

Zero-Deforestation Land Use Scenarios in the Brazilian Cerrado: Pasture Intensification for Agriculture, Livestock and Regeneration

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Abstract

Pastures cover approximately 50 Mha (25%) of the Brazilian Cerrado and vary widely in productivity. As Brazil seeks to expand soybean and livestock production while advancing climate and conservation commitments, an important regional question is whether projected demand for agricultural products can be accommodated without additional deforestation. We develop two zero-deforestation land-use scenarios for 2030 that integrate projected cattle herd growth and soybean expansion with spatially explicit pasture intensification. Using the CENTURY ecosystem model, we estimate changes in pasture carrying capacity, allocate a projected herd of 61 million animal units, identify areas suitable for soybean expansion, and evaluate the regeneration potential of remaining pasturelands. We then quantify changes in aboveground, belowground, and soil carbon stocks through 2050 relative to a business-as-usual baseline. Under modeled biophysical conditions and assuming rapid adoption of improved pasture management, upgrading ~13 Mha of low- and medium-vigor pasture could allow livestock production to occupy ~29 Mha, freeing 3.1 Mha for soybean expansion and ~18 Mha for native vegetation regeneration or alternative uses. These land-use transitions increase regional carbon stocks by up to 0.23 Pg by 2030 and 0.47 Pg by 2050. While implementation depends on institutional, financial, and adoption constraints, the scenarios illustrate the potential for integrated land-use planning to support agricultural production, climate mitigation, and ecosystem restoration within the Cerrado.

Keywords Agricultural production; Soil carbon; Deforestation; Conservation; CENTURY model; Cattle Stocking

Introduction

The Brazilian Cerrado is one of the world's most species-rich savannas and a recognized global conservation hotspot (Mittermeier et al. 2011). Despite this status, only 14.5% of the biome is protected within conservation areas and Indigenous reserves (Vieira et al. 2022), and approximately 46% has already been converted to agriculture and rangeland through widespread land-use change (MapBiomas col.10). Pasture extent varies slightly depending on the source and scale of the estimate, but covers roughly 50 million hectares or a quarter of the Cerrado, and an estimated 67% are degraded (<https://atlasdaspastagens.ufg.br/map>). Because pasture soils represent one of the largest manageable carbon pools in the Cerrado, recovering degraded pastures offers a unique opportunity to simultaneously increase carbon storage, reduce land demand for cattle production, and create opportunities for agricultural expansion and ecosystem restoration without further native vegetation loss (Abreu et al. 2024). The resulting surplus land could potentially accommodate agricultural expansion or the native vegetation regeneration, creating opportunities to reconcile food production, climate mitigation, and biodiversity conservation within the existing agricultural footprint (Strassburg et al. 2014; Feltran-Barbieri et al. 2021).

Recognizing this potential, public policies and private initiatives increasingly target the recovery of degraded pastures. Programs such as ABC+ (Plan for Adaptation and Low Emissions of Carbon in Agriculture) and Caminho Verde Brasil promote the restoration or conversion of degraded pastures into more sustainable land uses, including intensified pasture systems, technified agriculture, forestry, and native vegetation restoration (Brasil 2023; MAPA 2021). Parallel efforts in the private and non-governmental sectors (e.g., SEEG, Reverte) pursue similar goals (Zimbres et al. 2024). Recent studies further underscore the

potential of pasture improvement, agricultural expansion within existing lands, and native vegetation regeneration, while examining their environmental consequences (Santos et al. 2024; Silva et al. 2023; Bolfe et al. 2024).

However, realizing this potential depends on accurately estimating how pasture productivity responds to management under different climatic and edaphic conditions. Pasture productivity and carrying capacity vary substantially across the Cerrado due to differences in climate, soils, and degradation status, making regional assessments challenging. Process-based ecosystem models provide a means of evaluating management scenarios while explicitly accounting for this spatial heterogeneity. Previous simulations suggest that improving pasture quality alone may increase soil carbon stocks sufficiently to offset 27–42% of annual emissions from cattle production (Santos et al. 2024). The CENTURY model (Parton et al. 2001), a process-based ecosystem model widely applied to estimate carbon stocks under alternative land uses, has been calibrated for Cerrado pastures across degradation levels (Santos et al. 2022; Santos et al. 2024) and applied to major Brazilian cropping systems, including soybean, corn, wheat, and rice (Bortolon et al. 2011; Gonçalves et al. 2017; Vogado et al. 2024; Wendling et al. 2014).

Despite these advances, demand for soy, meat, and dairy is projected to increase, placing additional pressure on land and potentially expanding Brazil's cattle herd. Although recent work suggests that substantial soybean expansion could occur within degraded pastures (Bolfe et al. 2024), these projections typically do not account for secondary displacement of cattle production or competing land uses within the same areas. Consequently, it remains unclear whether existing pasturelands can simultaneously support future soy and cattle demand, avoid additional deforestation or shifts in agricultural production to other biomes (e.g., Amazonia), and allocate land for Cerrado restoration.

Recovered pasture area represents a finite land resource that could alternatively support livestock production, crop expansion, or restoration of native vegetation, creating important trade-offs for regional land-use planning.

This study addresses that gap by evaluating alternative zero-deforestation pathways within existing pasturelands and quantifying their effects on regional carbon stocks. By integrating future demand scenarios with ecosystem modeling, we assess whether climate mitigation, agricultural production, and restoration objectives can be achieved without further conversion of native Cerrado vegetation.

Methods

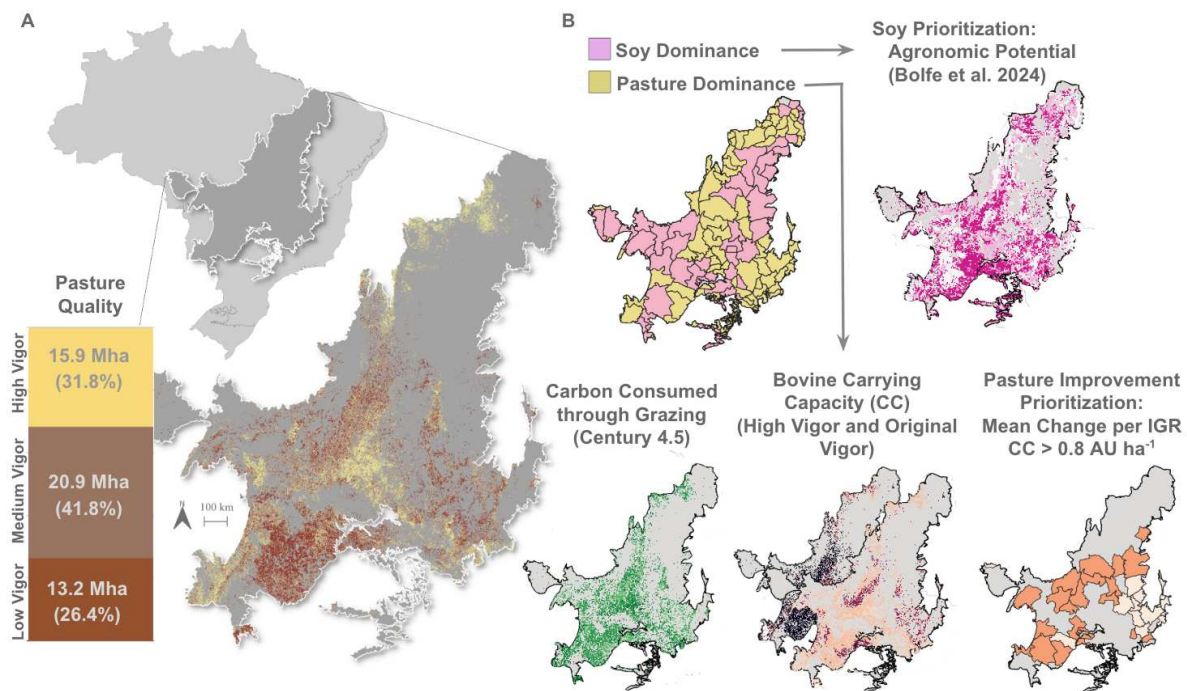


Fig. 1 (a) Pasture condition and spatial distribution in the Cerrado biome (2021) and (b) development of zero-deforestation scenarios prioritizing Intermediate Geographic Regions

for pasture improvement and soybean expansion based on bovine carrying capacity and agronomic potential respectively.

Study Area

The current study analyses pasture areas within the Brazilian Cerrado, as defined by the Brazilian Institute of Geography and Statistics (IBGE 2024). The soils in the region tend to be acidic with low fertility, and are dominated by Latossols, Argissolos and Quartzarenic Neossols following the Brazilian soil classification. From the 1970s onward, livestock production became a major economic activity within the region, and other agricultural production increased in subsequent decades (Leite et al. 2012; Zalles et al. 2018). Currently, 85% of pasture areas are covered by *Urochloa spp.* as it is well adapted to the soils of the region (da Silva et al. 2020).

Pasture land cover was derived from MapBiomas collection 7.1 for the year 2021. . Following MapBiomas, pastures are classified into three vigor categories (low, medium, and high) based on time series of MODIS Enhanced Vegetation Index (EVI), an indicator of pasture vegetation productivity (Fig. 1a). Lower vigor classes are generally associated with reduced pasture productivity and increasing levels of pasture degradation (Ferreira Jr et al. 2026). At the 1 km resolution considered in this study, pasture covers approximately 50 Mha, of which 15.9 Mha (31.8%) is classified as high vigor and the remaining 34.1 Mha as medium or low vigor.

Development of Zero-Deforestation Scenarios

Zero-deforestation scenarios are developed based on projected herd size and soybean production for 2030 and the general structure is shown in Figure 1b. Intermediate Geographic Regions (IGR – IBGE, 2017) were prioritized for pasture improvement or new soy

cultivation based on the existing prevalence of soybean cultivation and high vigor pasture. Pasture carrying capacity is first estimated under baseline (current pasture vigor) and improved pasture conditions, where all low- and medium-vigor pastures are modified to high vigor. The resulting increase in carrying capacity determines the reduction in pasture area required to support the projected cattle herd and identifies land that becomes available for alternative uses. Because these estimates account for local climate and soil conditions, the effects of pasture improvement on carrying capacity vary across the Cerrado. Carrying capacity is derived from simulated carbon removed through grazing and assumes extensive grazing systems without supplemental feed. Additional soybean production is allocated within prioritized regions on low and medium vigor pastures based on the aptitude for cultivation (Bolfe et al. 2024). Natural regeneration is simulated in the case of remaining low and medium vigor pasture land. The carbon implications of these alternative land-use allocations are quantified by estimating changes in aboveground, belowground, and soil carbon stocks relative to a baseline pasture management scenario. Further details on the development of each layer are included in specific sections below.

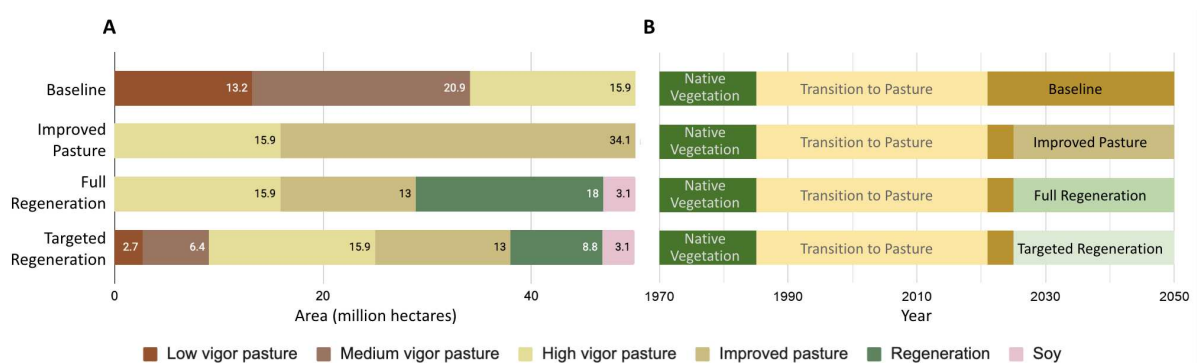


Fig. 2 Overview of the baseline, improved pasture, and zero-deforestation scenarios. **(a)** Allocation of pasture, soybean, and regeneration areas under the Baseline, Improved Pasture, Full Regeneration, and Targeted Regeneration scenarios. **(b)** Timeline of land-use transitions

simulated in the CENTURY model from native vegetation through pasture establishment and the future land-use scenarios.

Carbon Modeling and Data Inputs

Carbon stocks associated with each land-use class were estimated using the CENTURY 4.5 ecosystem model (Parton et al. 2001). These estimates provide the basis for evaluating the zero-deforestation scenarios. The model is run pixel-by-pixel at the ~1 km scale, and initialized for a period of 10,000 years or until carbon pools in soils and vegetation stabilize (Ferreira 2013). After stabilization, climate data from the TerraClimate database was applied for the 1958 - 1985 period to native vegetation. Land-use change to pasture was modeled beginning in 1985, and published calibrations of the CENTURY model specific to low, medium and high vigor pasture were applied (Santos et al. 2024). These calibrations are sensitive to pasture age and soil type (Santos et al. 2023). Scenarios of future land-use, including change in pasture quality, soybean plantation, or regeneration of native vegetation, were applied in 2025 and run through 2050 to determine the effects of land use change on carbon stocks (Fig. 2).

To determine pasture coverage at the ~1 km scale, MapBiomas col.7.1 with 30 m original resolution were resampled, and classified as pasture in the case that more than 50% of pixels were classified as pasture. This re-scaling increased total pasture area from 47 Mha to 50 Mha. Given that the duration of pasture coverage and quality are factors in the productivity and carbon dynamics, the initial year of conversion to pasture was extracted from a time-series of land cover maps for Brazil covering the period 1985-2021, as was the pasture vigor (Souza et al. 2020). In spatial resampling, the pasture vigor and year of conversion were defined as the modal value. Areas that were converted to pasture prior to

1985 were defined as having been converted in 1985. This is expected to have a minimal effect on final carbon stocks as soil carbon stocks stabilize after 20 years in pasture (Corbeels et al. 2016).

For spatialization of the simulations, monthly data on accumulated precipitation (mm) and minimum and maximum temperatures (monthly average in °C) were obtained from the Terraclimate database, referring to the period from 1958 to 2023 (Abatzoglou et al. 2018). For the period from 2024 to 2050, the values for each climate variable were stochastically generated by the CENTURY model, based on the historical data series (Metherel et al. 1993; Srikanthan and McMahon, 2001). To correct systematic underestimation of temperature in the TerraClimate data, correction factors were calculated by Santos et al. (2023) based on data from 30 weather stations.

Soil texture, pH and bulk density were obtained through Vasques et al. (2021) 90 m resolution, developed within the scope of the Brazilian National Program for Soil Survey and Interpretation (PronaSolos) of the Brazilian Agricultural Research Corporation (EMBRAPA). All input datasets were resampled to 1 km spatial resolution using nearest neighbor approximation.

Estimation of Pasture Carrying Capacity

Pasture carrying capacity was estimated to determine the pasture area required to support the projected 2030 herd under each zero-deforestation scenario. The amount of carbon in dry matter removed from pasture ecosystems across different quality levels was estimated using CENTURY model outputs for the carbon in live (shrema) and dead (sdrema) forage biomass. This carbon content was converted to dry matter following Sanquetta et al. (2022) who report that 40 - 45% of the dry weight of *Urochloa brizantha* is carbon.

Following Arantes et al. (2018) we estimate that one animal unit, equivalent to an adult bovine with a live weight of 450 kg (Ramos et al. 2005), requires 11.25 kg of dry matter per day (2.5% of its body weight). This was then used to approximate the carrying capacity of pastures following Equation 1.

$$CC = AGC_{day} * 2.4 / 11.25 \quad \text{Eq. 1}$$

Where: CC is the bovine carrying capacity in Animal Units ($AU \text{ ha}^{-1}$) and AGC_{day} is the amount of aboveground carbon removed from pasture via forage per hectare per day.

Carrying capacity was estimated under two alternative pasture conditions. In the baseline scenario, pasture vigor remained unchanged. In the improved pasture scenario, all low and medium-vigor pastures were modified to high vigor in 2025. In both scenarios, local edaphoclimatic conditions determined the extent to which pasture improvement increased forage production (estimated as carbon removed through grazing) and the resulting carrying capacity. The increase in carrying capacity between the baseline and improved pasture simulations was then used to estimate the reduction in pasture area required to support the projected 2030 herd, thereby identifying land available for soybean expansion or native vegetation regeneration within the zero-deforestation scenarios simulated through 2030 and 2050.

Projected Livestock and Soybean Demand for 2030

Projected herd size determines the pasture area required within each scenario. To determine the area required for pasture in 2030, we combined estimates of the current herd size in the Cerrado from the Atlas das Pastagens (LAPIG/UFG), derived from IBGE municipal livestock statistics and expressed as animal units (AU), with projected herd growth from MAPA (2023). This Brazilian government report estimates that the cattle herd will grow

by 12% over the decade following 2023, or approximately 1.2% per year. Given an estimated 54.5 million AU (AU) in the Brazilian Cerrado in 2020, the herd size in 2030 is projected at 61 million AU. The area required for 61 million AU depends on pasture quality and spatial distribution in our scenarios. Further increases in cattle productivity are assumed to require supplemental feeding and are not addressed in the current model simulation.

Projected soybean demand determines the area allocated to crop expansion in each scenario. MapBiomas col. 10 estimates that 38 million hectares of soy production was present in Brazil in 2021, of which 18.46 Mha were within the Cerrado biome. MAPA (2023) projects a national increase in the area of soy planted of 27.5% over the subsequent decade. Applying the pro-rated increase for 9 years to the MapBiomas estimate of soy area we estimate the demand for new area for soy in the Cerrado at 3.1 million hectares.

Spatial Allocation of Future Land-Use

To determine an optimal distribution of pasture and soy within the Cerrado, we analysed 2021 land use by region, using the Immediate Geographic Regions (IGR) classification (IBGE 2017). This regionalization of Brazil is related to the search for goods and services and ranges from 1000 to 100,000 km² with smaller areas in São Paulo state, and larger areas in Mato Grosso. For each region, we compare the prevalence of high vigor pastures with soy under the assumption that regions with a given land-use prevalent have the know-how and conditions to support their expansion.

Pasture Area Distribution

All high vigor pastures were maintained as pastures for future land use scenarios. This covered 15.9 million hectares and accounted for 34.1 million AU. Given the 2030 demand for 61 million AU, the remaining 26.9 million AU were distributed within low and

medium vigor pastures. In the simulations, we adopted a land-sparing approach in which increases in bovine carrying capacity resulting from pasture recovery reduce the area required for pasture, thereby freeing land for alternative uses (Strassburg et al. 2014). Selection of pasture areas was based on the regional mean change in carrying capacity with improved pasture quality.

Soy Area Distribution

Within regions with a predominance of soybean production, we considered the agronomic potential of pastures for soybean expansion as published by Bolfe et al. (2024). This data considers pasture quality, potential for mechanized agriculture, infrastructure, climate and protected status and rates areas as very good, good, moderate or restricted potential for agricultural expansion. The initial data source is published at 30 m resolution and combines pasture vigor and agronomic potential following Eq. 2.

$$PS = \text{VigorClass} * 10 + \text{Ag. Potential} \quad \text{Eq. 2}$$

Where PS is potential for soybean expansion in pastures, VigorClass is: 1: low, 2: medium, and 3: high vigor and Agronomic Potential is: 0: very good, 1: good, 2: moderate, 3: restricted, 4: water, 5: very restricted and 6: urban.

To resample this data set to 1 km, the vigor class was removed, and the agronomic potential was resampled to 1 km using the modal class.

Areas with very good and good potential for soy production within regions with a predominance of soybean production were considered for soy expansion within the Cerrado. These regions were ranked giving preference to very good potential areas and then areas of

good potential in low and medium vigor pastures. Within each subset, individual regions were ranked by their soy coverage percentage.

Approximately a third of the IGR were dominated by soybean production, concentrated in the states of Mato Grosso, Goiás, and Piauí (Figure 1b) and 6.06 Mha were low- or medium-vigor pastures and showed very good or good potential for conversion to soybean production. To meet the 3.1 Mha of estimated demand for new soybean production area for 2030, three of the four combinations of pasture vigor (low and medium) and soy potential (good and very good) were used in their entirety. Within the fourth, medium vigor pastures with good potential, 19 IGR were included.

Remaining Areas

In areas that were not required to meet demand for cattle or soy, two cost-neutral options were considered: regeneration of native vegetation without intervention and maintenance as pastures without improving pasture quality. This area occurs in pasture regions with lower improvements to cattle stocking capacity, and in soy regions with lower agronomic potential. Silva et al. (2023) present a map of regeneration potential used to assess regeneration in these remnant areas. An initial scenario is presented wherein all remaining areas are allowed to regenerate native vegetation, and a secondary scenario in which only remnant areas with low potential for regeneration are maintained as pasture without improvement.

Zero-deforestation Scenarios

To evaluate the carbon implications of alternative land allocations, two zero-deforestation scenarios were defined (Fig. 2). In the “Full Regeneration” Scenario (FR), the entire 18 Mha of remaining pasture area was allocated to passive native vegetation

regeneration. In the “Targeted Regeneration” Scenario (TR), regeneration was restricted to areas with medium or high regeneration potential, while areas with low potential were maintained as unimproved pasture. Note that we consider a zero-deforestation approach in these two scenarios, where future economic demand for beef and soybeans is met solely through modification to land use and management.

Simulation and Validation of Soybean and Regeneration Scenarios

Soybean cultivation was simulated using parameters pre-set by the model developers (SYBN) (Metherel et al. 1993), considering the most common planting and harvesting period in the Cerrado region (October - February). The simulations were performed considering the adoption of no-till farming and average fertilization levels. Between crop cycles, medium-vigor pasture without grazing maintained soil cover.

The data used to validate the model for soybean cultivation in the Cerrado were obtained through a literature review and partner researchers (Madari et al. 2024). Published information regarding the physical and chemical properties of the soil (particle size distribution, density, pH, and carbon stock) at a depth of 0-20 cm was compiled. The studies also gathered information on land-use history, including year of conversion, planting type (conventional or no-till), cultivation time, and year of sampling. In total, data from 42 sites were found that are well distributed throughout the biome. Further details of model parameters and validation are available in Online Resource 1.

The average simulated C stock in the soybean areas for the 42 sites was 34.4 ± 8.4 (mean $\pm$ sd) MgC ha⁻¹, similar to the value found in the literature (37.2 ± 13.3). The model's coefficient of efficiency (COE) was 0.67, and the correlation between observed and simulated values (r) was significant (0.82; $p \leq 0.01$).

Regeneration of native vegetation was modeled using the same parameters as those used for native vegetation in the savanna formation. Specific regeneration parameters were not found in the existing literature, nor were sufficient data available to calibrate a new set of parameters for this use.

Carbon stocks were calculated by aggregating CENTURY model outputs into aboveground, belowground, and soil carbon pools (see Online Resource 2 for detailed variable mapping).

Evaluation of Change in Carbon Stocks

Overall changes in carbon stocks were evaluated for aboveground carbon, belowground carbon, and soil carbon for the years 2030 and 2050 based on changes in land use beginning in 2025. The comparison was conducted for each year considering no change in land use as the baseline value, as shown in Eq. 3.

$$\Delta C(t) = C_{\text{Scenario}}(t) - C_{\text{BL}}(t) \quad \text{Eq. 3}$$

Where C represents the total carbon stock considering carbon in vegetation and soil at year (t) for scenarios of modified land use (Scenario) and with no change to the initial land use or vigor present in 2021 (BL).

Results

Under baseline pasture conditions, the model estimated a carrying capacity sufficient to support 73.1 million AU in 2023. Considering the total pasture area and simulating improvement of all low- and medium-vigor pastures in 2025 increased the potential herd size to approximately 101.1 million AU by 2030 (38%) under a grazing-based production system. Mean carrying capacity increased from 1.14 to 1.96 AU ha⁻¹, although substantial regional

variation remained (1.1–2.3 AU ha⁻¹), with values increasing from the northeast toward the southwest of the Cerrado in response to spatial variation in soil texture and climate (Fig. 3a; Online Resource 3).

The increase in carrying capacity allows a reduction in the area of pasture within the Cerrado, creating space in potentially degraded pastures for other land uses. Selecting areas with a mean increase in carrying capacity of 0.8 AU ha⁻¹ or greater (Fig. 3b) meets the 26.9 million AU demand and adds a total of 13 million hectares of high vigor pasture. Given that we did not quantify adoption rates, 2030 outcomes may represent an upper bound on adoption speed. Of the 6.06 Mha identified as suitable for soybean expansion, 3.1 Mha were allocated to meet projected 2030 demand, concentrated in 35 IGR.

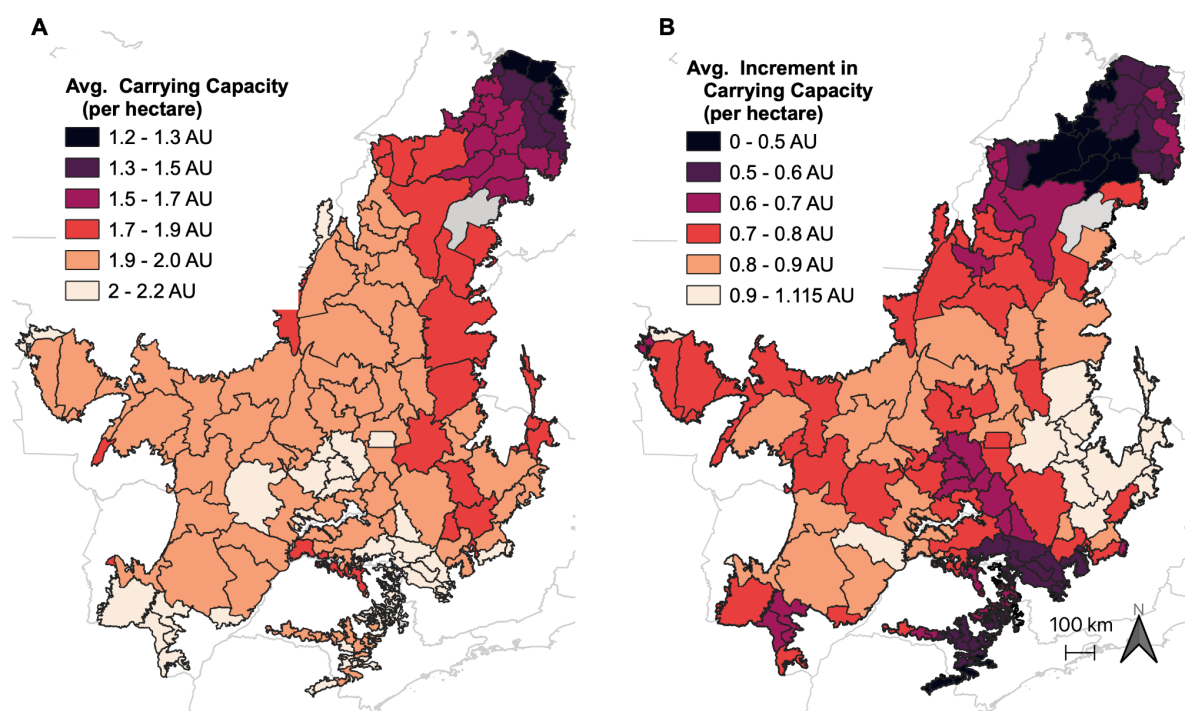


Fig. 3 (a) Average carrying capacity per hectare of pastures after improvement to high vigor by immediate geographic region based on CENTURY 4.5 model estimates and Eq. 1 and **(b)**

average increment in carrying capacity with change from baseline low or medium vigor to high vigor.

Considering the original 50 Mha of pasture, 28.9 Mha are necessary for the estimated herd size for 2030, and an additional 3.1 Mha for the expansion of soybean, with 18 Mha of low and medium-vigor pastures remaining (Fig. 4). Within this area, 63% could be used for native vegetation regeneration according to Silva et al. (2023); 8.7% with high regeneration potential, 40.6% with medium regeneration potential, and 14.1% with low regeneration potential. These areas form the basis of the Full Regeneration and Targeted Regeneration scenarios, whose spatial allocation is shown in Fig. 4.

Within the baseline scenario, with no changes in pasture quality from 2021 to 2050, the total carbon stock decreased by 0.08 Pg from 2030 to 2050 (Table 1). This reduction occurred mainly due to C losses from the soil. Further investigation demonstrates that this loss is primarily attributed to a gradual decline in the passive pool of the CENTURY model, which represents stable carbon with slow turnover rates.

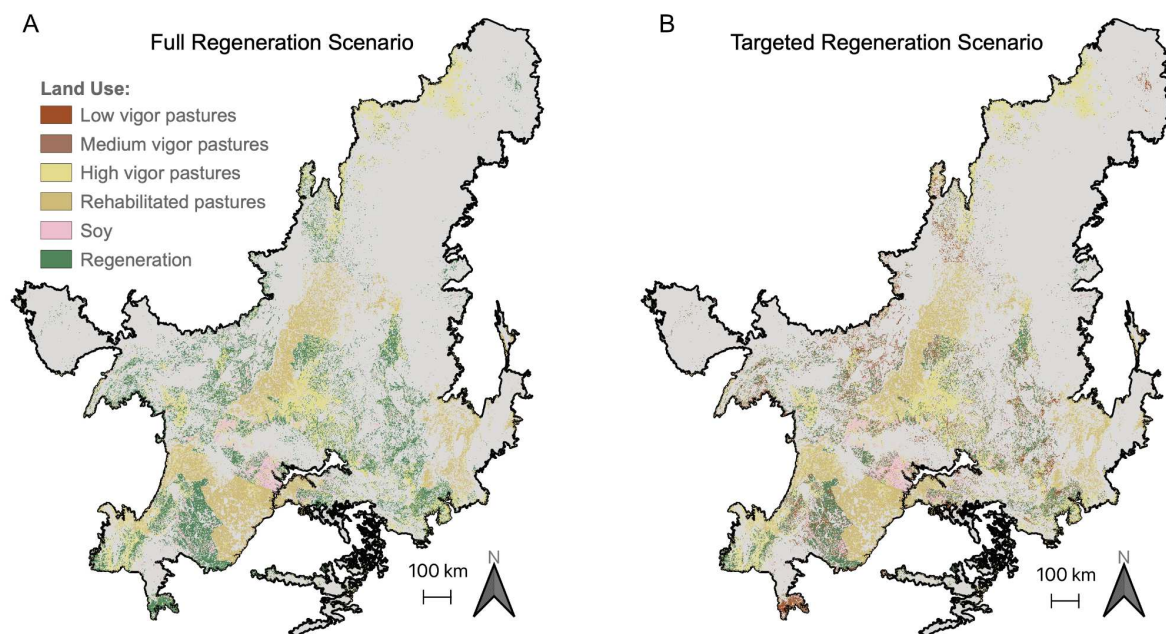


Fig. 4 Spatial distribution of land uses in the two zero-deforestation scenarios developed to meet the 2030 demand for cattle and soy. **(a)** The Full Regeneration Scenario includes regeneration of native vegetation in all areas that are not required for cattle (28.9 Mha) and soy (3.1 Mha). **(b)** The Targeted Regeneration Scenario limits regeneration to areas with medium and high regeneration potential (8.8 Mha) and maintains pasture in areas with low potential (9.1 Mha).

In both Full Regeneration (FR) and Targeted Regeneration (TR) scenarios, total carbon stocks increased by 2030, with further increases by 2050 (Table 2). Average carbon stocks per area increased in pastures due to improved quality, and total stocks in both aboveground and belowground compartments increased despite the smaller pasture area in 2030. The decrease in pasture area is reflected in the corresponding decrease in the total stock of carbon held within soil organic matter.

When compared to 2021 values we find that the aboveground carbon stocks increase by 0.05 Pg in both Regeneration scenarios by 2025 and by 0.07 Pg by 2030 (Table 1). The largest initial increase was found for belowground carbon, of 0.14 Pg and 0.08 Pg, for Full and Targeted Regeneration Scenarios respectively. While both aboveground and belowground carbon in vegetation and roots increased, carbon in soil decreased in this initial period. The increase in belowground carbon is primarily, but not exclusively, due to regenerating native vegetation. When all compartments are considered and compared to the stable land-use scenario, we find a 0.23 Pg increase in carbon stock for the FR Scenario, and a 0.16 Pg increase for the TR Scenario.

These increases in carbon stocks continue through the year 2050. Increases in belowground (root) carbon continue to outpace increases in aboveground carbon increase,

and both exceed the decrease in soil carbon. The FR Scenario shows greater increases in aboveground and belowground carbon, driven by regeneration of native vegetation. In this scenario, the regeneration of native vegetation alone accounts for a 0.18 Pg carbon increase between 2030 and 2050. While there is over twice (2.19 times) the belowground carbon as aboveground carbon in regeneration in 2030, this ratio decreases to 1.72 in 2050 as regenerating vegetation matures. When compared to the Baseline scenario, a total increase of 0.47 Pg in carbon stocks is observed for the FR Scenario. For the TR Scenario, an increase of 0.29 Pg is observed.

Table 1 Carbon stocks (Pg) by land use and compartment in 2021, 2025, 2030, and 2050 for the baseline scenario (BL) and two zero-deforestation scenarios: Full Regeneration (FR) and Targeted Regeneration (TR). Values were estimated using the CENTURY 4.5 model with future land-use changes implemented in 2025.

Year	Compartment	Pasture			Soy		Regeneration		Total		
		BL	FR	TR	FR	TR	FR	TR	BL	FR	TR
2021	AGC	0.16	0.16	0.16					0.16	0.16	0.16
	BGC	0.07	0.07	0.07					0.07	0.07	0.07
	Soil*	1.64	1.64	1.64					1.64	1.64	1.64
	Total 2021								1.87	1.87	1.87
2025	AGC	0.18	0.15	0.18	0.01	0.01	0.05	0.03	0.18	0.21	0.21
	BGC	0.08	0.06	0.08	0.006	0.006	0.14	0.07	0.08	0.21	0.15
	Soil*	1.61	0.97	1.25	0.10	0.10	0.57	0.28	1.61	1.64	1.63
	Total 2025								1.87	2.05	2.00
2030	AGC	0.19	0.16	0.19	0.01	0.01	0.07	0.03	0.19	0.24	0.23
	BGC	0.09	0.07	0.09	0.005	0.005	0.15	0.07	0.09	0.22	0.16
	Soil*	1.59	0.98	1.26	0.10	0.10	0.56	0.28	1.59	1.64	1.63
	Total 2030								1.87	2.10	2.03
2050	AGC		0.15	0.18	0.01	0.01	0.15	0.07	0.18	0.31	0.27
	BGC		0.07	0.08	0.004	0.004	0.26	0.13	0.09	0.33	0.21
	Soil*		0.98	1.25	0.09	0.09	0.55	0.27	1.52	1.62	1.61
	Total 2050								1.79	2.26	2.09

Discussion

Our simulations indicate that pasture improvement substantially increases carrying capacity across the Cerrado, reducing the pasture area required to support projected livestock demand. Under the zero-deforestation scenarios evaluated here, this land-saving effect creates opportunities for soybean expansion and native vegetation regeneration while increasing regional carbon stocks. The magnitude of these benefits, however, varies considerably across the biome because of regional differences in climate, soils, and existing pasture condition. This is particularly relevant as recent studies estimate 70% of pastures to exhibit some level of degradation (Santos et al., 2022).

By modeling the conversion of low- and medium-vigor pastures to high-vigor pastures throughout the Brazilian Cerrado, we assess how regional climate and soils influence pasture productivity and carrying capacity. Although pasture improvement nearly doubled the mean carrying capacity of low- and medium-vigor pastures, substantial spatial variation remained after improvement, demonstrating that identical improvements in pasture condition do not produce uniform productivity gains across the biome. Lower carrying capacities occurred in the northern Cerrado and increased toward the south and west, consistent with previous regional assessments (Telles et al. 2024; Batista et al. 2020). These findings highlight the importance of accounting for regional edaphoclimatic variability when evaluating the potential benefits of pasture intensification at biome scale.

The spatial distribution of stocking rates shows similar spatial trends to those presented by Batista et al. (2020) but lower carrying capacities. Batista et al. (2020) estimated potential stocking rates of 1 to 6.0 AU ha⁻¹ across Brazilian pastures, while Arantes et al.

(2018) reported maximum values of 1–3.6 AU ha⁻¹ based on remotely sensed dry matter production. In contrast, our estimates are derived solely from the carbon available for grazing simulated by the CENTURY model and therefore do not incorporate economic drivers, historical productivity trends, or supplemental feeding. Strassburg et al. (2014), which similarly considered extensive pasture systems, reported carrying capacities more comparable to those estimated here. Consequently, if our estimates are conservative, the potential land-saving effect of pasture improvement would be even greater than reported.

Carbon Dynamics by Land Cover

Soybean Systems

Although conversion of native Cerrado vegetation to annual crops generally reduces soil carbon stocks, no-till systems have been shown to increase soil carbon relative to conventional tillage, although gains remain below those of native vegetation and vary with soil texture and depth (Castellano et al. 2022; Maia et al. 2022). However, soil carbon responses can also vary with cropping system and residue inputs. Siqueira-Neto et al. (2020), for example, found greater carbon losses following conversion to single-season soybean cultivation than under no-tillage systems with two crops per year, highlighting the importance of crop-derived carbon inputs for maintaining soil carbon stocks.

In our simulations of continuous soybean cultivation under no-till management, soil carbon stocks remained broadly similar to those under pasture, with a slight short-term decline (–0.20 Mg C ha⁻¹ over five years after conversion, Online Resource 4). This suggests that soybean expansion within existing pasturelands does not substantially increase soil carbon stocks, but also does not generate large additional losses when compared to moderately managed pasture systems. These results are consistent with studies indicating that

soil carbon responses to no-till in the Cerrado are modest and influenced by prior land use, cropping system, and edaphoclimatic conditions.

Pasture Systems

The simulated increase in soil carbon following pasture improvement is consistent with numerous field studies demonstrating that improved *Urochloa* spp. pastures can increase soil carbon stocks in the Cerrado. Reported sequestration rates range from 0.2 to 0.7 Mg C ha⁻¹ yr⁻¹ depending on management, grazing intensity, soil properties, and climate (Batlle-Bayer et al. 2010; Marchão et al. 2009). In our simulations, newly improved pastures showed an average soil carbon increase of 0.28 Mg ha⁻¹ yr⁻¹ during the first five years following improvement, within the range reported in the literature. As observed elsewhere, sequestration rates declined over time as soil carbon approached a new equilibrium (Santos et al. 2023).

Conversely, degraded pastures consistently exhibit lower soil carbon stocks than well-managed systems, a pattern widely observed following forest or savanna conversion to poorly managed pasture in Brazil (Fearnside and Barbosa 1998). Our estimates for medium- and low-vigor pastures indicate annual soil carbon losses of 0.14–0.16 Mg ha⁻¹ yr⁻¹, with total stocks approximately 84–87% of those observed in high-vigor pastures. These values align with field studies reporting substantial carbon depletion under poorly managed grazing systems (Braz et al. 2013; Maia et al. 2009). Together, these findings reinforce the central role of pasture improvement as a mechanism for both productivity gains and carbon sequestration in the Cerrado.

Native Vegetation Regeneration

The gradual carbon recovery simulated during native vegetation regeneration is consistent with the limited empirical evidence available for the Cerrado, particularly for passive regeneration. Available studies and recent meta-analyses indicate that recovery of aboveground carbon in restored Brazilian biomes can take multiple decades and often remains below old-growth levels for extended periods (Milhomem and Nardoto 2015; Cava et al. 2018; Jakovac et al. 2024). Our modeled regeneration trajectories fall within the range reported in the literature, with gradual increases in aboveground carbon over 25 years and slower but sustained increases in belowground biomass.

Uncertainty remains regarding soil carbon dynamics under regeneration, as some studies indicate limited recovery of soil organic carbon relative to vegetation biomass (Zhou et al. 2023). Our simulations similarly suggest that gains in total carbon stocks are driven primarily by increases in above- and belowground biomass rather than soil carbon accumulation. Although soil carbon recovery may therefore be relatively slow, regeneration provides additional benefits beyond carbon storage, including increased biodiversity, improved water regulation, and non-timber forest products (Silva et al. 2023; Vieira et al. 2021). These co-benefits strengthen the case for allocating surplus pasture areas to restoration within integrated land-use planning strategies.

Regional Land-Use Implications

Our results demonstrate that pasture improvement creates opportunities to reconcile livestock production, soybean expansion, and native vegetation regeneration within a common zero-deforestation framework. Unlike previous studies that have evaluated these pathways independently (Strassburg et al. 2014; Feltran-Barbieri et al. 2021; Bolfe et al. 2024), our scenarios explicitly allocate the finite area released through pasture intensification among competing land uses while accounting for regional variation in productivity and

carbon dynamics. This highlights that the benefits of pasture improvement depend not only on increasing productivity, but also on how the resulting surplus land is subsequently allocated.

Implementation of Future Scenarios

While our modeling demonstrates that future soy and cattle demand could be met without additional deforestation, translating these scenarios into practice requires overcoming significant institutional and financial barriers. Pasture recovery and land-use reallocation at the scale modeled here depend on effective coordination among credit systems, monitoring institutions, and technical assistance networks.

Public credit programs such as Brazil's ABC Program have played an important role in promoting low-carbon agriculture, yet evidence suggests that implementation gaps remain. A portion of declared recovery areas do not correspond to degraded pastures, and monitoring systems often prioritize financial compliance over environmental performance (Rajão et al. 2020; Oliveira et al. 2024). As a result, the climate mitigation and restoration outcomes envisioned in national strategies have not yet been realized at scale. Moreover, fragmented institutional responsibilities across ministries and agencies complicate long-term planning and weaken policy coherence (Soares-Filho et al. 2014).

Financial risk also constrains adoption. Ecological restoration and pasture reform typically require substantial upfront investments in activities such as pasture renovation, fertilization, and fencing, while financial returns often accrue only over longer time horizons than short-cycle agricultural investments. These factors discourage private capital participation. Expanding access to rural insurance, strengthening technical assistance, and aligning credit incentives with verified environmental outcomes could reduce these barriers (Strassburg et al. 2014; Bragança et al. 2022).

Broader Environmental Effects

Although this study focuses on ecosystem carbon stocks, the overall climate implications also depend on methane, nitrous oxide, and other greenhouse gas emissions associated with pasture and crop systems. Intensified pastures increase emissions per hectare due to higher stocking densities and fertilization, yet improved productivity can reduce emissions per unit of beef produced by shortening slaughter age and improving feed efficiency (Abreu et al. 2024; Costa et al. 2025). The scenarios assume grazing-based pasture production throughout and do not evaluate transitions to semi-confinement or feedlot finishing systems, which could further alter both land requirements and greenhouse gas emissions.

In soybean systems, emissions arise from fertilizer production and application, agrochemicals, and fuel use. Reported values range from 0.3–0.9 tCO₂e per ton of soybean, increasing when direct land-use change is included (Pereira et al. 2025). Although these life-cycle emissions are not explicitly modeled here, they highlight trade-offs between intensification and total system emissions.

Study Limitations

The simulations were conducted at an approximately 1 km spatial resolution, which is appropriate for biome-scale scenario analysis but does not capture within-field heterogeneity in soils, management, or topography. In the present analysis, aggregation to this resolution increased the mapped pasture area from approximately 47 Mha at the original 30 m MapBiomass resolution to 50 Mha (~6%). Consequently, biome-scale estimates of total pasture carbon stocks and total carrying capacity may be similarly overestimated, although per-hectare estimates are not expected to be systematically affected. The magnitude of this

bias remains uncertain because the additional mapped pasture area is unlikely to be distributed uniformly across the biome, and both carbon stocks and carrying capacity vary spatially.

The scenarios assume rapid implementation of pasture improvement beginning in 2025. In practice, adoption is likely to occur more gradually and vary among regions depending on producer capacity, infrastructure, access to technical assistance, and policy incentives. Consequently, the simulated 2030 outcomes should be interpreted as representing the biophysical potential of coordinated pasture recovery rather than a prediction of adoption rates. Future work should evaluate alternative adoption trajectories and their implications for regional carbon stocks.

The scenarios also assume historical climate conditions throughout the simulation period and do not account for projected changes in temperature, precipitation, or atmospheric CO₂ concentrations. Future climate change could alter pasture productivity, soybean suitability, native vegetation recovery, and carbon sequestration rates, potentially affecting both the spatial distribution and magnitude of the land-use transitions presented here. Evaluating the interaction between climate change and zero-deforestation land-use scenarios represents an important avenue for future research.

The scenarios considered only three land uses within the Cerrado: pasture, soybean, and native vegetation. Other expanding land uses, particularly sugarcane and eucalyptus plantations, were not explicitly represented despite their increasing regional importance in parts of the biome, including Goiás and the Triângulo Mineiro (MapBiomass Collection 10). Consequently, some areas identified here as suitable for soybean expansion may instead be allocated to these production systems. However, because the combined area occupied by

these land uses remained relatively stable between 2021 and 2024 (8.9 and 8.7 Mha, respectively), their omission is unlikely to substantially affect the biome-scale estimates of land availability and carbon stocks. Future work should incorporate additional land-use classes into the scenario framework.

Model validation demonstrated good agreement between simulated and observed soil carbon stocks across the major Cerrado land uses. However, the validation primarily quantifies uncertainty in absolute carbon stock estimates rather than differences among alternative land-use scenarios. Because all scenarios share the same model structure, initialization, parameterization, soil properties, and climate forcing, a substantial component of systematic model error is expected to be common among scenarios. Consequently, the scenario comparisons presented here are likely more robust than the absolute carbon stock estimates because much of this error is shared across simulations. Explicit propagation of uncertainties in model parameters and spatial inputs would nevertheless provide valuable confidence intervals around these scenario differences in future studies.

Conclusion

Current pasture area in the Cerrado can support the projected 2030 herd size and soybean expansion within approximately 68% of its present extent (~32 Mha). Under improved management and without deforestation, the estimated 61 million animal units could be sustained on 28.9 Mha at an average stocking rate of 2.1 AU ha⁻¹, freeing substantial areas for alternative land uses.

The two zero-deforestation scenarios developed here demonstrate that strategic reallocation of pasturelands can simultaneously accommodate agricultural growth and generate measurable carbon gains. Depending on the extent of regeneration, total carbon

stocks increase by 0.16–0.23 Pg by 2030 and 0.29–0.47 Pg by 2050, driven primarily by gains in forest regeneration biomass and soil carbon under improved pasture. These findings indicate that intensification and restoration are not inherently competing objectives within the Cerrado landscape. However, these estimates represent changes in ecosystem carbon stocks and do not account for greenhouse gas emissions associated with livestock and crop production systems.

However, realizing these outcomes depends on coordinated institutional action, sustained policy support, and effective monitoring systems capable of aligning credit, technical assistance, and land-use governance. The feasibility of zero-deforestation intensification therefore rests not only on biophysical potential but on the capacity to implement integrated regional land-use strategies. By quantifying the trade-offs and synergies among livestock production, crop expansion, and regeneration, this study provides evidence to inform regional sustainability transitions in one of the world's most dynamic agricultural frontiers.

Online Resources

ESM_1.pdf

Validation and implementation of modeled Soybean production in the Brazilian Cerrado

ESM_2.pdf

Detailed CENTURY 4.5 model carbon pool mapping and variable codes

ESM_3.pdf

Meteorological data (average 1958-2023) and soil properties of the Brazilian Cerrado, including a) annual precipitation (mm); b) minimum annual temperature (°C); maximum annual temperature (°C); d) clay (%); e) sand (%); f) silt (%); g) soil bulk density (g m³); h) pH in water

ESM_4.pdf

Mean and standard deviation of carbon stocks (Mg ha⁻¹) in future land use scenarios for 2025, 2030 and 2050 by land cover, as estimated using the CENTURY 4.5 model simulating land cover change in 2025. Low and medium vigor pastures are specific to the TR Scenario. High vigor pastures (old and new), and soy cover the same areas in both scenarios. Regeneration of native vegetation in the TR Scenario covers a subset of areas included in the FR Scenario.

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Authors' Contributions

LF, MN, AP and CS designed the project and initial methodology that led to the current manuscript, implemented by AP, CS, MS, IM, GL, MN and MH. Modifications to the CENTURY model were led by AP, CS and MS with additional support from GL. Implementation of the CENTURY model was conducted by CS and IM, with summarization

of model results by IM, MH and CS. MH wrote the manuscript with assistance from MS, IN, MN and DV. AP also assisted with review and editing of the manuscript. LF supervised and acquired funding. All authors read and approved the final manuscript.

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Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability

The validation dataset, CENTURY v4.5 crop parameter file (crop.100), and an extended description of validation methodology of soybean systems are archived in Zenodo at <https://doi.org/10.5281/zenodo.18868132> (dos Santos et al. 2026). The scenarios presented in this manuscript, bovine carrying capacity estimates and modeled carbon stocks are archived in Zenodo at <http://doi.org/10.5281/zenodo.18172869> (Hunter et al. 2026). MapBiomass land-use data are publicly available at <https://mapbiomas.org>. The CENTURY model is available from the Natural Resources Ecology Laboratory, Colorado State University.

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