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Effects of Prescribed Burns on Soil Respiration in Semi-Arid Grasslands

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Abstract: Carbon fluxes are valuable indicators of soil and ecosystem health, particularly in the context of climate change, where reducing carbon emissions from anthropogenic activities, such as forest fires, is a global priority. This study aimed to evaluate the impact of prescribed burns on soil respiration in semi-arid grasslands. Two treatments were applied: a prescribed burn on a 12.29 ha paddock of an introduced grass (*Eragostis curvula*) with 11.6 t ha^{-1} of available fuel, and a simulation of three fire intensities, over 28 circular plots (80 cm in diameter) of natural grasslands (*Bouteloua gracilis*). Fire intensities were simulated by burning with butane gas inside an iron barrel, which represented three amounts of fuel biomass and an unburned treatment. Soil respiration was measured with a soil respiration chamber over two months, with readings collected in the morning and afternoon. Moreover, CO_2 emissions by combustion and productivity after fire treatment were quantified. The prescribed burns significantly reduced soil respiration: all fire intensities resulted in a decrease in soil respiration when compared with the unburned area. Changes in albedo increased the soil temperature; however, there was no relationship between changes in temperature and soil respiration; in contrast, precipitation highly stimulated it. These findings suggest that fire, under certain conditions, may not lead to more CO_2 being emitted into the atmosphere by stimulating soil respiration, whereas aboveground biomass was reduced by 60%. However, considering the effects of fire in the long-term on changes in nutrient deposition, aboveground and belowground biomass, and soil properties is crucial to effectively quantify its impact on the global carbon cycle.

Keywords: biomass combustion; carbon dioxide; wildfire; ecosystem respiration

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1. Introduction

Climate change is the result of the increased emission of greenhouse gases (GHGs) primarily from the use of fossil fuels (coal, natural gas, and oil), as well as land-use changes due to livestock farming, agriculture, and forest fires [1]. These activities have released large quantities of GHGs into the atmosphere, such that the concentration of CO_2, the gas with the largest contribution to global warming, has increased from 320 ppm in 1960 to around 420 ppm in 2022 [2].

The concentration of CO_2 in the atmosphere varies seasonally, as large quantities of atmospheric CO_2 are removed by oceans and terrestrial ecosystems [3]. These carbon (C) sinks have retained 55% of anthropogenic CO_2 emissions in recent decades [4]. However, about half of the absorbed C is released back into the atmosphere through plant respiration, and another 50% is released through the decomposition of soil organic matter [5]. Fires around the world are another important source of CO_2 in many ecosystems. In the last

fire season, 2.4 Pg C was emitted to the atmosphere, which was 16% above the average due to some extreme events at different ecosystems in South and North America, Europe, and Hawaii, but is expected that at the end of this century fires of these magnitudes will be between 6 and 10 times more frequent under a moderate climate change scenario [6]. These increases are associated with weather; future drier and warmer conditions will favor wildfires, but also more available biomass fuel is projected in future through the enhancement of the primary productivity of forests in a richer CO_2 atmosphere [7].

Fire is a natural disturbance in many ecosystems like grasslands and savannas, which contribute to 80% of the wildfires around the world [8]; in these ecosystems, more than having negative effects, periodic wildfires may contribute to enhance productivity by accelerating nutrient cycling [9] and removing dead standing biomass [10] that blocks light to new photosynthetic leaves. The function and the structure of the ecosystem are determined to a large extent by fire frequency; however, highly recurrent fires, more than the negative effects on vegetation, may contribute to increase atmospheric CO_2 concentrations by combustion of biomass and by stimulation of soil respiration, whose effect may last for a longer time. Fire alters soil microclimatic conditions by changing the albedo due to the generation of a dark soot cover and increased soil exposure. This, in turn, raises soil temperature and reduces moisture due to increased evaporation [11]. These conditions may either increase or decrease soil respiration. However, information on the effects of fire on soil respiration and its indirect contribution to net CO_2 emissions in grassland ecosystems is limited.

Soil is the most important C reservoir, as it can store three times more C than vegetation [12]. Part of this C is released through the respiration process of microorganisms that degrade organic matter contained in the soil [13], and their activity is controlled by soil moisture and temperature, and the quantity and quality of organic matter and root content [3]. Soil respiration represents approximately 75% of total ecosystem respiration [14,15] making its study and the quantification of its controls crucial in climate change management and adaptation plans [16]. For instance, soils managed sustainably could mitigate the effects of climate change, whereas poorly managed soils could act in the opposite direction, increasing CO_2 concentrations and exacerbating climate change effects [12,17].

In Mexico, arid and semi-arid ecosystems occupy approximately 52% of the national territory and contain various types of vegetation, such as shrubs and grasslands [18]. This portion of land and vegetation is significant in terms of carbon storage reserves, which can reach up to 90% in grasslands and 45% in shrublands [19]. Most of these ecosystems are affected by land-use changes, primarily for livestock grazing, and in the worst cases, they are converted into rainfed agricultural land [20,21]. This has caused a drastic reduction in the amount of biomass above and within the soil, as well as the loss of carbon due to erosion [22]. The reduction of aerial biomass has also altered fire regimes, a disturbance that historically kept shrub densities low. Conversely, some management programs have intentionally excluded fire, resulting in greater biomass accumulation, which has led to more severe accidental wildfires [4,23]. For this reason, the integrated use of fire has gained attention recently as a measure for managing and restoring grassland ecosystems [24,25]. Prescribed fires are indicated for recovering ecosystem functionality and productivity in semi-arid grasslands of north of Mexico, mainly for those invaded by shrubs; however, carbon emissions and productivity postfire are rarely quantified.

Considering the longer-lasting effects of fire on soil, we aimed to quantify the contribution of soil respiration to CO_2 emissions, as an additional source to the combustion of aboveground biomass. Our hypothesis is that the increase in soil temperature due to the direct effect of fire and changes in soil albedo will result in increased soil respiration; thus, more intense fires will lead to greater CO_2 emissions from combustion and from soil respiration. We evaluate these hypotheses on a burned area of a semi-arid grassland and by simulating three fire intensities based on three levels of available biomass in the plains of Ojuelos, Jalisco, Mexico, which are part of the central grasslands of North America.

2. Materials and Methods

2.1. Study Area

The experimental area is located in the Llanos de Ojuelos, Jalisco (21°46′52.25″ N, 101°36′29.56″ W, 2240 m above sea level) in central Mexico (Figure 1). The average annual precipitation is 424 mm, with rainfall occurring between July and September, and the average annual temperature is 18 °C. The topography is nearly flat, with a slope of less than 3%. The soils are shallow, of the haplic xerosol type, with a medium texture (sandy loam) and a duric phase (tepetate) at a depth of 50 to 100 cm [26].

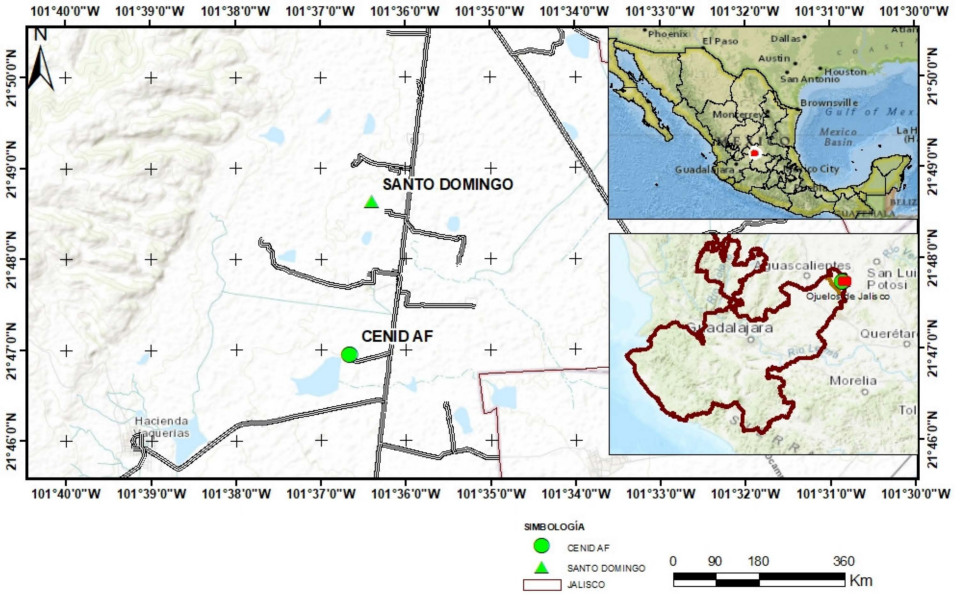


Figure 1. Location map of the study area and experimental plot design.

The plant community is dominated by shrubs and grasslands. The grasslands mainly consist of species such as blue grama (*Bouteloua gracilis*), wolf tail (*Lycurus phleoides*), scorpion grass (*Bouteloua scorpioides*), three-awn grass (*Aristida divaricata*), buffalo grass (*Bouteloua dactyloides*), silver beardgrass (*Bothriochloa barbinodis*), muhly grass (*Muhlenbergia rigida*), and hairy grama (*Bouteloua hirsuta*), interspersed with shrubs and woody plants such as huizache (*Vachelia schaffneri*), catclaw mimosa (*Mimosa biuncifera*), and mesquite (*Prosopis laevigata*). The herbaceous vegetation includes species such as brickellbush (*Brickellia spinulosa*), serrated stevia (*Stevia serrata*), button eryngo (*Eryngium carlinae* F. Delaroche), and silverleaf nightshade (*Solanum elaeagnifolium*), among others.

Two areas were selected for the study. One of them was located in the Santo Domingo Ranch, where a prescribed burning was applied to a high-biomass prairie of *Eragrostis curvula* was applied. The second site was located in the National Center of Interdisciplinary Research on Family Farming (CENID AF), where simulations of different intensities of fire on a native grassland were performed with a portable butane gas barrel (Figure 1). Both sites shared similar characteristics of soil, climate, and vegetation.

2.2. Prescribed Burning

To evaluate the effect of prescribed burns on soil respiration, a treatment was applied over a 20 ha area with a slope of less than 3%, predominantly covered by *Eragrostis curvula* (weeping lovegrass) and some *Acacia schaffneri* shrubs, with a fuel load of 11.60 t/ha. The amount of biomass in this site was 5–6 times higher than common natural/pristine semiarid grassland in the Chihuahuan desert. It consisted of a fenced paddock with cultivated weeping lovegrass, which was unburned and under moderate grazing for 15 years. This led to an overaccumulation of grass standing biomass in dead tussocks of highly lignified tissues not palatable for cattle. The aim of the prescribed burning was to

regenerate productivity by removing the dead standing biomass, stimulating the regrowth of new more palatable leaves.

For effectively control and management of the fire, the area was divided in the middle and prescribed burns were conducted on different dates minimizing risks and ensuring that the most favorable weather conditions were selected. The first prescribed burn was conducted on 29 March 2021. A head-fire burn was applied, with relative humidity exceeding 30% and wind speeds below 10 km/h from the south-southeast. The second prescribed burn was performed on 26 April 2021, with relative humidity again exceeding 30% and wind speeds under 7 km/h from the south. The higher fuel load resulted in flame heights reaching approximately 10 m. Fires on grasslands are characterized by being fast and intense. The fire consumes all biomass aboveground leaving large amounts of ashes and charcoal above the soil. Higher temperatures are reached at the crown of fire, whereas just above the soil they do not increase drastically, and minimum temperature changes are observed deeper in soil. In our site, the burning treatment lasted for less than 10 min, which was enough to consume all the grass biomass.

In the first area, estimations of the combustion of biomass and the charcoal residues were made at the end of fire as described in the following section. Also, an eddy covariance tower was installed for monitoring carbon fluxes (see following sections). In the second area, soil respiration measurements were taken. There was not any precipitation event, and weather conditions of temperature and relative humidity remained similar between the burning dates.

2.3. Aboveground Biomass

Ten 1 m^2 (1 m × 1 m) random plots were established. In each plot, biomass and species diversity were measured before and after treatment application. The samples were separated into live and dead matter to differentiate the biomass from the previous year. Additionally, the percentages of grasses and herbaceous plants were identified and quantified.

2.4. CO_2 Emissions from Combustion

Carbon emissions from combustion were estimated by calculating the difference between the fuel load and the charcoal residues. After the burn, carbon residues and partially burned material were collected from 1 m^2 plots adjacent to those used for fuel load estimation. This material was dried in an oven at 60 °C for 72 h until a constant weight was achieved. It was assumed that 50% of the biomass consists of carbon, and the following formula was used to calculate the carbon emissions from combustion (*Ec*):

$$Ec = (biomass\ before\ burn - charcoal\ residues) \times 0.5 \quad (1)$$

2.5. Net Ecosystem Exchange of Carbon (NEE)

Net ecosystem carbon exchange (NEE) was monitored using the eddy covariance method [27] in the prescribed burn area. NEE represents the sum of CO_2 uptake by plants through photosynthesis and CO_2 release to the atmosphere from soil microorganisms (heterotrophic respiration) and plant respiration (autotrophic respiration from roots and aboveground biomass). The eddy covariance system measures the balance between these fluxes. To determine the contribution of photosynthesis and respiration, flux partitioning methods [28] are required. However, when all vegetation is in senescence or during nighttime (when no photosynthesis occurs), the measured fluxes come solely from respiration. The measurements were conducted during the same period as the soil respiration measurements, which were used as reference data to determine grassland productivity during the growing season. The data were processed according to standard procedures, including spike removal, coordinate rotation, time delay correction, WPL correction for air density fluctuations, stationarity checks, and turbulence generation [29]. A four-component net radiation sensor (NR01, Hukseflux, Delft, The Netherlands) was mounted in the tower of the eddy covariance for monitoring changes in albedo.

2.6. Fuel Load Simulation

To simulate different fuel loads and fire intensities, controlled burns with the barrel method [30] were conducted. Seven sampling plots were randomly selected for each treatment, along with a control (no burn) on a 500 m^2 strip where *Bouteloua gracilis* was the dominant species. A total of 28 plots (3 treatments + control × 7 replicates) were established and marked with metal tags prior to the burn. Three biomass loads of 800, 1500, and 2500 kg/ha were simulated (Table 1). This corresponded to a low, medium, and high biomass load for a natural semi-arid grassland. A linear regression equation based on butane gas pressure and time [31] was applied to simulate fire intensity.

Table 1. Temperatures reached with the simulation of fuel loads using a portable butane gas burner.

Kg DM	Temperature (°C)	Pressure (PSI)	Time (S)
800	112.48	10	5.58
1500	142.28	10	10.8
2500	184.83	10	18.24

Calibration:

$$Fire\ intensity = -30.613 + 157x_1 + 5.719x_2\ (R^2 = 0.881) \quad (2)$$

where:

x_1 = gas pressure (kg/cm^2)

x_2 = time (seconds).

2.7. Soil Respiration

To determine the effect of burning on soil respiration, CO_2 fluxes from the soil were measured using a portable photosynthesis system (LI-6400/XT; Li-Cor, Lincoln, NE, USA) attached to a soil respiration chamber (6400-09). Measurements were taken one day before the burn and for one month following the burn. Two measurements were made per day between 7 and 9 a.m., and between 3 and 5 p.m. (morning and afternoon) to better represent the response of respiration to soil temperature. PVC collars 5 cm in height were placed in position one day before the measurements began and remained on site throughout the monitoring period. The PVC collars were inserted into the soil to prevent horizontal flow into or out of the chamber. The respiration chamber was placed over the collars for the measurements.

Moreover, to determine the effect of fire intensity on the sensitivity of soil respiration to temperature, data were fitted to an exponential model:

$$SR = Rb * \exp(k * Ts) \quad (3)$$

where:

SR = soil respiration

Rb = basal respiration (empirical coefficient)

k = empirical coefficient

and,

$$Q_{10} = \exp(10 * k) \quad (4)$$

where:

Q_{10} = respiration sensitivity to temperature (the factor by which respiration increases with an increase of 10 °C of soil temperature).

2.8. Data Analysis

All data were checked to ensure they met the assumptions of normality and homogeneity of variances (Shapiro–Wilk test) before parametric tests were performed. To analyze

the effect of fire intensity on soil respiration, a repeated measures analysis of variance ($\alpha = 0.05$) was performed comparing respiration rates across different fire intensities over time. The respiration data collected in the morning and afternoon were analyzed separately to avoid the effects of the diurnal temperature cycle on respiration. A non-linear regression (Marquardt–Levenberg method) was performed for calculating the parameters of an exponential relationship between soil respiration and soil temperature. All analyses were conducted using R software (version 3.3.2) [32].

3. Results and Discussion

3.1. Aerial Biomass

The fuel availability (dry aerial biomass) was 11.3 ± 0.38 t ha^{-1} (Figure 2), which was very high compared to natural grasslands in the region (<2.5 t ha^{-1} under moderate grazing conditions). It is worth noting that this grassland had not been subject to a prescribed burn or accidental fire for 15 years. However, the grassland has been under moderate grazing for the past 10 years.

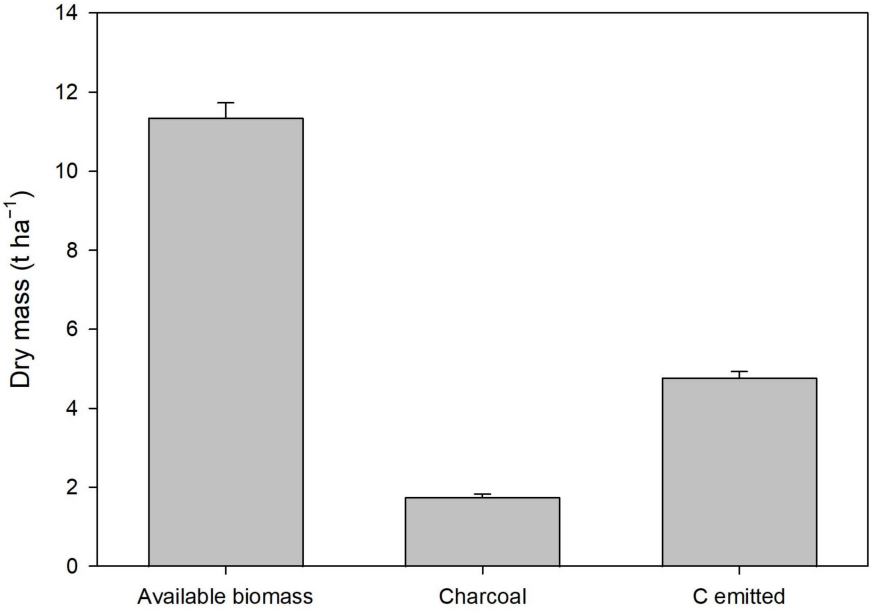


Figure 2. Availability of initial biomass, residual biomass, and emitted carbon after prescribed burn application.

This condition of overaccumulation of biomass is rare in semi-arid grasslands of Mexico since most of these lands are overgrazed. High pressures of cattle and goats herds consume almost all grass and herbaceous cover, and lands tend to soil erosion and the invasion of native and nonnative shrubs [33].

3.2. Biomass Productivity After Prescribed Burning Treatments

The productivity of the plots after the application of the treatments (5 months) was on average 3.42 t ha^{-1} of dry biomass, representing 30.2% of the biomass productivity from the initial load. Eight months after the burning treatments with the barrel, biomass productivity showed 75% regeneration in the low-intensity treatment compared to the control, while the medium- and high-intensity treatments had 67% and 61% regeneration, respectively (Table 2).

Table 2. Averages of aboveground (g m^{-2}) and roots productivity after burns with tonnage.

Treatment Intensity	Regenerated Biomass	Level (0–15)	Level (15–30)
Low	215.32	0.17	0.16
Medium	191.64	0.17	0.15
High	173.64	0.17	0.12
Control	284.60	0.17	0.16

3.3. Biomass Productivity After Prescribed Burns

All three treatments with varying fire intensities reduced their productivity in the first phenological cycle, ranging from 61% to 75% relative to the control. The low-intensity treatment exhibited the highest regeneration percentage, with 75% compared to the control.

Bock et al. [34] observed in a savanna and grassland that coverage with two types of vegetation was significantly lower in burned sites compared to unburned sites. However, by the first year, the plots showed 80% similarity in coverage relative to the control, and by the second year, around 90%. Flores Ancira et al. [35] also reported increased productivity and forage quality following prescribed burns, with 168.7 g m^{-2} for the first year and 393.7 g m^{-2} for the second year. In contrast, unburned areas showed decreased productivity, with values of 53.9 g m^{-2} in the first year and 192.7 g m^{-2} in the second year.

Finally, Johnson and Matchett [36] found that in a pasture managed with grazing and fire, there was a 25% increase in root growth in the four years following prescribed burns, while grazing had the opposite effect, resulting in less than 30% of the growth observed in controls. They also noted an increase in soil respiration, which was associated with the increase in root biomass. This contrasts with our study, where reduction in soil respiration was observed (see following sections).

These results also contrast with those observed in other studies where increases in plant biomass have been observed. Nitrogen and phosphorus deposition and light availability are the factors increasing productivity [10]. In our experiment on fire intensities, low biomass is likely to provide lower amounts of nutrients for productivity, likely less root biomass, and no excess of dead standing biomass that could block light to new shoots. In the prescribed fire experiment, we did not have a similar area to measure productivity in an unburned site.

3.4. Carbon Emissions from Combustion

The prescribed burning was a severe fire that consumed almost all available grass biomass. Of all biomass, 84% (9.55 4.77 t C ha^{-1}) was consumed by fire, and 1.76 t ha^{-1} remained over the soil as carbon residues and partially burned tillers. The C emissions to the atmosphere from the combustion process amounted to 4.77 t C ha^{-1}. Meanwhile, the 1.76 t ha^{-1} of pyrogenic carbon residues may act as a long-term C reservoir, since these residues may last for decades without being degraded and mineralized by microorganisms [37,38]. Black carbon emissions to the atmosphere during the burn were not measured (Figure 2).

3.5. Soil Energy Flux

The energy flux at the site changed dramatically after the burning event. The reflected longwave radiation doubled following the burn, while the shortwave radiation decreased to less than half. This change was due to the carbon residues left on the soil, creating a dark surface that absorbed more shortwave radiation (285–3000 nm), thereby increasing the soil temperature. In turn, this led to an increase in the longwave radiation (4500–42,000 nm) emitted by the darkened surface (Figure 3). Albedo decreased on average from 0.22 to 0.05 after fire treatment.

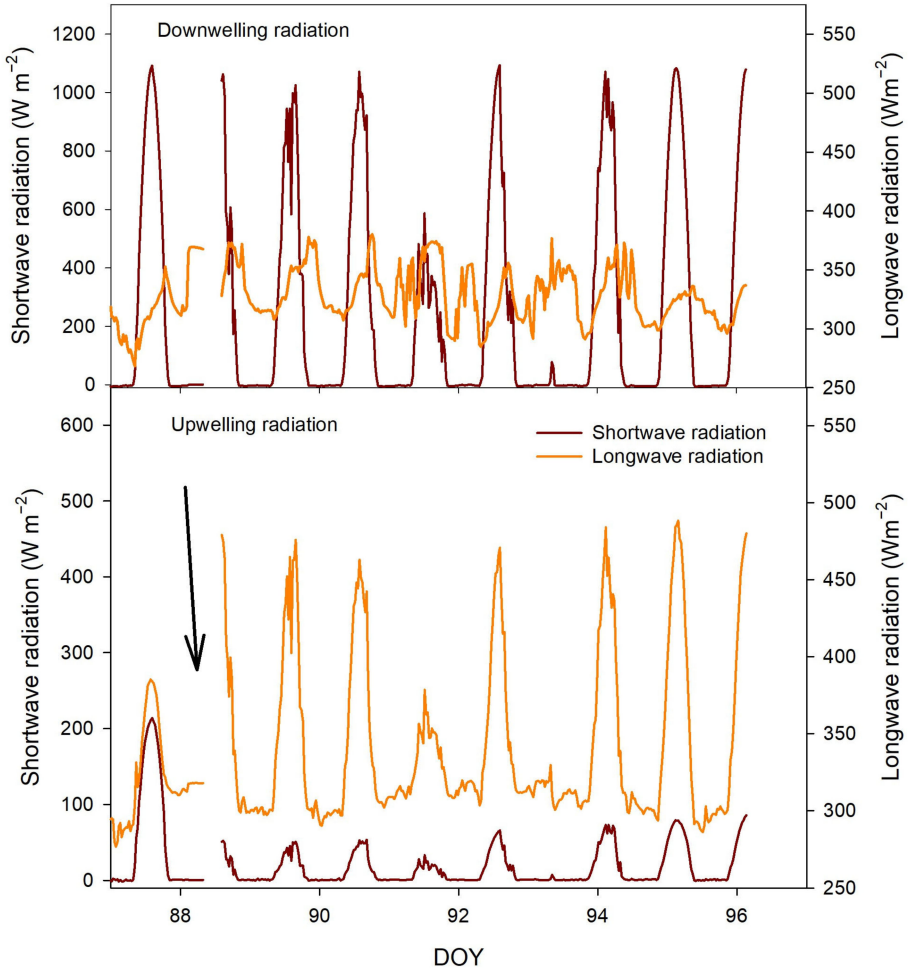


Figure 3. Time series of shortwave (285–3000 nm) and longwave radiation (4500–42,000 nm) at the study site one day before the burn (arrow indicates the day of the burn) and days after it. The upper panel shows downwelling radiation, while the lower panel presents upwelling radiation. Day of year (DOY).

The increase in shortwave upwelling radiation for a darker surface may be significant positive feedback for atmospheric warming. It accounts for up to 62% of annual warming effects due to the CO_2 emissions from wildfires [10]. This effect on grasslands is less severe than forest ecosystems due to changes in albedo recovering to previous values a few months after fire treatment [39]. However, the major extension and recurrence of fires in grasslands compared to other ecosystems make more relevant contributions due to changes in albedo in global warming.

3.6. Soil Respiration Response in Relation to Soil Temperature

The soil respiration rates before the prescribed burn treatment averaged less than 0.5 µmol m^2 s^{-1}. A slight decrease in respiration, by 0.2 µmol m^2 s^{-1}, was observed immediately after the burn, but two days post-burn, respiration rates recovered to pre-burn levels, with a sustained decline in the following days (Figure 4). Respiration rates increased up to 6 times when the first precipitation events occurred, with a total of 39.8 mm over 5 days. These rates peaked on day 135 at 3.1 µmol m^2 s^{-1} and subsequently decreased to pre-precipitation levels by day 147. No significant relationship was found between soil respiration and soil temperature. Under low soil moisture content, it has been shown that soil respiration is out of phase (hysteresis effect) with soil temperature to a greater extent than in wet conditions [40]; in the worst cases, minimum soil temperatures coincide with the maximum in soil respiration. This generates a loop in the temperature–respiration

relationship and the lack of fitting with the exponential model [41]. The hysteresis effect is argued to occur by differences in diffusion through the soil between CO_2 and heat (temperature) [41,42].

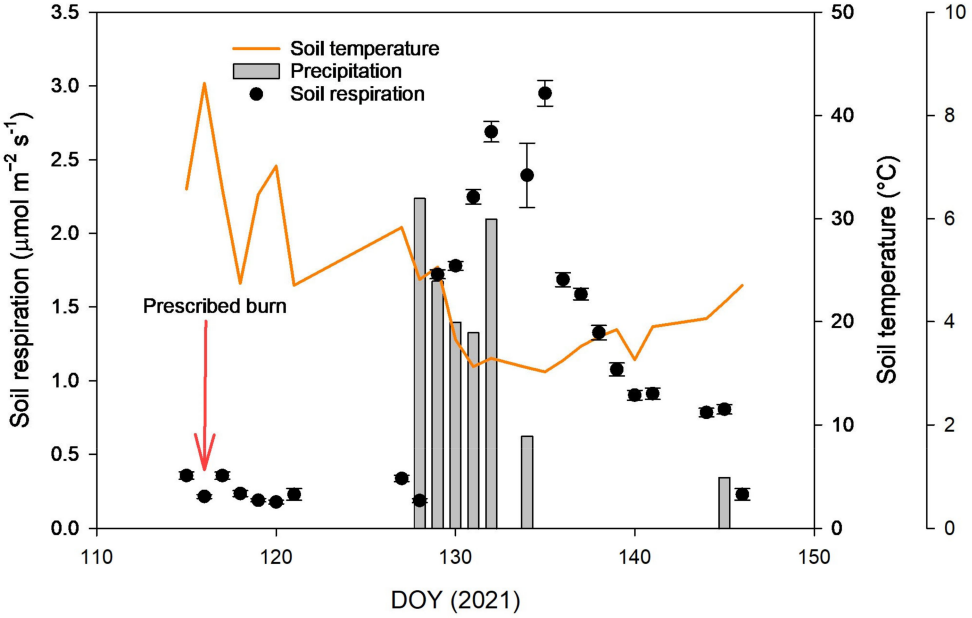


Figure 4. Soil respiration rates, soil temperature, and precipitation before and after burn prescription. Day of year (DOY).

Notwithstanding the soil temperature increase from 30 °C to over 40 °C after the burn, and the significant increase in soil temperature due to changes in soil albedo, this was not reflected in the respiration rates. In contrast, when soil temperature decreased to 15 °C in the days following the first precipitation events, instead of a suppression effect, soil respiration increased (Figure 4). According to several studies, the primary factor stimulating respiration in arid ecosystems is water availability, not temperature [43,44].

These results reject the hypothesis that increased soil temperature, either directly or indirectly due to burning, would increase soil respiration rates. Since fires in grasslands move relatively quickly, they usually consume biomass rapidly, and the heat received by the soil is relatively low, leading to minimal warming of the soil surface [45]. However, the absence of vegetation after a burn leads to greater exposure to solar radiation, increasing evaporation, and reducing soil moisture, which in turn reduces the soil respiration in the long-term [46].

3.7. Net Ecosystem Carbon Exchange (NEE)

Similar to soil chamber measurements, the net ecosystem carbon exchange (NEE) rates remained below 1.5 µmol m^2 s^{-1} before the first precipitation events occurred at the site. No significant change in NEE rates was observed before or after the prescribed burn treatment. Corresponding with soil CO_2 fluxes, NEE increased more than 6 times with the rain (Figure 5). Continuous monitoring of carbon fluxes with the eddy covariance system allowed observation of the diurnal cycle of carbon fluxes (inset in Figure 5). Maximum CO_2 fluxes were observed at midday and decreased toward the evening. Some energy issues at the site led to several gaps in eddy covariance measurements, which prevented further measurements of the carbon fluxes.

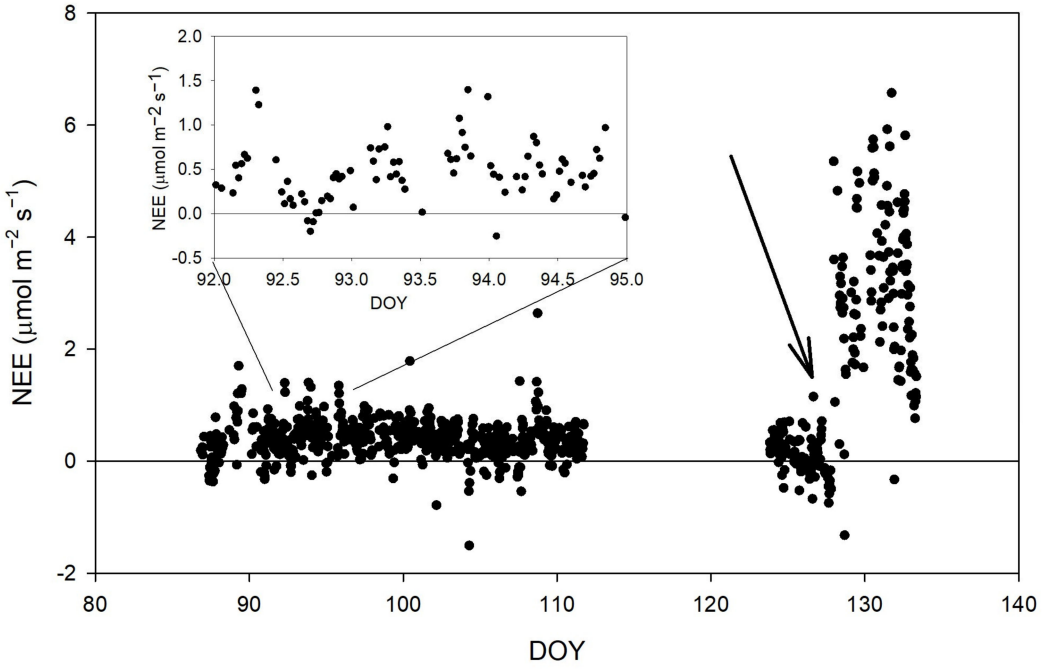


Figure 5. Diurnal carbon fluxes recorded with the eddy covariance system. The arrow indicates the occurrence of precipitation on day 130. Day of year (DOY).

3.8. Soil Respiration Response to Three Fire Intensities

The morning respiration rates over the 56-day measurement period were 3.85, 3.72, and 3.5 µmol m^{-2} s^{-1} for low, medium, and high fire intensities, respectively, and 6.15 µmol m^{-2} s^{-1} for the control (no burning). The afternoon respiration rates were 4.08, 4.46, and 4.6 µmol m^{-2} s^{-1} for low, medium, and high fire intensities, respectively, and 6.83 µmol m^{-2} s^{-1} for the control. Overall, respiration rates in the control treatment were higher than those in the other treatments throughout the measurement period, both in the morning and afternoon.

In all three fire intensity treatments and the control, an increase in respiration rate was observed 21 days after the start of measurements, which coincided with a period of rain that increased soil moisture. At this time, there was a total precipitation of 278.8 mm, slightly over 50% of the region's annual precipitation (Figure 6).

According to the repeated measures ANOVA, significant differences in respiration rates were found between treatments ($p < 0.05$) and between the control (no burning) in both morning and afternoon measurements. No significant differences were observed between the three fire intensities (Tukey test, $p < 0.05$; Table 3).

Table 3. Averages of respiration for the treatments in the morning soil respiration measurements.

Treatment / Intensity	Average	Standard Error	Degrees of Freedom	
	Morning			
Low	3.85	0.409	26.7	a
Medium	3.72	0.408	26.7	a
High	3.5	0.41	24.1	a
Control	6.15	0.41	23.9	b
	Afternoon			
Low	4.6	0.409	26.7	a
Medium	4.46	0.413	26.7	a
High	4.08	0.42	24.1	a
Control	6.83	0.419	23.9	b

Different letters stand for significant differences among treatments ($p < 0.05$).

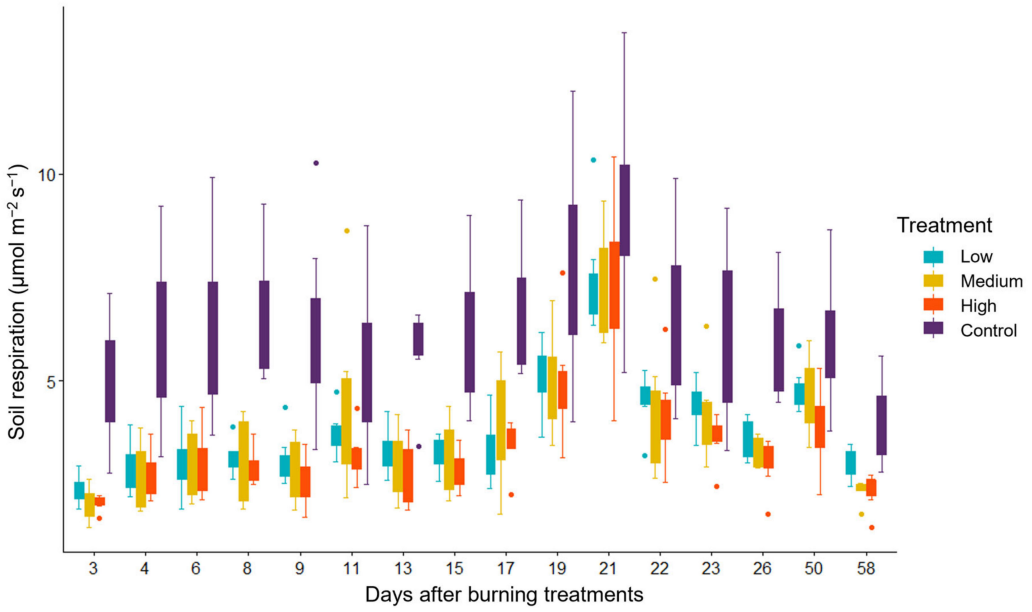


Figure 6. Temporal variation of soil respiration in the three intensity treatments and the control, during the period from 21 June to 17 August 2021.

Fire treatment did not affect the sensitivity of soil respiration to temperature (Q_{10}); modification of the respiration–temperature relationship was observed in the basal respiration of the no-burn plots. The Q_{10} remained below 1.5 at all times and treatments (Table 4), which indicates that the change in respiration rates will remain constant among treatments and control under warmer conditions. In contrast with the prescribed fire where no relationship between soil respiration and temperature was found, here, soil moisture was at a level that both roots and soil microorganism were fully active. The experiment on fire intensities was developed at the time when 278 mm of precipitation had fallen.

Table 4. Parameters of temperature and soil respiration relationship (Equations (3) and (4)) for the morning and the afternoon (mean ± SE).

Treatment	***Rb***	***k***	**Q_{10}**
		Morning	
Low	1.44 ± 0.23	$3.82 \times 10^{-2} \pm 6.20 \times 10^{-3}$	1.47
Medium	1.24 ± 0.23	$4.87 \times 10^{-2} \pm 7.25 \times 10^{-3}$	1.63
High	1.72 ± 0.24	$3.45 \times 10^{-2} \pm 5.61 \times 10^{-3}$	1.41
Control	3.90 ± 0.68	$1.95 \times 10^{-2} \pm 7.04 \times 10^{-3}$	1.22
		Afternoon	
Low	3.65 ± 0.62	$4.29 \times 10^{-3} \pm 6.36 \times 10^{-3}$	1.04
Medium	3.18 ± 0.51	$1.31 \times 10^{-2} \pm 5.67 \times 10^{-3}$	1.14
High	3.02 ± 0.52	$1.51 \times 10^{-2} \pm 6.11 \times 10^{-3}$	1.16
Control	5.22 ± 0.93	$9.91 \times 10^{-3} \pm 6.31 \times 10^{-3}$	1.10

Based on the results, the hypothesis that fire would stimulate soil respiration and that this effect would be dependent on fire intensity was rejected. Similar to the observations in the prescribed burning of *Eragrostis curvula* paddock, the application of fire decreased soil respiration rates.

It is important to consider that in the burns of *Eragrostis curvula* paddock, soil respiration measurements were not conducted on a similar unburned site (control), so it was not possible to determine if, over time and with the onset of rains, the respiration remained unchanged compared to a control site. Future studies will need to include a reference site to monitor these temporal changes in respiration.

This result coincides with several studies of different ecosystems [47], where soil respiration was suppressed 11% on average; however, in contrast with our study, the reduction degree was not modulated by fire severity. The reduction in respiration rates can have several causes. Fire decreases soil extracellular enzyme activities by reducing soil microbial biomass and organic matter substrates, and decreases nitrogen availability in turn [48]. Moreover, increased soil temperature can lead to greater evaporation of water, resulting in lower soil respiration due to reduced water availability for microorganisms and plants [49]. Additionally, the passage of fire could cause the death of microorganisms right at the soil surface, but this response may depend on the type of microorganism, bacteria or fungi, the last being more sensitive to fire [50]. Although Pressler et al. [51] mention that soil microorganisms are relatively fire-resistant, Palmer et al. [52] report that fire has short-term negative effects, reducing biological crust coverage by 50%; however, they also describe a rapid recovery of populations due to the functional and ecological succession strategies of these groups, depending on the level of disturbance from the fire. Similarly, Barreiro and Díaz-Raviña [53] mention that soil temperatures above 120 °C can cause damage such as microorganism death; however, the temperatures reached on the soil surface during burns are typically high but of very short duration. Anderson [54] notes that grassland fires are relatively fast, with high temperatures affecting only a few millimeters below the soil surface. However, changes in albedo cause soil temperatures to exceed 60 °C after midday on days following the burn. This would reduce respiration rates due to decreased active microbial biomass, and likely it was observed in the prescribed burning, when soil respiration declined the first day after the burning and then it recovered (Figure 4). The continuous decrease after that could be caused by the even lower soil water content due to greater water evaporation from the darker soil surface (lower albedo; Figure 3).

In our study site, biological soil crust communities are very important components of grasslands soils, covering up to 70% of plant interspaces in grazing-excluded conditions and up to 30% in overgrazed sites [55], and the reduction of these surface microorganisms by fire at some degree could cause a reduction in soil respiration. Moreover, controlled burns conducted on paddocks near to our study site on grasslands with high fuel availability (>10 t ha^{-1}) have recorded temperatures up to 500 °C on the crowns of the tussocks, but with a duration of less than 1 min. In contrast, the soil temperature at 1 cm depth did not exceed 22 °C during the burn [56], indicating that soil microorganisms very close to the surface do not experience stress from high temperatures. Thus, it is likely that soil respiration reductions were caused more by reduction of water availability than by the death of soil microorganisms.

Under moist conditions, when soil microorganisms and roots are fully active (simulation experiment), negative effects of fire on active leaf tissues could suppress photosynthesis, root activity and their associated microorganism; and the soil respiration rate. In the long-term, reductions of root biomass may reduce carbon storage [57].

4. Conclusions

In general, soil carbon dioxide fluxes in a semi-arid grassland slightly decreased after a prescribed burn during the spring season, but the magnitude of soil respiration decrease was independent of fire intensity. This means that soil respiration was not a positive feedback effect for increasing atmospheric CO_2 concentrations by fire, but in contrast, it reduced the emission. However, prescribed burns decreased productivity, with a 30% biomass regeneration in the first year, which translates to net carbon capture.

Finally, the increase in soil temperature by the direct effects of fire and by changes in albedo did not stimulate soil respiration; in contrast, soil moisture was the main driver that enhanced it.

It is necessary to consider the effects of fire in the long-term for changes in nutrient deposition, aboveground and belowground biomass, and soil properties to effectively quantify its impact on the global carbon cycle. Moreover, this could lead us to propose effective fire management strategies for conserving and increasing the carbon uptake

capacity of grasslands, and to know its future under more recurrent wildfires due to more arid and warmer climatic conditions.

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