

Article

Biomass Recovery Dynamics and Fire Behavior in *Stricto Sensu* Grassland After Low-Intensity Prescribed Burns

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Highlights

What are the main findings?

- Low-intensity controlled burns reduced the total fine fuel load compared to pre-disturbance levels.
- *Stricto sensu* Grassland vegetation demonstrated resilience, rapidly recovering its initial vigor without suffering losses in its functional stability.
- The Gompertz growth model was applied with good accuracy to the total load and can be used to describe and predict regeneration dynamics.

What are the implications of the main findings?

- The use of prescribed fire is a safe and viable tool not only for reducing the risk of forest fires, but also for the conservation of fire-dependent ecosystems.
- The validated regeneration model offers important quantitative support to assist managers of Conservation Units in making decisions in Integrated Fire Management plans.

Abstract

This study investigated the effects of controlled burns on biomass dynamics and fire behavior in areas of *stricto sensu* grassland in southern Brazil. The experiment consisted of conducting controlled burns in three experimental plots divided into five subplots, with data collection on fire behavior (rate of spread, fireline intensity, residence time, and heat released) followed by monitoring of vegetation recovery over 19 months. To assess the influence of fire on biomass increase, the Gompertz model was fitted, correlating the Absolute Growth Rate (AGR), the time to peak productivity and the time at which the growth curve reaches 95% of the asymptote with the fire behavior variables. The results demonstrated that low-intensity controlled burns were effective in reducing fuel load. Correlation analysis indicated that fire behavior variables had little influence on the rate of vegetation recovery, suggesting that the ecosystem tolerates low-severity disturbances well. The Gompertz model showed a satisfactory fit ($R^2 = 0.86$ for total biomass), proving to be a useful tool for management. It is concluded that the use of low-intensity prescribed burns is a viable and safe practice for protected areas.

Keywords: biomass increase; prescribed burns; growth modeling



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1. Introduction

Most Brazilian biomes are prone to wildfires on a larger or smaller scale [1], with savannas and grasslands being the most frequently managed using fire [2]. The Campos Gerais region, located on the second plateau of Paraná, comprises areas of *stricto sensu* grassland and savannas fields, which for a long time were preserved due to the low agricultural suitability of the region and isolation provided by the geomorphological barrier created by the Devonian Escarpment [3,4].

Wildfires are constantly cited as one of the main threats to protected areas, especially those located in grassland physiognomies, as their vegetation presents characteristics considered to be of high fire risk [5], with anthropogenic actions being the main source of ignition [6]. Therefore, for many years, managers of protected areas included in this typology adopted the “zero fire policy” [7]. This resulted in an accumulation of biomass, altering the characteristics of the vegetation in a way that made it more prone to fires [8].

A change in approach came about because of the understanding that by suppressing fire or making it too frequent, the fire regime can become detrimental to the ecosystem, resulting in habitat degradation and reduced biodiversity [8].

Fire-dependent environments differ from each other in their growth forms and adaptive characteristics, as these are related to the fire regime of each environment [9], thus fire can be considered a mutagenic agent [10]. For example, Pellegrini [11] demonstrated a strong link between fire and the variability in bark thickness of tree species across different biomes worldwide, thus confirming that investment in bark is a widespread adaptation in frequently burned areas, both in temperate and tropical regions. However, even though grasslands are fire-dependent, they are semi-natural environments developed and formed under the influence of fires and wildlife grazing, as well under anthropogenic pressure altering land use and fire regimes [12,13].

Fuel is understood to be all types of organic matter, living or dead, present in the environment, capable of combustion and burning [14]. Wild fuel is the only element of the fire triangle subject to anthropogenic actions and is, therefore, controllable. Thus, its quantification is related to firefighting and controlled burning actions, as it is responsible for characteristics of fire behavior such as intensity and rate of spread [15]. This variable is normally expressed in terms of kiln dry matter mass per unit area [5].

The term fire behavior refers to the result of the interaction between meteorological conditions, terrain, burning technique, ignition method, and fuel material conditions, being basically described by the parameters of propagation speed, energy released, residence time, and fire intensity [14]. This last variable is considered one of the most important, as it describes the magnitude of combustion in terms of energy released. Thus, it is also the most used factor to compare controlled burns and wildfires, as well as to evaluate the effects of fire on the environment [16].

According to Batista et al. [2], open-environment experiments on fire behavior are arduous due to the difficulty in controlling and/or monitoring the various factors involved; however, they are fundamental for understanding the relationship between the forest environment and combustion, enabling the establishment of a basis for predicting fire behavior in forest areas of Brazil.

In this sense, many researchers have been dedicated to understanding how the characteristics of fuel influence fire propagation. However, many of these studies focus on savanna fields (Cerrado), especially long-term studies. Regarding Campos Gerais, there are still few studies analyzing fuel, fire behavior, and its effects on vegetation and fauna.

With the enactment of Law 14,994 of July 2024 [17], the National Policy for Integrated Fire Management was established, addressing the prevention, suppression, and use of fire in an ecologically sound manner. Hence the need for research related to the regime and

effects of fire on the environment and an understanding of the dynamics of regeneration, so that fire is not only a means of prevention and control, but also a conservation tool for these remnants of fire-dependent ecosystems.

Considering the limited knowledge about the effects of fire on *stricto sensu* grasslands in Southern Brazil, the present study aimed to monitor the increase in biomass after a controlled burn and to test two hypotheses: (a) The use of prescribed burns reduces the total stabilized fine fuel load compared to the pre-fire baseline (before-and-after comparison). (b) Low-intensity prescribed burns do not compromise biomass resilience or vegetation recovery capacity.

2. Materials and Methods

2.1. Study Area

The Vila Velha State Park is located on the second plateau of Paraná, in the region known as Campos Gerais, in the municipality of Ponta Grossa in the state of Paraná, between the coordinates 25°12'34'' to 25°15'35'' S and 49°58'04'' to 50°03'37'' W (Figure 1), 20 km from the municipal seat and approximately 90 km from the capital of Paraná via the BR-376 highway, the main access road connecting the coast to the northwest, southeast and north regions of the state [18].

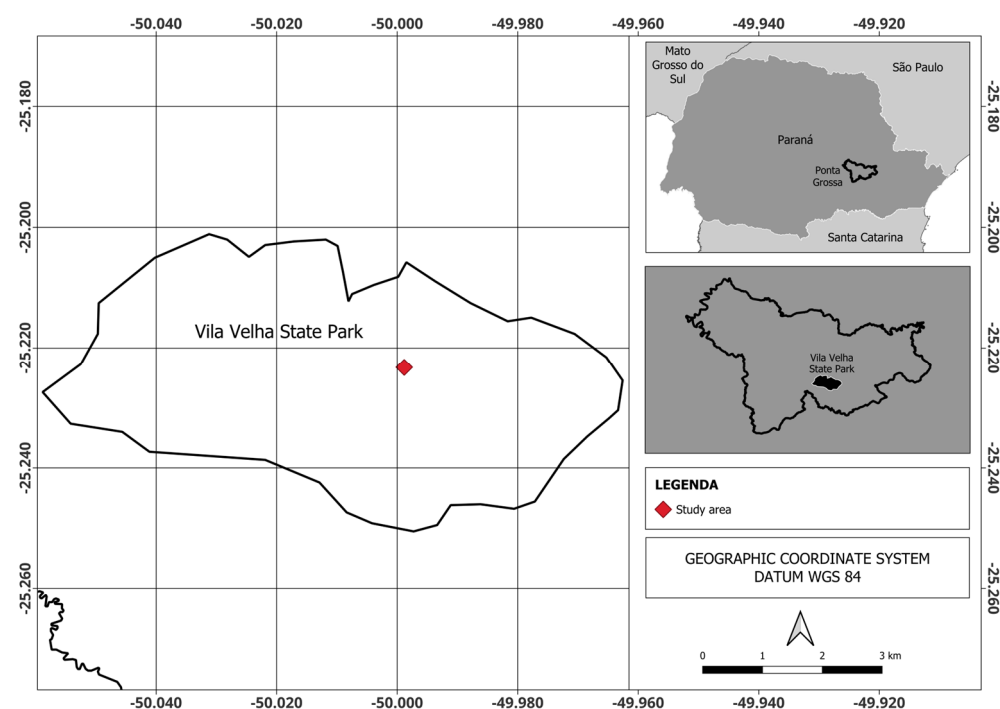


Figure 1. Location of the study area.

With an area of 3269.41 hectares, the park is in a Cfb climate region, according to the Köppen classification, meaning a humid temperate climate without a dry season, with cool summers and periodic frosts [19]. The average annual rainfall observed for the municipality was 1553.7 mm, distributed over 124 days. The rainiest months are January, February, and October, while July, August, and April have the lowest rainfall. The average annual temperature is 17.8 °C, with the average maximum temperature recorded in January (27.6 °C) and the minimum in July (9.1 °C). The prevailing wind direction is northeast, with an average monthly speed varying from 2.9 to 4.0 m·s⁻¹. Frost occurrences are concentrated between May and August [20].

The Campo Gerais region presents itself as relictual forms of an ancient Pleistocene semi-arid climate, thus constituting the oldest floristic formation in the state of Paraná [3]. The region is characterized by extensive areas of open fields with high physiognomic homogeneity, predominantly herbaceous, devoid of or with low density of shrubs, by forest formations that occur in valleys, depressions and marginal areas to rivers or streams [2,4] and, occasionally, by fragments of *Cerrado* (savanna) [4].

2.2. Field Experiments

The experiments were carried out in the park's original use zone, an area not intended for visitation located in the northern part of the park. This zone refers to locations where little or minimal human intervention has occurred, which is important for conservation [18].

In addition to conserving the area, the following criteria were considered in selecting the study plot locations: vegetation typology, terrain slope, contour line orientation, prevailing wind direction, accessibility, park burning calendar, and history of fire occurrence. According to the park's fire occurrence records, the last fire in the study area occurred in November 1999 and affected approximately 686.1 ha.

The typology studied was the *stricto sensu* grassland [5]. The vegetation is predominantly herbaceous, with shrubby and arboreal plants sparsely distributed. The predominant wind direction is northeast, with an average speed of $3\text{--}4\text{ m}\cdot\text{s}^{-1}$. The predominant slope class in the study area is "undulating" (8–20%). The plots were installed parallel to the firebreaks and in areas with the same slope to reduce the slope's interference with fire behavior.

2.2.1. Controlled Burns

For the controlled burns, three plots, each approximately 0.08 ha, were spaced approximately 150 m apart in the northern portion of the park, and each area was divided into 5 subplots ($3 \times 20\text{ m}$). The determination of which subplots would receive the treatment was carried out at random by lottery. In total, 15 subplots were designated for burning. Two campaigns were conducted to implement controlled burns: the first on 31 August 2017, and the second on 4 September 2017.

Before the burning was carried out, samples of herbaceous fuel material were taken at three distinct points along each subplot, using a template ($20 \times 20\text{ cm}$), to determine the fuel load ($\text{kg}\cdot\text{m}^{-2}$) and its moisture content (%). Destructive samples of wet biomass were prepared, packaged in hermetic bags, and transported to the Wildfire Laboratory at UFPR. To determine the moisture content, the samples were oven-dried at $75\text{ }^{\circ}\text{C}$ until a constant mass was reached.

The initial ignition was carried out with a drip torch to form a line parallel to the subplot width, at the opposite end from the wind direction. Data collection on fire behavior was carried out systematically, with reading points spaced 2 m apart and marked with a 2 m-high stake graduated in 10 cm increments. In this way, 10 observations were made per plot. The fire behavior variables obtained during the burns were: (a) fire spread rate-ROS ($\text{m}\cdot\text{s}^{-1}$); (b) fireline intensity ($\text{kW}\cdot\text{m}^{-1}$); (c) residence time (s); (d) heat released per unit area ($\text{kW}\cdot\text{m}^{-2}$) [21,22].

At the beginning and end of each burn, the time and wind speed ($\text{m}\cdot\text{s}^{-1}$) were recorded, obtained using a Kestrel 4500® portable weather station. During the controlled burns, wind direction was monitored using a windsock located near the burning area and at a height of 2 m. Additionally, hourly data on air temperature ($^{\circ}\text{C}$), relative humidity (%), wind speed ($\text{m}\cdot\text{s}^{-1}$), and precipitation (mm) were obtained for the period from 18 August 2017 to 6 September 2017, from the standard weather station of the Sistema Meteorológico do Paraná (2017), located 4.7 km from the study area. After the burns, samples

were collected using a template (20 × 20 cm) at three different points in the subplot to determine the mass of residue left after the fire.

The fireline intensity was calculated using Byram's Equation (1):

$$I = Hwr, \quad (1)$$

where I is the fireline intensity ($\text{kW} \cdot \text{m}^{-1}$), H is the heat of combustion ($15,500 \text{ kJ} \cdot \text{kg}^{-1}$ [23]), w is the fuel load ($\text{kg} \cdot \text{m}^{-2}$), and r is the fire spread ($\text{m} \cdot \text{s}^{-1}$). To calculate the residence time, it was necessary to measure the flame depth. The flame length was obtained from the fireline intensity using Equation (2) [24].

$$L = 0.087I^{0.493}, \quad (2)$$

where L is the flame length (m), the flame depth was calculated using the Length-to-Depth ratio for grass fuel [25] (Equation (3)).

$$D = L/1.67, \quad (3)$$

where D is the flame depth (m). Thus, the residence time was calculated by Equation (4).

$$t_r = D/r, \quad (4)$$

where t_r is the residence time in seconds. The heat released per unit area was obtained using the following Equation (5):

$$H_a = I/r, \quad (5)$$

where H_a is the heat released per unit area ($\text{kW} \cdot \text{m}^{-2}$). To assess differences between the plots prior to the burns, a one-way ANOVA, followed by Tukey's HSD test, was applied to the mean values of the meteorological variables and fuel characteristics. The same test was applied to assess differences among the fire behavior variables. The data were processed using Microsoft 365 spreadsheets and Python's statsmodels library (version 0.14.6).

2.2.2. Monitoring of Fine Fuel

The characterization of fine surface fuel material followed methodological elements proposed by Brown et al. [26]. Five field campaigns were conducted over 19 months, as shown in Table 1:

Table 1. Post-burn sampling schedule.

Month	Year	Season	Interval
Nov/Dec	2017	Summer	3 months after the burning
Feb/Mar	2018	Autumn	6 months after the burning
Jun/Jul	2018	Winter	10 months after the burning
Sep/Oct	2018	Spring	13 months after the burning
Mar/Apr	2019	Autumn	19 months after the burning

Samples were collected using a 1 m² template. The collected material was classified according to the following categories: (a) live fuel with a diameter less than or equal to 0.7 cm, including herbaceous material, up to 1.80 m in height; (b) dead or dry fuel with a diameter less than or equal to 0.7 cm, including herbaceous material, up to 1.80 m in height. The sampling points were marked on a sketch to avoid overlapping the sampled areas.

After separating the combustible material, the total wet mass of each class within the 1 m² plot was measured with a balance. To obtain the dry mass, subsamples were prepared

for each fuel class and dried in an oven at 75 °C until no mass variation was observed. To determine the moisture content of the live fuel, the following Equation (6) was used:

$$MC = 100 (m_w - m_d)/m_d \quad (6)$$

where MC is the moisture content (%), m_w is the wet mass (kg), and m_d is the dry mass (kg). The moisture content was determined by considering both live and dead fuels.

2.2.3. Growth Modeling

Gompertz Equation (7) was used to model biomass increment dynamics. The model was individually fitted for each subplot and fuel component (live, dead, and total) using the non-linear regression method [27].

$$w = A_s \times e^{(-b_2 * b_3^{age})}, \quad (7)$$

where A_s is the upper asymptote (max fuel load in $\text{kg} \cdot \text{m}^{-2}$), b_2 is the y-intercept, b_3 determines the rate at which the asymptote is reached, and age is the time in months. To ensure comparability between experimental units, growth rates were calculated using the methodology proposed by Paine et al. [28]. The Absolute Growth Rate (AGR) in $\text{kg} \cdot \text{m}^{-2} \cdot \text{month}^{-1}$ was defined as the first derivative of the Gompertz function (Equation (8)).

$$\text{AGR} = (-\ln b_3 \times A)/e, \quad (8)$$

To characterize the rate of vegetation recovery, the time to peak productivity and the time at which the growth curve reaches 95% of the asymptote were calculated analytically using this formulation. To assess the influence of fire behavior on productivity, Spearman's correlation was computed among the variables: fireline intensity, residence time, heat released per unit area, Absolute Growth Rate, peak productivity time, and time to reach 95% of the asymptote.

The adjustment of a single global growth model for the plant typology studied was based on Tukey's HSD test results. In the event of a statistically significant difference, a model will be fitted per plot. All data were processed using Microsoft 365 spreadsheets and the Python libraries Scikit-learn and Scipy.

3. Results

3.1. Controlled Burns

Weather variables like temperature (T), relative humidity (RH), and wind speed (W) were recorded during the study period and remained within the recommended ranges for controlled burns. The average relative humidity on the first day of burning was 76.4%, with a maximum of 80.1% and a minimum of 71.6%. In comparison, on the second day, the average RH during the fires was 51.0%, and the average air temperatures were 17.2 °C and 22.4 °C on the first and second days of burning, respectively.

Table 2 shows a comparison of the means of the meteorological variables by plot (A, B, and C).

Weather conditions varied depending on the day and time the plots were burned. However, no statistically significant difference was observed for air temperature. Plot A showed a statistically significant difference, with an average relative humidity of 65.2%, while Plot C showed the highest average relative humidity at 77.8%. Plot B showed the highest wind speed ($2.2 \text{ m} \cdot \text{s}^{-1}$), being statistically similar to Plot A and significantly different from Plot C.

Table 2. Mean weather values for each subplot referring to the beginning and end of each burn.

Plot	Subplot	Weather Variables		
		RH (%)	T (°C)	W (m·s ⁻¹)
A	5	65.2 ^b	18.9 ^a	1.6 ^{ab}
B	5	74.0 ^{ab}	18.5 ^a	2.2 ^a
C	5	77.8 ^a	16.6 ^a	1.1 ^b

Means within a column followed by different letters differ significantly according to Tukey's HSD test ($p < 0.05$).

The one-way ANOVA revealed no statistically significant differences among the experimental plots (A, B, and C) for both initial fuel characteristics and fire behavior parameters. The plots showed homogeneity in pre-fire fuel load ($F = 3.79$, $p = 0.053$) and moisture content ($F = 1.69$, $p = 0.224$). The same pattern was observed during the prescribed burns, with no significant variations for the amount of fuel consumed ($F = 1.67$, $p = 0.229$), rate of spread ($F = 0.05$, $p = 0.949$), fireline intensity ($F = 1.89$, $p = 0.192$), and heat released ($F = 1.67$, $p = 0.229$). Consequently, the Tukey HSD post hoc test ($p < 0.05$) grouped all plots into a single class for all analyzed variables, confirming the uniformity of the applied disturbance. The variables of fire behavior and fuel characteristics are presented in Table 3.

Table 3. Characteristics of fuel before burning and fire behavior parameters.

Plot	Subplot	Fuel Load (kg·m ⁻²)	Moisture Content (%)	Fuel Consumed (kg m ⁻²)	ROS (m·s ⁻¹)	Fireline Intensity (kW m ⁻¹)	Residence Time (s)	Heat Released (kJ·m ⁻²)
A	1	1.52	39.23	1.08	0.0169	282.03	49.76	16,688.33
	2	0.9	23.33	0.65	0.0221	224.73	34.06	10,179.51
	3	0.95	34.83	0.48	0.0204	151.78	30.37	7440.00
	4	0.93	59.41	0.52	0.0148	118.52	37.06	8008.33
	5	0.85	47.50	0.71	0.0108	119.41	50.98	11,056.67
	Mean	1.03 ^a	40.86 ^a	0.69 ^a	0.0170 ^a	179.30 ^a	40.44 ^a	10,674.57 ^a
B	1	0.70	33.83	0.33	0.0181	92.58	26.83	5115.00
	2	0.70	29.81	0.31	0.0201	97.62	24.80	4856.67
	3	0.53	36.65	0.12	0.0169	32.31	17.10	1911.67
	4	1.05	35.43	0.75	0.0161	187.99	42.77	11,676.67
	5	0.70	50.38	0.46	0.0128	90.27	37.47	7052.50
	Mean	0.75 ^a	37.09 ^a	0.45 ^a	0.0167 ^a	116.72 ^a	31.79 ^a	7011.17 ^a
C	1	0.62	36.83	0.44	0.0110	75.59	39.95	6871.67
	2	0.49	37.91	0.35	0.0110	59.11	35.39	5373.33
	3	0.82	24.27	0.70	0.0114	123.10	49.02	10,798.33
	4	0.80	24.21	0.64	0.0103	102.71	49.62	9971.67
	5	0.70	24.01	0.34	0.0346	182.34	19.60	5270.00
	Mean	0.69 ^a	29.44 ^a	0.49 ^a	0.0157 ^a	108.57 ^a	38.72 ^a	7657.00 ^a

Means within a column followed by different letters differ significantly according to Tukey's HSD test ($p < 0.05$).

The fire spread rate showed averages between 0.0103 and 0.0346 m·s⁻¹. The fireline intensity ranged from 32.31 to 282.03 kW·m⁻¹. Neither variable showed a statistically significant difference.

The amount of fuel consumed ranged from 0.12 to 1.08 kg·m⁻², corresponding to an average consumption of 66% of the total dry load. The thermal effects on the ecosystem, measured by heat released and residence time, also showed no statistically significant difference. The average heat released ranged from 7011.17 kJ·m⁻² (Plot B) to 10,674.57 kJ·m⁻² (Plot A), values directly linked to the fuel consumed. The flame residence time showed averages between 31.79 and 40.44 s.

The absence of significant differences in these variables reinforces the idea that, despite occasional variations in meteorological conditions, the experiments yielded homogeneous results regarding fire behavior.

3.2. Monitoring of Fine Fuel

The dynamics of biomass recovery after controlled burning revealed a response typical of fire-dependent ecosystems. Three months post-disturbance, the total fine fuel load was $0.228 \text{ kg}\cdot\text{m}^{-2}$, composed entirely of living material (100.0%), with no accumulated dead material present. The results regarding the load of fine fuel material (dry mass) and the representativeness of each class for the five field campaigns are presented in Table 4.

Table 4. Overall means of biomass increase and live fuel moisture content.

Interval	Fuel Load (kg·m ⁻²)					Moisture Content (Live and Dead) (%)
	Live	%	Dead	%	Total	
3 months after burning	0.228	100.0	0.0	0.0	0.228	188.13
6 months after burning	0.359	72.5	0.136	27.5	0.495	148.94
10 months after burning	0.217	46.2	0.253	53.8	0.47	111.44
13 months after burning	0.315	53.8	0.27	46.2	0.585	128.6
19 months after burning	0.277	42.0	0.382	58.0	0.659	119.94

At six months, the live fuel reached its highest load value ($0.359 \text{ kg}\cdot\text{m}^{-2}$), representing 72.5% of the total load. Simultaneously, the emergence of dead fuel ($0.136 \text{ kg}\cdot\text{m}^{-2}$) was observed, reflecting the leaf renewal cycle and natural senescence. The evolution of vegetation's physiognomy can be observed in Figure 2.

The fine fuel moisture content (live and dead) showed a decreasing trend throughout the study period. At three months, the live fuel achieved a maximum value of 188.13% due to the young regrowth. At 10 months, the lowest overall mean value of moisture content (111.44%) was observed.

Although the vegetation appeared denser throughout the analyzed period, live fuel load declined during the winter (10 months after the fire) to $0.217 \text{ kg}\cdot\text{m}^{-2}$, while dead fuel load increased to $0.253 \text{ kg}\cdot\text{m}^{-2}$.

Samples collected 19 months after the fire showed the vegetation transitioning to a more flammable state. The total load reached $0.659 \text{ kg}\cdot\text{m}^{-2}$, with an increase in dead fuel ($0.382 \text{ kg}\cdot\text{m}^{-2}$), representing 58.0% of the total.

3.3. Growth Modeling

Alday's reparametrized Gompertz model proved suitable for modeling biomass increment, with almost all R^2 values above 0.8. Table A1 presents the adjustment coefficients for each subplot.

The fitted parameters indicated that the maximum potential load (As) of the total biomass ranged from 0.442 to $0.759 \text{ kg}\cdot\text{m}^{-2}$ —the dead fuel fraction, on average, exhibited higher asymptotes than the living component. The coefficients b_2 and b_3 reflected heterogeneity in maturation rates and initial regrowth vigor among sampling units. In some subplots, the b_2 coefficient reached the upper fit limit of 50,000, reflecting the mathematical requirement for the model to start the curve at a zero-biomass value at time zero. Table 5 presents the biological indicators of regeneration, highlighting a striking contrast between the dynamics of the living and dead components.

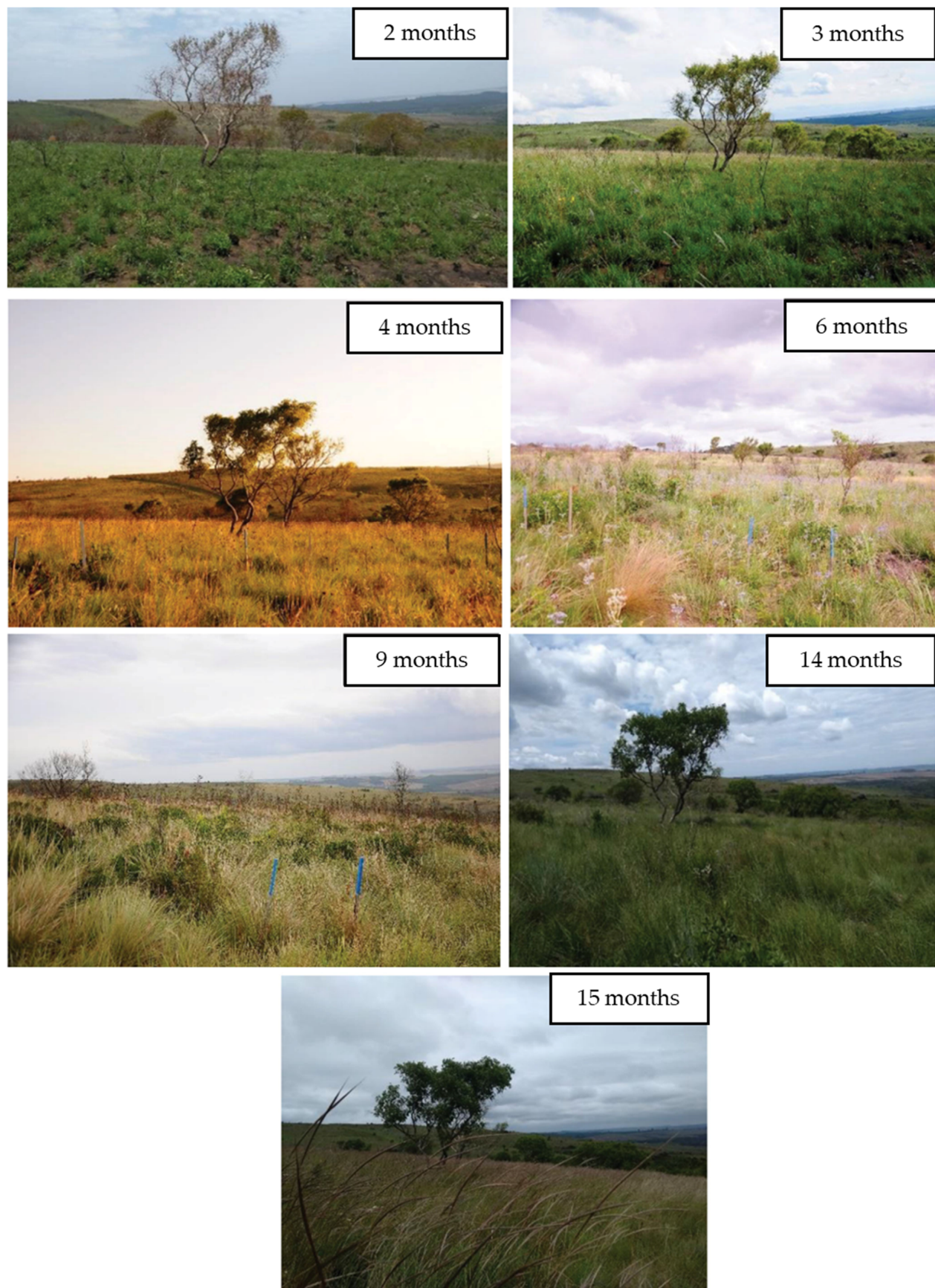


Figure 2. Monitoring biomass increase over 19 months.

Table 5. Values related to the biological dynamics of regeneration derived from the Gompertz models.

Plot	Subplot	Dead			Live			Total		
		AGR (kg·m ⁻² · month ⁻¹)	Peak (Month)	As95% (Month)	AGR (kg·m ⁻² · month ⁻¹)	Peak (Month)	As95% (Month)	AGR (kg·m ⁻² · month ⁻¹)	Peak (Month)	As95% (Month)
A	1	0.026	9.901	34.249	0.185	2.152	3.786	0.110	2.886	8.609
	2	0.041	7.369	17.863	0.417	0.477	1.122	0.074	2.762	11.054
	3	0.037	7.574	18.556	0.184	1.844	3.244	0.056	3.503	14.728
	4	0.071	5.834	10.264	0.200	1.764	3.103	0.144	2.664	6.399
	5	0.030	12.883	37.069	0.179	2.017	3.548	0.042	5.934	25.872
	Mean	0.0411 ^a	8.712 ^a	23.000 ^a	0.233 ^a	1.651 ^a	2.960 ^a	0.0852 ^a	3.550 ^a	13.332 ^a
B	1	0.018	8.415	36.100	0.395	0.439	1.084	0.126	1.843	5.807
	2	0.076	5.314	9.348	0.121	1.298	3.614	0.086	2.879	9.817
	3	0.032	6.293	14.868	0.222	1.665	2.929	0.087	2.324	8.249
	4	0.064	4.754	8.816	0.355	0.450	1.095	0.079	2.275	8.409
	5	0.079	6.507	11.448	0.170	2.677	4.710	0.100	3.823	11.159
	Mean	0.0538 ^a	6.257 ^a	16.116 ^a	0.253 ^a	1.306 ^a	2.686 ^a	0.0954 ^a	2.629 ^a	8.688 ^a
C	1	0.066	7.595	13.362	0.140	1.336	3.736	0.057	4.393	18.406
	2	0.048	5.227	12.078	0.455	0.462	1.107	0.112	2.227	7.395
	3	0.074	4.874	8.575	0.187	2.372	4.173	0.266	2.905	5.110
	4	0.070	5.738	10.095	0.190	1.919	3.376	0.117	2.665	7.382
	5	0.036	5.704	14.070	0.198	2.029	3.570	0.258	2.775	4.882
	Mean	0.0587 ^a	5.828 ^a	11.636 ^a	0.234 ^a	1.624 ^a	3.193 ^a	0.162 ^a	2.993 ^a	8.635 ^a

Means within a column followed by different letters differ significantly according to Tukey's HSD test ($p < 0.05$).

The one-way ANOVA revealed no statistically significant differences among the experimental plots (A, B, and C) regarding the growth variables and biological regeneration dynamics. This homogeneous pattern was confirmed for total biomass increment (Absolute Growth Rate-AGR: $F = 2.38$, $p = 0.135$; Peak time: $F = 1.03$, $p = 0.387$; Maturity time/As95%: $F = 1.16$, $p = 0.346$), as well as for the live and dead components individually (all with $p > 0.05$). Consequently, the Tukey HSD post hoc test grouped all three plots into the same similarity class. Despite the apparent variations in the absolute means of Plot A compared to the others, the high data variance confirms the statistical homogeneity, indicating that the ecosystem responded uniformly to the disturbance.

Live fuel showed the highest Absolute Growth Rates (AGRs), with peak values frequently occurring within 2 months and a minimum of 0.43 months. In contrast, the dead component showed the lowest AGRs and significantly later peak times, occurring mostly between the fifth and ninth months. Only plot A5 showed a production peak at 12.88 months.

For total biomass, AGRs ranged from 0.042 to 0.266 kg·m⁻²·month⁻¹, with peak production occurring within an intermediate window between 1.84 and 5.93 months. Regarding the fuel load stabilization time (As95%), total values ranged from 4.88 to 25.87 months. In all plots, the dead component showed higher final stabilization values and greater variability than the live component, as reflected in the evolution of the total load.

Spearman's correlation analysis ($n = 15$) revealed that fire behavior variables were not significantly associated with the vegetation recovery timelines, supporting the hypothesis of biological independence from low-severity fire variations. For instance, fireline intensity showed non-significant coefficients close to zero for the peak time ($r = 0.11$, $p = 0.685$) and maturity time ($r = 0.10$, $p = 0.723$) of the living component. Similarly, heat released and residence time showed no significant correlations with the biological parameters; the highest association observed was between residence time and the peak time of total biomass, which remained statistically non-significant ($r = 0.43$, $p = 0.114$).

Regarding the fire variables themselves, the data showed expected behavior, with highly significant positive correlations between heat released and residence time ($r = 0.78$, $p < 0.001$), and between heat released and fireline intensity ($r = 0.69$, $p = 0.005$). Regarding

fire variables, the data showed expected behavior, with positive correlations between heat released and residence time (0.78), and between heat released and fireline intensity (0.68).

Since there was no statistically significant difference in the growth variables according to the Tukey HSD test, modeling was performed for each of the three components. Table 6 presents the fitted coefficients from the Gompertz model for all data.

Table 6. Gompertz model fitted coefficients.

Component	A_s ($\text{kg}\cdot\text{m}^{-2}$)	b_2	b_3	R^2	RMSE ($\text{kg}\cdot\text{m}^{-2}$)	MAE ($\text{kg}\cdot\text{m}^{-2}$)
Dead	0.294	15.791	0.622	0.777	0.0610	0.0471
Live	0.261	50.000	0.124	0.698	0.0630	0.0421
Total	0.530	3.400	0.628	0.859	0.0792	0.0573

The Gompertz global model fit presented asymptotes (A_s) ranging from $0.2608 \text{ kg}\cdot\text{m}^{-2}$ for the living component to $0.5305 \text{ kg}\cdot\text{m}^{-2}$ for the total biomass. The shape coefficients b_2 and b_3 described the different accumulation trajectories, highlighting the living component, in which the model captured accelerated growth. For the dead fuel, the asymptote of $0.2939 \text{ kg}\cdot\text{m}^{-2}$ slightly exceeded that of the living component, showing a greater proportion of this component. Figure 3 shows the curve fitted for each fuel component.

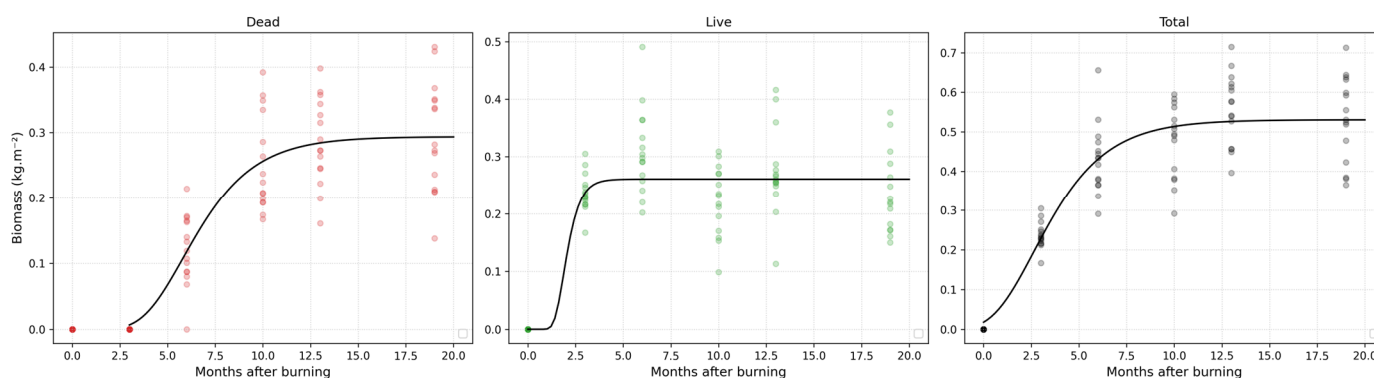


Figure 3. Fitted Gompertz growth curves.

In terms of statistical accuracy, the model demonstrated a good fit, especially for total biomass, which achieved the highest coefficient of determination ($R^2 = 0.86$). The mean absolute errors (MAE) ranged from 0.0471 to $0.0573 \text{ kg}\cdot\text{m}^{-2}$, and the root mean square errors (RMSE) ranged from 0.0421 to $0.0792 \text{ kg}\cdot\text{m}^{-2}$.

4. Discussion

4.1. Controlled Burns

As demonstrated previously, air temperature alone did not show a statistically significant difference. The variability of weather variables within the same experiment is noted by other authors, who cite this as one of the main difficulties in conducting experiments in open environments [2,16,29].

Described as a limiting factor for fire occurrence, precipitation easily alters the moisture content of vegetation and soil. The experiment was carried out 10 to 14 days after the last rain, which occurred on the 20th ($\sim 40 \text{ mm}$) and 21st ($\sim 10 \text{ mm}$) of August [30]. However, Santos et al. [31] observed that even with dew-induced precipitation raising the moisture content to $\sim 140\%$ at that same location, the fine fuel's exposure to wind and solar radiation means its moisture content quickly reaches $\sim 10\%$ during the hottest hours of the day.

The average moisture content of herbaceous fuel material (live and dead) from the collections conducted on 31 August and 4 September was lower than that reported by Seger et al. [5] but close to that reported by Fidelis et al. [32], ranging from 37.8 to 44.5%. Seger et al. [2] experimented with the same type of fuel at an average post-winter moisture content of 50%, with variations ranging from 38 to 61%. However, it is worth noting that the time lag (response time to weather variations) of the two fuel types differs across weather variables. Even though they are fine fuels, the live component varies seasonally in response to the dry season, while dead fuel responds to meteorological variation within a 1 h interval. The degree of curing is a determining factor in the fire behavior of grasses [33–35].

The average load of herbaceous fuel material (oven-dried) observed *stricto sensu* grassland before the burns was lower than that reported by Santos [33], Seger et al. [5], and Fidelis et al. [32] for southern grasslands with six years without fire ($\sim 1 \text{ kg} \cdot \text{m}^{-2}$).

The mean fire ROS observed was similar to the maximum observed by Seger et al. [2] using the backing fire technique. Conceptually, even in uncontrolled fires, the part propagating against the wind direction has a lower propagation rate than the fire front [36]. The average fireline intensity values were lower than those observed by Seger et al. [2]. This is due to both the low fire ROS and the low fuel consumption. Rego et al. [36] highlight the importance of prescribed burns for understanding fire growth, particularly the acceleration phase, in which fireline intensity determines fire controllability.

Batista et al. [16], in controlled burns conducted in *Pinus elliottii* stands, observed an empirically derived average residence time of 174 s. Silva [37] reports that wind speed is one of the factors that affect both the ROS and the intensity of the fireline, and consequently the residence time.

It is known that variable residence time influences the thermal effects of fire on the vegetation and soil in the affected area; however, the differences among the values discussed also reflect differences between the environments in which each test was carried out. The high value obtained empirically from the burns conducted by Batista et al. [16] can be explained by the experiment being carried out inside the settlement and with an average wind speed of $0.25 \text{ m} \cdot \text{s}^{-1}$. Burns carried out in environments with a predominant lack of wind tend to have a narrower flame depth and a proportionally much lower ROS due to reduced oxygen availability, thereby increasing the residence time [14,22,36]. However, Seger et al. [2], in burns conducted in southern grasslands, observed 60 s values higher than those in this study. Even with similar mean ROS, the authors found higher average fireline intensities due to greater fuel availability and consequent higher consumption.

The average values observed for heat released were lower than those recorded by Seger et al. [2]. When comparing the technique against the wind, the authors did not find a statistically significant difference in heat released.

4.2. Monitoring of Fine Fuel

Seger [38] observed that the total biomass load in a similar grassland area recovered in approximately six months. The author suggests that the area's meteorological and environmental conditions were the main factors behind the accelerated increase in total biomass, since the burning was carried out after the winter (dry season) and was followed by the rainy season, a situation similar to that of the present study. Dimitrakopoulos and Bemmerzouk [39] point out that moisture deficiency in the topsoil layer during this initial phase, or its reduction due to dry, hot weather, can affect growth.

In this regard, Rissi [40] reported a delay in the increase in total biomass, compared to the previous biomass rate, for burns carried out before (12 months) and in the middle of the dry season (7 months) in relation to burns carried out at the end of the dry season (3 months) in *cerrado* scrubland areas. The live biomass load recovered in the first two

months, with regrowth observed seven days after the burn; in some cases, recovery may occur in just two days [38]. The live biomass can be re-established within 3 to 4 months [40]. The tufts are useful in the plant's resistance to fire, allowing for almost immediate regrowth after disturbance, a characteristic of grasses. The seed bank influences vegetation's rapid response [13,38]. However, the great adaptation of perennial species lies in their underground organs, which, due to the insulating effect of the topsoil layer, escape the destructive effects of fire and can sprout days or weeks after its occurrence [13]. Another factor mentioned is the availability of mineral nutrients after burning that are immobilized in the inert, dry biomass [14].

The mean total fuel load after biomass increase stabilized was lower than that observed for the area before the burns (~18 years without fire), showing that hypothesis (a) is true. Controlling the fine fuel load is beneficial mainly for preventing large-scale fires, reducing fireline intensity, and mitigating negative effects on vegetation [14]. However, Franke et al. [41] state that prescribed burns can reduce only hazardous fuel, not total biomass. Other authors also add that biennial burns in grasses do not reduce the total load in the long term [42].

4.3. Growth Modeling

The use of the Gompertz model reparametrized by Alday et al. [27] proved adequate. It reflected a typical response of fire-dependent ecosystems, where the resilience of the vegetation allows a return to pre-disturbance growth patterns [28]. Although variations in fuel load were observed between plots, the model accurately represented the average behavior of the evaluated increase in biomass.

When testing hypothesis (b), that low-intensity controlled burns do not compromise biomass resilience, the modeling results reinforce the vegetation's rapid recovery capacity. The correlation analysis of Absolute Growth Rates (AGRs) and peak productivity times with fire behavior variables indicated that vegetation rapidly recovers its initial vigor. Gomes et al. [42] found that grasses demonstrated resilience to fire, rapidly recovering their previous total biomass approximately 15 months after the disturbance.

However, it is important to consider that the proportions of live and dead fuels differed. Seger [43] described the following class representation: 9.97% live, 55.16% dead, and 34.87% miscellaneous. Dead biomass exhibited higher final asymptotes than the live component, reflecting the natural cycle observed in post-fire vegetation [27]. The variation observed in the load of live fuel material after its stabilization can be explained by the influence of precipitation seasonality [40].

Finally, the adjusted models confirm that the biomass resilience and recovery capacity of the *stricto sensu* grassland is not adversely affected by low-intensity controlled burning. The good fit obtained with the Gompertz model, especially for total load, allows the use of this tool for decision-making in protected areas. As suggested by Paine et al. [28], the choice of a biologically interpretable model is fundamental to the management of these ecosystems, allowing managers to use fire not only as a fuel-control measure but also as a conservation tool that respects the regeneration dynamics and stability of the vegetation typology under study.

5. Conclusions

Based on the results obtained, it can be concluded that:

- The use of prescribed low-intensity burns reduced the total load relative to the pre-disturbance fuel load.
- The results confirm hypothesis (b), indicating that controlled low-intensity burns do not compromise the biomass resilience and recovery capacity of the *stricto sensu*

grassland vegetation. The rapid recovery observed attests to the resilience of this ecosystem in the face of low-severity fire disturbances.

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Appendix A

Table A1. Coefficients for modeling biomass increase, where A_s is the maximum potential load, b_2 relates to the y-intercept, and b_3 determines the rate at which the asymptote is reached.

Plot	Subplot	Dead				Live				Total			
		A_s (kg·m ⁻²)	b_2	b_3	R^2	A_s (kg·m ⁻²)	b_2	b_3	R^2	A_s (kg·m ⁻²)	b_2	b_3	R^2
A	1	0.580	3.346	0.885	0.904	0.277	50.000	0.162	0.736	0.578	4.473	0.595	0.984
	2	0.391	8.052	0.753	0.882	0.246	8.978	0.010	0.870	0.560	2.689	0.699	0.886
	3	0.375	7.757	0.763	0.914	0.235	50.000	0.120	0.962	0.575	2.527	0.767	0.917
	4	0.288	50.000	0.511	0.761	0.246	50.000	0.109	0.653	0.493	8.324	0.451	0.913
	5	0.671	4.865	0.884	0.978	0.251	50.000	0.144	0.494	0.759	2.420	0.862	0.862
B	1	0.448	2.466	0.898	0.654	0.233	7.548	0.010	0.802	0.459	3.978	0.473	0.850
	2	0.280	50.000	0.479	0.831	0.256	5.282	0.277	0.921	0.543	3.429	0.652	0.976
	3	0.255	8.843	0.707	0.964	0.257	50.000	0.095	0.937	0.471	3.206	0.606	0.990
	4	0.237	32.331	0.481	0.900	0.210	7.958	0.010	0.763	0.442	3.009	0.616	0.839
	5	0.358	50.000	0.548	0.978	0.316	50.000	0.232	0.819	0.668	4.702	0.667	0.984
C	1	0.350	50.000	0.597	0.983	0.307	5.221	0.290	0.899	0.731	2.538	0.809	0.944
	2	0.298	9.643	0.648	0.890	0.268	8.412	0.010	0.641	0.532	3.596	0.563	0.926
	3	0.250	50.000	0.448	0.988	0.308	50.000	0.192	0.613	0.536	50.000	0.260	0.915
	4	0.280	50.000	0.506	0.666	0.254	50.000	0.130	0.834	0.504	5.357	0.533	0.862
	5	0.276	7.579	0.701	0.962	0.279	50.000	0.145	0.664	0.498	50.000	0.244	0.961

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