegetation. None of the study farms are included in the area captured by these images.

I used NDVI as a measure of vegetation greenness. NDVI is a ubiquitous remotely sensed metric that detects green vegetation, used to monitor vegetation cover and quality and terrestrial primary production. NDVI is the following ratio of near-infrared (NIR) to red light (Rouse *et al.*, 1974):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{red}}{\mathrm{NIR} + \mathrm{red}}$$

Green vegetation absorbs red light and reflects NIR, giving a high NDVI value. I used band 4 (red) and band 5 (NIR) of Landsat 8 satellite imagery to calculate NDVI, processing them in QGIS to generate an NDVI raster image.

I calculated forest perimeter-to-area ratio to measure forest configuration and therefore fragmentation. Among measures of habitat configuration, perimeter-to-area ratio captures both shape complexity and extent of habitat: a habitat will have a greater perimeter-to-area ratio if it has a more complex shape and if it covers a smaller area. Habitat fragmentation results in three changes to habitat configuration: greater patch shape complexity, smaller patch size, and greater distance between patches. This final configurational change, increased patch distance, is not captured by perimeter-to-area ratio; however, patch distance is more relevant at a landscape scale than a local scale. The goal of this study is to examine farm-level productivity and conservation performance. When taking a single farm as a frame of reference, nearby habitat patches on different farms are not considered within patch distance, potentially giving a false representation of patch configuration.

The pasture quality data I used were produced by the Image Processing and Geoprocessing Laboratory (Lapig) at the Federal University of Goiás (UFG) and published on the MapBiomas platform. Lapig's pasture quality data cover all of Brazil and are based on enhanced vegetation index (EVI) – NDVI corrected for atmospheric effects (Huete *et al.*, 2002) – normalised for seasonal variation in pasture greenness. The data I used were of 2023 pasture quality.

Forest Geometries and Data Extraction

To detect forest patches and their geometries, I used Tolan *et al.*'s (2024) canopy height dataset alongside Brazilian government shapefiles. Whole farm, legal reserve, and APP boundaries are documented for every registered farm in Brazil by the Brazilian government for its Rural Environmental Register (CAR). These boundaries are free to download as shapefiles, which I did for each of the 22 study farms. Within these farms, I detected forest patches as areas with a canopy height greater than 0 m that overlap with farm legal reserve and APP shapefiles, and that have an area greater than 1000 m^2. Government shapefiles did not correspond to forest patches accurately enough to use alone at a single-farm scale, whereas the canopy height data are incredibly precise (1 m resolution) and accurate. Tree cover on farms in the study region is typically either trees and small groves in pasture, forest patches in legal reserves and APPs, or forestry plantations. Forest patches and plantations were overwhelmingly, if not all, larger than 1000 m^2, so this threshold excludes trees in pasture. Forestry plantations were excluded as they do not fall within legal reserves or APPs. Due to the coastline paradox, the high resolution of the canopy height map had the potential to greatly exaggerate the perimeters of detected forest patches which had irregular, bumpy outlines at a small scale. To prevent this problem and make comparing perimeters across forests reliable, I standardised forest geometries' outlines to have a minimum distance of 0.00005 coordinate degrees between nodes using the "simplifyGeom" function in the "terra" R package. The correspondence between coordinate degrees and overland distance changes with latitude and longitude, but the variation in this correspondence between farms is small because of how close together they are.

Remotely sensed variables, excluding pasture quality, were extracted for the forest geometries generated in the manner described above. Perimeter and area were properties of these geometries, and the mean of canopy height, heterogeneity, and NDVI were taken for the portions of the respective maps within the geometries. Mean pasture quality was taken from within the geometry of the CAR whole-farm shapefile of each farm.

For heterogeneity and NDVI, I chose Landsat 8 images based on: (a) the month they were taken in, (b) whether they included the farms in my study, and (c) their cloud cover. I chose images in January and August of 2024, as most of my fieldwork was conducted in August 2024, which is at the height of the dry season, and January 2024 is the height of the previous wet season. The dry season in the study region is pronounced, and many woody species are dry season deciduous, so it is important to analyse the two seasons separately. Because no single image in January or August 2024 captured all 22 farms, I used two images taken on consecutive days for each month that together contained all the farms. Additionally, I had to choose pairs of images in which clouds did not obscure the farms. Given all these considerations, I chose images taken on the 7th and 8th of January 2024 and the 18th and 19th of August 2024.

2.2.3. Control Variables

To account for environmental variation among different forests and different pastures, I included soil type and habitat type – dry or wet – as control variables. I used a soil type map of Brazil by the Brazilian Agricultural Research Corporation (Embrapa) published in 2001 by the Brazilian Institute of Geography and Statistics (IBGE). The farms in this study covered only two soil types, tropical red earth and tropical red clay, referred to locally and henceforth as sandy soil and clay soil, respectively. I observed in the field that forest along watercourses consisted of a different plant assemblage and was greener and lusher than other forest. Because APPs are designated along watercourses, I classified forest patches that overlapped with the APP shapefiles as wet and other patches as dry. I included soil type as a control variable for both forests and pasture, but habitat type only for forest, as it was impossible to extract for pasture with the method I used.

Table 1. A table of all the datasets used in this study. In the "Resolution/Scale" column, resolutions are given in meters (m) and scales are given as ratios (x:y). Information for cells marked with an asterisk (*) was not available. The full names of organisations that are given as acronyms in this table, and are not written in full in the main text or in the bibliography, are as follows: NASA is the National Aeronautics and Space Administration, a US government agency; USGS is the United States Geological Survey, a US government agency; and WRI is the World Resources Institute.

Dataset	Extent	Variable	Resolution / Scale	Year	Author	Publisher	Year published
Landsat 8 satellite imagery	World	NDVI	30 m	2024	NASA & USGS	USGS	2024
	World	Homo-geneity	15 m	2024	NASA & USGS	USGS	2024
Pasture quality map	Brazil	Pasture quality	10 m	2023	Lapig, UFG	MapBiomas	2024
Canopy height map	World	Canopy height	1 m	2009-2020	Tolan *et al.*	Meta & WRI	2024
Soil type map	Brazil	Soil type	1:5000000	–	Embrapa	IBGE	2001
APP shapefiles	Brazil	Habitat type	*	*	CAR	CAR	*

2.2.4. Farm Conservation Performance

The four aspects of conservation performance I assessed were total woodland volume, legal reserve area-to-perimeter ratio, proportion legal reserve cover, and cattle access to legal reserves. The first, total woodland volume, was the total tree cover of a farm, including trees outside of legal reserves, multiplied by the average canopy height across the whole farm. I chose this variable as a proxy for aboveground carbon storage. The second, legal reserve area-to-perimeter ratio, is the inverse of perimeter-to-area ratio, and is likewise an indicator of fragmentation of protected forest. I used area-to-perimeter ratio instead of perimeter-to-area ratio so the variable would be positively associated with conservation performance. The third, proportion legal reserve cover, measures the relative extent of protected land and compliance with Law 12.651. It is not necessarily illegal to have less than 20% of one's farm under native vegetation, so long as one maintains 20% across all of one's properties. Consequently, farmers may offset their properties' noncompliance by buying land elsewhere with sufficient native vegetation. The fourth, cattle access to legal reserves, is another aspect of compliance with Law 12.651, and potentially an indicator of forest health (see results below).

A composite conservation performance index was constructed from the first three variables. I measured the correlation between these variables with Cronbach's alpha to assess the index's internal consistency. The three variables were each standardised to a scale from 0 to 1 by dividing each value by the maximum value for that variable. The three variables were then summed, giving a maximum possible conservation performance index value of 3 and minimum of 0.

2.3. Statistical Analysis

To analyse the association of my variables of interest, I constructed a linear model for each research sub-question (see Table 2). To determine association between the response variable of each sub-question and its possible explanatory variables, I performed backward stepwise model selection, using the Akaike Information Criterion (AIC) to compare goodness of fit between candidate models, and yielding one final, best-fitting model for each response variable.

I performed two separate analyses each for canopy height, homogeneity, and NDVI. In one, each datapoint corresponds to the total legal reserve of one farm, and in the other, each datapoint corresponds to an individual forest patch. The association between forest quality and fragmentation might be different between the farm and patch levels. To account for possible association between patches on the same farm, the patch-level models were mixed-effects models with farm identity as a random effect. The habitat type control variable was incorporated differently into farm-level and patch-level models: for farm-level models, it was the proportion of the total legal reserve area within APPs, as a continuous variable between 0 and 1; and for patch-level models, it was whether or not a patch fell within an APP, as a binary variable. I used the "lme4" R package to construct mixed models, the "performance" R package to calculate mixed model R^2 values, and the "afex" R package to calculate fixed effect p-values.

Table 2. A table of all the analyses performed in this study. Each row represents one linear model with a maximum number of explanatory variables. For each analysis, this maximal model was constructed, then variables were removed until a best-fitting model (per the Akaike Information Criterion) was achieved. "Homog." = homogeneity; CPI = conservation performance index.

Hypothesis	Response variable	Non-control explanatory variables	Control variables	Random effects
1 & 2	Mean farm canopy height	Perimeter/area; Cattle access	Soil type; Proportion wet	–
	Mean patch canopy height	Perimeter/area	Soil type; Habitat type (wet/dry)	Farm
	Mean farm January homog.	Perimeter/area; Cattle access	Soil type; Proportion wet	–
	Mean patch January homog.	Perimeter/area	Soil type; Habitat type (wet/dry)	Farm
	Mean farm August homog.	Perimeter/area; Cattle access	Soil type; Proportion wet	–
	Mean patch August homog.	Perimeter/area	Soil type; Habitat type (wet/dry)	Farm
	Mean farm January NDVI	Perimeter/area; Cattle access	Soil type; Proportion wet	–
	Mean patch January NDVI	Perimeter/area	Soil type; Habitat type (wet/dry)	Farm
	Mean farm August NDVI	Perimeter/area; Cattle access	Soil type; Proportion wet	–
	Mean patch August NDVI	Perimeter/area	Soil type; Habitat type (wet/dry)	Farm
3a	Mean pasture quality	Lime use; Fertiliser use; Herbicide use; Insecticide use	Soil type	–
3b	Productivity	Mean pasture quality	Soil type	–
4	CPI	Productivity	–	–
	Legal reserve cattle access	Productivity	–	–

3. Results

3.1. Forest Configuration and Quality

The canopies of forests with a greater perimeter-to-area ratio were shorter, more open (lower image homogeneity), and less green (lower NDVI) (see Figure 7 and Table 3). This association was true in both January (wet season) and August (dry season), and at both a farm level and a forest patch level, except for the combination of NDVI at the farm level in August.

3.2. Cattle Access and Forest Quality

All forest patches fenced off from cattle had dense understorey throughout, whereas all forest patches to which cattle had access had a low, simple understorey, either throughout or alongside patches of dense understorey (see Figure 6).

The association between cattle access and NDVI was somewhat significant: $p = 0.06$ in January and $p = 0.07$ in August. I found no association between cattle access and canopy height or homogeneity.

Figure 6. A photograph of the understorey of an evergreen forest in Aparecida do Taboado, Mato Grosso do Sul. To the left of the red dotted line, cattle are excluded by a fence, and the understorey consists of forbs, ferns, shrubs, and lianas. To the right of the red dotted line, cattle have access, and the understorey consists only of forbs.

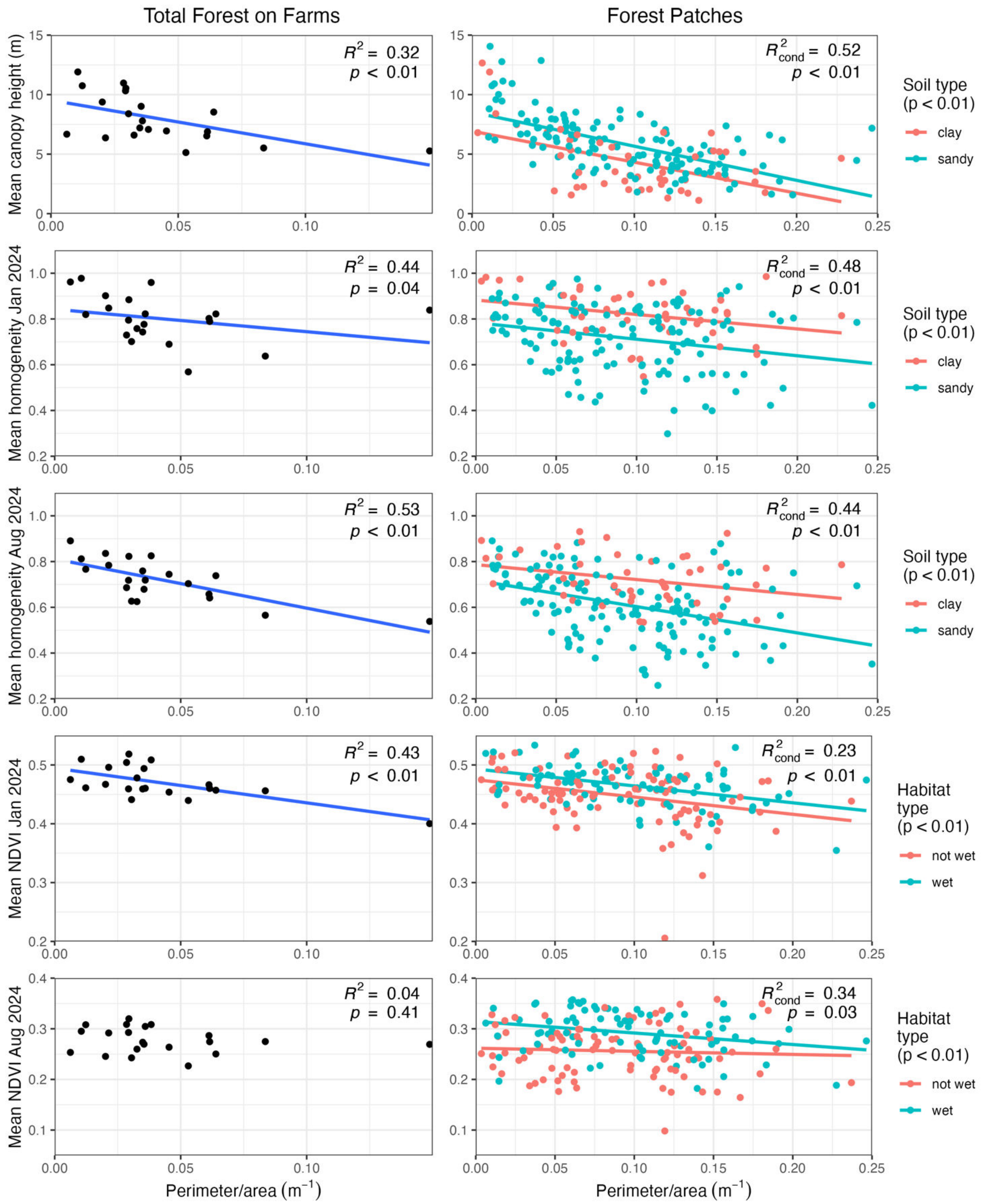

Figure 7. Scatterplots of forest quality variables against perimeter-to-area ratio. In the left-hand column, each datapoint represents the total legal reserve forest area on one study farm, and in the right-hand column, each datapoint represents one forest patch in a study farm legal reserve. Lines through points are linear regression lines, the absence of which indicates an insignificant association between perimeter-to-area ratio and the *y*-variable. In plots where a control variable was significantly associated with the *y*-variable, points are coloured by the control variable. R^2 values are calculated from the coefficient of multiple correlation of the whole model (taking both explanatory and control variables into account). R^2_{cond} is the conditional R^2 of mixed models, which takes both fixed effects and random effects into account. The *p*-values on plots are for perimeter-to-area ratio as a term in the model of the *y*-variable, and the *p*-values in plot legends are for the stated control variable as a term in the model of the *y*-variable.

3.3. Intensifying Beef Farming

Farms that used fertiliser annually and farms that used herbicide annually had higher pasture quality. Farms that used insecticide and lime did not have higher pasture quality, though only one farm used lime annually (see Figure 8).

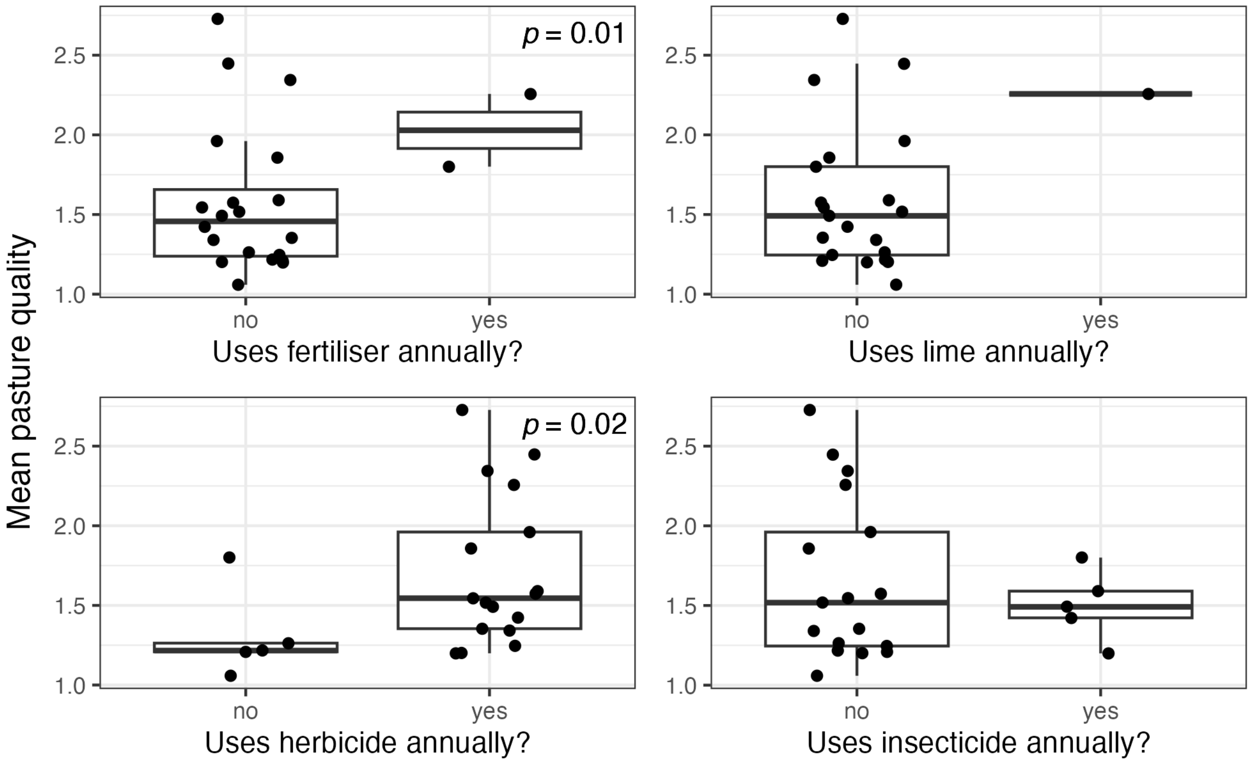

Figure 8. Scatterplots of mean pasture quality against agrochemical use. Each datapoint represents one farm. The *p*-values for fertiliser use and herbicide use are for fertiliser use and herbicide use, respectively, as terms in the same linear model of mean pasture quality, which also includes soil type as a term. The plots for lime use and insecticide use have no *p*-values, as both variables were eliminated as model terms during backward stepwise model selection, and were insignificant ($p > 0.1$) before elimination.

I found no association between pasture quality and farm productivity (see Supplementary Figure 1). Productivity ranged from 30 to 549 kg liveweight ha $^{-1}$ yr $^{-1}$, with a mean of 189. This is about 1.5-fold greater than my estimate of the average Brazilian beef farm productivity in 2024, 129 kg liveweight ha $^{-1}$ yr $^{-1}$ (see footnote[1]).

[1] Calculated from the following statistics:

- Total weight of slaughtered cattle carcasses in Brazil in 2024 = 10,237,583,549 kg deadweight yr $^{-1}$ (IBGE, 2025)
- Total area of pasture in Brazil in 2023 (assumed for 2024) = 164,574,066 ha (MapBiomas, 2024);
- Average male and female cattle carcass yield 2010 in RS, Brazil (assumed for rest of Brazil and 2024) = 46.8% and 49.5%, respectively.

3.4. Productivity and Conservation Performance

I found no association between productivity and conservation performance index (see Figure 9). Instead, who owns the farm seems to be associated with conservation performance: there were 4 farmers who owned more than one farm in the sample, of which 3 have farms with a similar conservation performance index (farmers A, B, and C in Figure 9). The index's component variables – total woodland volume, legal reserve area-to-perimeter ratio, proportion legal reserve cover – were correlated (see Supplementary Figure 2): Cronbach's alpha was 0.772 (where 1 represents perfect reliability). The average farm was 11% legal reserve, compared to Law 12.651's requirement of 20%. Below 20% legal reserve cover is not illegal if reserve areas are owned off-farm. Farms with legal reserves fenced off from cattle had higher productivity (p = 0.04).

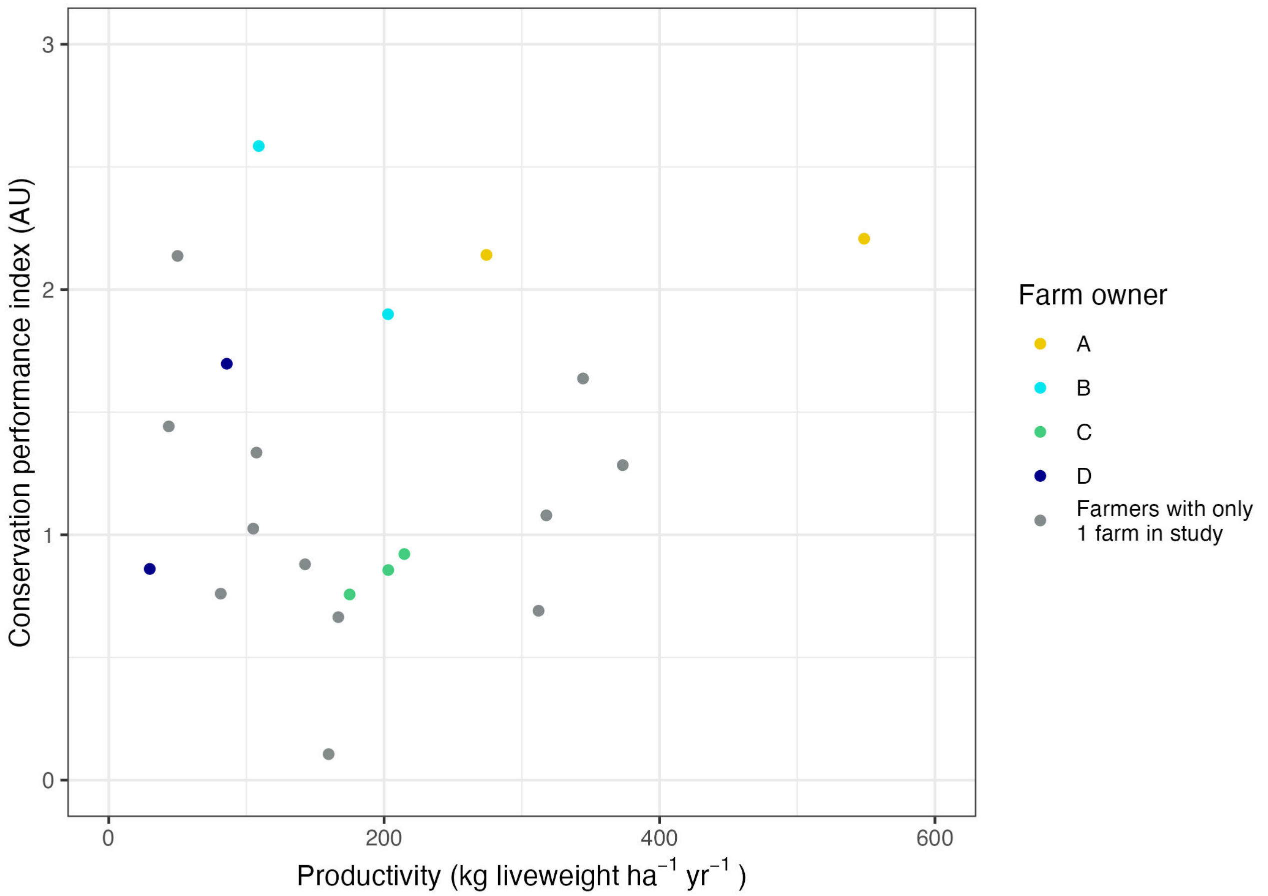

Figure 9. A scatterplot of farm conservation performance index (in arbitrary units) against productivity, coloured by farm owner. Farm owners are anonymised. Those with only one farm in the study sample are grouped together. Pearson's r = 0.17.

Table 3. A table of significance results of all the models in my analysis. 0 indicates an insignificant association ($p > 0.1$ or removed during model selection), while other symbols indicate a positive (**+**), negative (**−**), or other (*) significant association. 1 such symbol means $0.05 < p < 0.1$; 2 such symbols mean $0.01 < p < 0.05$; and 3 such symbols mean $p < 0.01$. “NA” indicates that the association between an explanatory variable and a response variable was not tested. “Hom.” is homogeneity, and “CPI” is conservation performance index. For the full table containing *p*-values and model coefficients, see Supplementary Table 1.

Response variables	Explanatory variables				
	Perimeter/area	Cattle access	Proportion wet, or habitat type	Soil type	
Canopy height (farm)	− − −	0	0	0	
Canopy height (patch)	− − −	NA	0	* * *	
January hom. (farm)	− −	0	*	* * *	
January hom. (patch)	− − −	NA	0	* * *	
August hom. (farm)	− − −	0	0	0	
August hom. (patch)	− − −	NA	0	* * *	
January NDVI (farm)	− − −	−	0	0	
January NDVI (patch)	− − −	NA	* * *	0	
August NDVI (farm)	0	−	0	0	
August NDVI (patch)	− −	NA	* * *	0	
	Lime	Fertiliser	Herbicide	Insecticide	Soil type
Pasture quality	0	+ +	+ +	0	* * *
	Pasture quality		Soil type		
Productivity	0		0		
	Productivity				
CPI	0				
	Cattle access				
Productivity	+ +				

4. Discussion

Brazilian beef farming is the biggest driver of deforestation, making it critical to find ways of producing beef in Brazil with the least impact on forests and climate. I found evidence that forest management on farms, namely legal reserve configuration and fencing against cattle, has significant implications for both biodiversity and carbon. Evidence for the feasibility of sustainable intensification was mixed. Though agrochemical use was associated with higher pasture quality, this did not seem to translate into greater productivity, and I found no trade-off between farms' productivity and conservation performance.

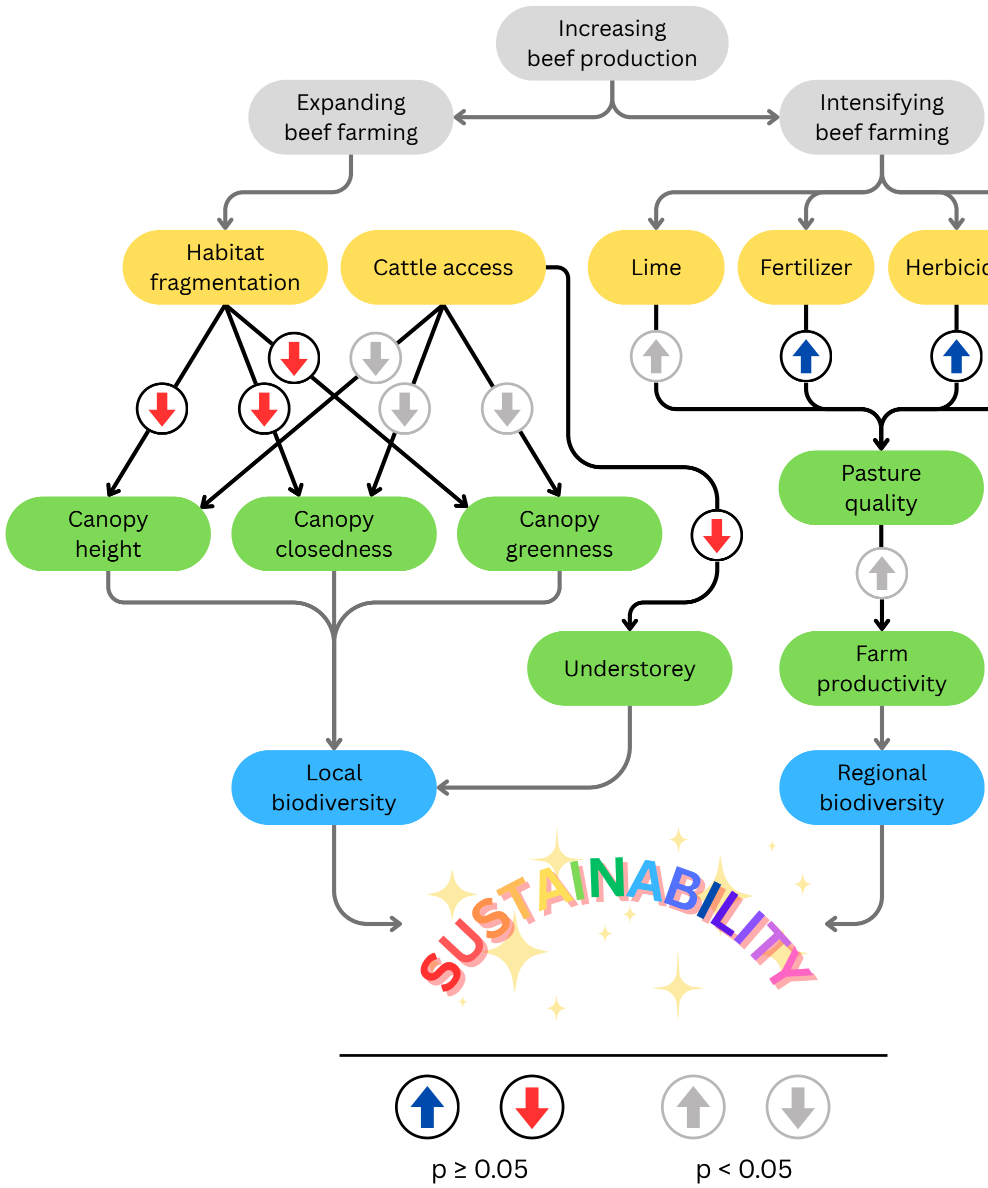

Figure 10. A flowchart based on Figure 1 summarising the conceptual relationship between this study's findings, excluding those regarding farm conservation performance index. Hypothesised associations are shown in grey if insufficient evidence for them was found, and in colour if significant supporting evidence was found.

My finding that forest with a greater perimeter-to-area ratio was shorter, more open, and less green has implications for carbon storage, and likely also for biodiversity. Forests with shorter, more open canopies have a lower aboveground biomass (Fischer *et al.*, 2019), and thus likely less aboveground carbon storage. More fragmented forests being shorter, more open, and less green could be explained by a variety of factors, from different plant species composition to reduced ecosystem functioning. More fragmented forests might contain more pioneer species (Santo-Silva *et al.*, 2016), likely making them shorter and more open. Fragmentation has been linked to reduced ecosystem functioning through two diverse groups of processes: loss of functionally important species and changed environmental conditions (Liu *et al.*, 2018). An example of the former group of processes is the association of fragmentation with severely reduced diversity of insectivorous and frugivorous bird species (Bregman *et al.*, 2014; Peter *et al.*, 2015), which are in turn associated with reduced quality of herbivore control (Peter *et al.*, 2015) and seed dispersal (García & Martínez, 2012), respectively, two essential ecosystem services for plants (Marquis & Whelan, 1994; Plue & Cousins, 2018). An example of the latter group of processes is reduced microclimate buffering at tropical forest edges, an edge effect which has been found to penetrate up to 20 m into forests, and which naturally affects forests with greater perimeter-to-area ratio of patches more severely (Ewers & Banks-Leite, 2013). Regardless of the drivers of reduced forest quality and their implications for biodiversity, shorter, more open, and less green forests likely harbour less biodiversity. Shorter forests tend to have lower vertical structural complexity and more open forests tend to have lower horizontal structural complexity (Fischer *et al.*, 2019), both associated with lower biodiversity (Davies & Asner, 2014; MacArthur & MacArthur, 1961). Additionally, NDVI has been found to be positively associated with bird diversity at local and regional scales elsewhere in South America (Nieto *et al.*, 2015). My results strongly suggest that it is better for biodiversity conservation and carbon storage to have farm legal reserves in larger, more simply shaped patches.

I found that cattle access to legal reserves has a strong, negative effect on below-canopy vegetation structure, making it likely that cattle access is detrimental to both animal and plant diversity in legal reserves. To conserve biodiversity effectively, it is evidently critical that beef farmers fence their legal reserves. I found no evidence for an effect of cattle access on forest canopy; my below-canopy observations suggest that the association detected between cattle access and NDVI is likely due to differences in the understorey rather than the canopy. There was therefore a large discrepancy in the detectability of forest ecological condition between field observations and remote sensing. I found that sub-canopy vegetation structure can vary drastically with little to no detectable difference from above. Remote sensing of sub-canopy vegetation is becoming more sophisticated with a combination of LiDAR and statistical methods (Jarron *et al.*, 2020), though caution must evidently be exercised when inferring forest condition from less sophisticated conventional canopy-only methods.

The association found of annual fertiliser and herbicide use with higher pasture quality is likely causal (Parfitt *et al.*, 2010; Pereira *et al.*, 2018). Insecticide may have shown no association because its positive effect on pasture quality is balanced by the pastures it is used on being of low quality due to insect pests, such as termites and caterpillars. Contrary to my hypothesis, pasture quality was not associated with productivity, though the relationship between the two is unlikely to be straightforwardly linear. While higher pasture quality can be expected to enable higher productivity, farmers can only maximise productivity by optimising the efficiency of grazing, for example by optimising stocking density and pasture rotation. Excessive grazing due to high stocking densities can drive pasture quality down (overgrazing) (Costa & Rehman, 1999; Pulido *et al.*, 2018), while low stocking densities and leaving pasture ungrazed for too long can waste grass growth (Fales *et al.*, 1995; Macdonald *et al.*, 2008). How successfully farmers efficiently allocate resources will vary between farms due to a variety of factors. Among the study farms, there was wide variation in productivity and therefore efficiency, which might explain the lack of association between pasture quality and productivity.

There is no evidence for a farm-level association between productivity and conservation performance in my sample of farms. This contrasts with studies such as those by Carvalho *et al.* (2020) and Marcilio-Silva *et al.* (2018), which found productivity to trade off with forest conservation and tree diversity, respectively, while corroborating Koch et al. (2019). None of these studies were in the Cerrado ecoregion and none were at a farm scale, unlike this study. From the farms in my sample, it appears to be possible for Brazilian beef farms to simultaneously intensify and both store carbon and conserve biodiversity effectively; however, my sample might not be representative of, for example, younger farmlands nearer the deforestation frontier. Furthermore, there is evidence of intensification driving agricultural expansion and therefore deforestation by making farms more profitable, in Brazil (Garrett *et al.*, 2018), elsewhere in Latin America (Garrett *et al.*, 2021), and in other parts of the world (Lim *et al.*, 2024).

Only two of the farms sampled in this study met the 20% legal reserve requirement of Law 12.651. This is legal if farmers own adequately compensatory off-site legal reserves, which is likely the case for the farms in this sample. This finding demonstrates a shortcoming of Law 12.651, where regions deforested before the introduction or enforcement of the Forest Code are allowed to preserve less native vegetation, provided landowners can compensate by buying natural areas elsewhere.

My finding that farms with fenced reserves are more productive is unlikely to be causal; rather, it may be that more productive farms are more profitable and can therefore better afford to maintain fencing around legal reserves.

Because of the complexity of beef farming systems, the data were widely scattered and the models constructed could not capture all the variation in the data. In future work, single-farm lifecycle assessments and more direct measures of biodiversity, ecosystem functioning, and carbon storage could elucidate specific components of farms' environmental impacts more clearly. There is also a need to bring a farm-level approach for studying farm environmental impacts nearer to Brazil's deforestation frontier, and to investigate the nature of the link between increasing efficiency of farms away from the frontier, such as those in my study region, and changing frontier deforestation dynamics. Additionally, owing to the Cerrado's considerable belowground carbon storage (Terra *et al.*, 2023), future work is needed to relate legal reserve configuration and management to belowground biomass and carbon

5. Conclusion

Remotely sensed evidence was found suggesting that forests in Brazilian beef farm legal reserves with more complex configuration are of lower quality for conservation and carbon storage. A considerable negative impact of cattle access to forests on below-canopy forest quality was observed, while above-canopy detectability of this impact was inconsistent. Fertiliser use and herbicide use – key practices in pasture intensification – were found to be positively associated with pasture quality. However, pasture quality was not in turn associated with productivity, suggesting that farmers were not always able to make full use of improved pasture. No evidence was found for an association between farms' productivity and conservation performance. Conserving forest in simpler configurations and excluding cattle from forests is evidently important for effective forest conservation on beef farms, and beef farms seem to be able to conserve biodiversity and store carbon as effectively regardless of productivity.

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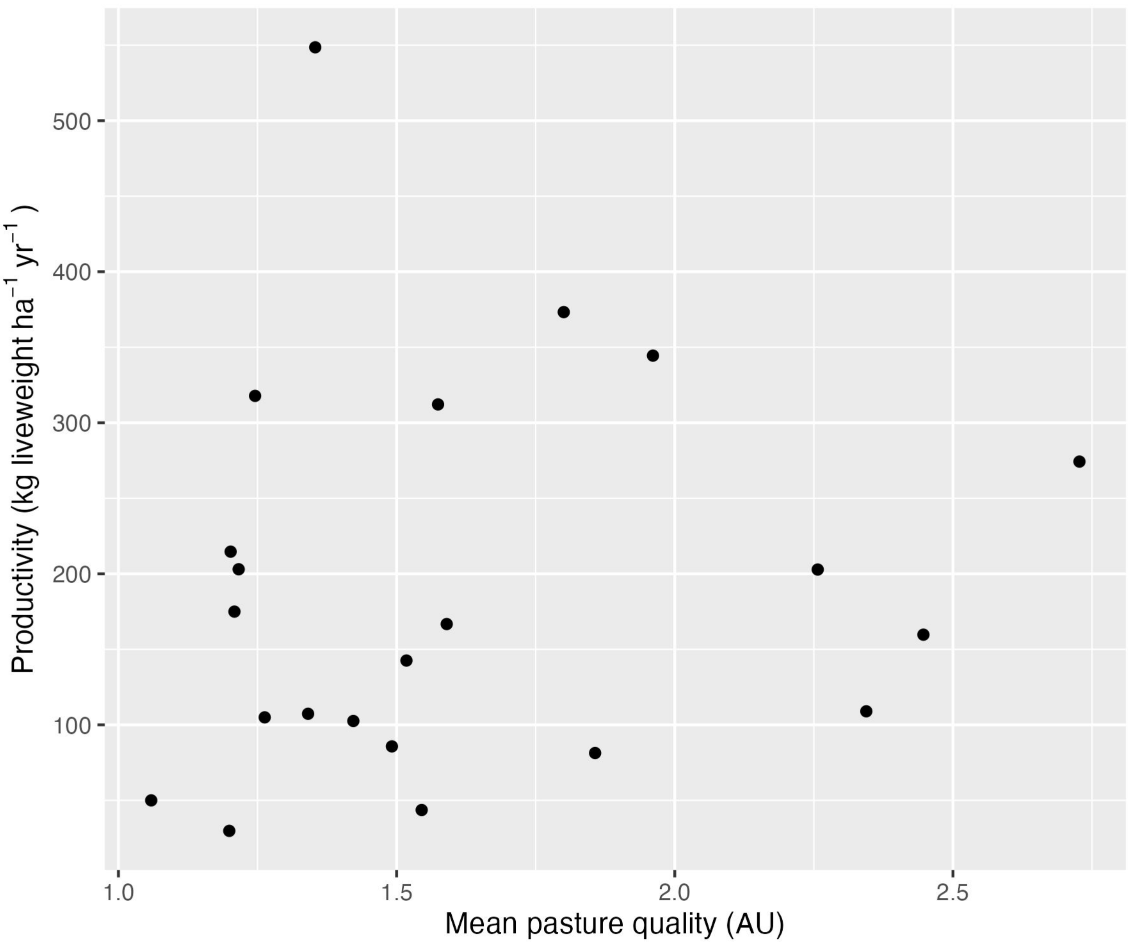
Management Report

My initial plan was to collect questionnaire data in the field over the summer (June 2024 to August 2024), collect remotely sensed data in Michaelmas term, analyse data in Michaelmas and Hilary term, and begin writing up in Hilary. Remotely sensed data collection and data analysis took longer than anticipated, as I had to learn how to acquire and handle remotely sensed data mostly independently. This involved learning to handle geographic data in R, searching for and evaluating different candidate datasets, seeking assistance from academics, and developing all the specific steps of my methods along the way to account for challenges and limitations with the datasets. In the end, data analysis only began at the very end of Michaelmas (end of November/beginning of December 2024) and lasted until the end of Hilary (mid-March 2024), with writing up lasting from the end of Hilary through to Trinity term (mid-March to mid-May 2024).

Supplementary Materials

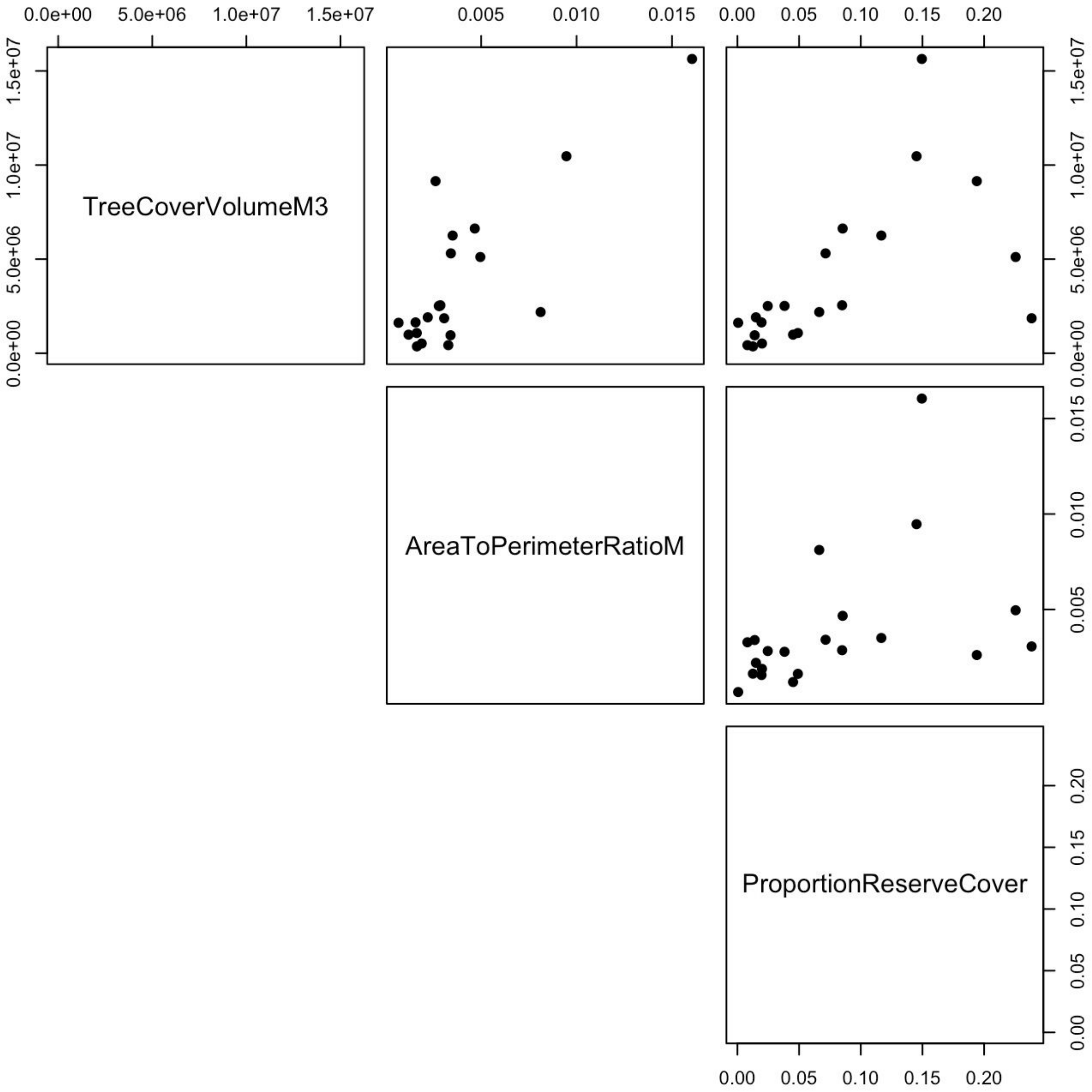
1. Supplementary Figure 1

A scatterplot of farm productivity against mean pasture quality.



2. Supplementary Figure 2

A scatterplot matrix of the three components of farm conservation performance index – tree cover volume (m^3), area-to-perimeter ratio (m), and proportion legal reserve cover – all plotted against each other.



3. Supplementary Table 1

A table of the linear models made in my analysis. Model coefficients are shown as 'β'. '0' indicates that an explanatory variable was removed during backward stepwise model selection. 'NA' indicates that an explanatory variable was not used to model the response variable.

* For patch models, a positive β value means dry patches < wet patches, and vice versa.

† A positive β value means sandy < clay, and vice versa.

‡ The p-values for fixed effects terms of mixed models generated by the "afex" R package do not exceed 3 decimal places.

Response variables	Explanatory variables				R^2
	Perimeter/area (m^{-1})	Cattle access (yes/no)	Proportion wet, or habitat type (dry/wet) *	Soil type (sandy/clay) †	
Canopy height (m), farm	$\beta = -0.0037$ $p = 0.0074$	0	0	0	0.32
Canopy height (m), patch	$\beta = -0.0027$ $p < 0.001$ ‡	NA	0	$\beta = -1.4$ $p = 0.002$ ‡	0.52
January hom., farm	$\beta = -1.6\times10^{-4}$ $p = 0.026$	0	$\beta = 0.097$ $p = 0.072$	$\beta = 0.12$ $p = 0.033$	0.44
January hom., patch	$\beta = -8.3\times10^{-5}$ $p < 0.001$ ‡	NA	0	$\beta = 0.079$ $p = 0.006$ ‡	0.48
August hom., farm	$\beta = -2.2\times10^{-4}$ $p = 1.8\times10^{-4}$	0	0	0	0.53
August hom., patch	$\beta = -1.1\times10^{-4}$ $p < 0.001$ ‡	NA	0	$\beta = 0.099$ $p < 0.001$ ‡	0.44
January NDVI, farm	$\beta = -7.1\times10^{-5}$ $p = 2.5\times10^{-4}$	$\beta = -0.020$ $p = 0.058$	0	0	0.43
January NDVI, patch	$\beta = -2.9\times10^{-5}$ $p < 0.001$ ‡	NA	$\beta = 0.021$ $p < 0.001$ ‡	0	0.23
August NDVI, farm	$\beta = -2.9\times10^{-5}$ $p = 0.13$	$\beta = -0.023$ $p = 0.066$	0	0	0.04
August NDVI, patch	$\beta = -1.4\times10^{-5}$ $p = 0.025$ ‡	NA	$\beta = 0.037$ $p < 0.001$ ‡	0	0.34

Response variables	Explanatory variables					R^2
	Lime (yes/no)	Fertiliser (yes/no)	Herbicide (yes/no)	Insecticide (yes/no)	Soil type (sandy/clay)	
Pasture quality (AU)	0	$\beta = 0.74$ $p = 0.013$	$\beta = 0.46$ $p = 0.022$	0	$\beta = -0.51$ $p = 0.0078$	0.52
	Pasture quality (1 to 3, AU)			Soil type (sandy/clay)		
Productivity (kg lw ha^{-1} yr^{-1})	$\beta = -8.9$ $p = 0.90$			$\beta = -69$ $p = 0.39$		0.11
	Productivity (kg lw ha^{-1} yr^{-1})					
CPI (AU)	$\beta = 0.00083$ $p = 0.46$					0.03
	Cattle access (yes/no)					
Productivity (kg lw ha^{-1} yr^{-1})	$\beta = 122$ $p = 0.039$					0.21

4. Note about data sharing

Sharing data and scripts used to generate the results in this study would compromise the anonymity of participating farmers.