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Interannual Variation and Control Factors of Soil Respiration in Xeric Shrubland and Agricultural Sites from the Chihuahuan Desert, Mexico

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Abstract: Arid and semi-arid ecosystems dominate the R_S variability due to the multiple changing factors that control it. Consequently, any variation, in addition to climate change and land use change, impacts the concentration of CO_2 in the atmosphere. Here, the effect of the interannual variation and the controlling factors of R_S in native xeric shrublands and agricultural systems is investigated. This study was conducted in four sites per condition for two years (2019 to 2020), where R_S and the soil properties were measured. The R_S presented a higher variation in the xeric shrubland. The agricultural plots showed the highest R_S (0.33 g CO_2 m^{-2} hr^{-1}) compared to the xeric shrubland (0.12 g CO_2 m^{-2} hr^{-1}). The soil water content was the main controlling variable for R_S in both land uses. However, soil temperature affected R_S only in agricultural plots. The variation in the R_S under different land uses confirms that changes in the soil and environmental conditions (i.e., season) control the R_S. In addition, if current management practices are maintained in agricultural sites and under a temperature increase scenario, a significant increase in the R_S rate is expected.

Keywords: arid ecosystems; climate change; microbial activity; land use change; soil organic matter; soil temperature; soil water content

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1. Introduction

Soils contribute to climate change mitigation due to their large C storage capacity [1], representing approximately 62% of the global soil organic carbon (SOC) pool with 2500 Pg C [2]. For this reason, soils also represent one of the largest fluxes of CO_2 to the atmosphere, with 98 Pg of C per year [3]. Soil respiration (R_S) is the second-largest C flux between terrestrial ecosystems and the atmosphere [4] and is based on a series of chemical, physical, and biological processes. Consequently, any slight variation in the R_S significantly affects the concentration of atmospheric CO_2 [5].

Changes in R_S are controlled by several abiotic and biotic factors, including soil moisture, soil temperature, fertility, vegetation type and physiology, microbial activity (which is related to the availability of C substrates for microorganisms), and other soil organisms [6]. Additionally, R_S is also affected by management activities, such as land management and land use change (LUC). Climate change and LUC can alter the C cycle and release a substantial amount of terrestrial C [7]. Human activities associated with land cover change have resulted in a significant net loss of soil C, accumulating CO_2 emissions from 1850 to 2019 for approximately 210 Pg C [8]. The synergy between climate change and LUC will also profoundly impact the C global dynamics.

LUC modifies the vegetation cover and stimulates SOC loss, which affects the soil's physical, chemical, and biological properties and, in turn, impacts R_S [9]. However, there still needs to be a consensus regarding the direction and magnitude of the impacts of LUC on the soil C dynamics. In some places, such as the Caatinga, a semi-arid region in Brazil, LUC negatively impacted the R_S [10]. LUC from natural Caatinga, with higher productivity, to degraded pastures increases soil moisture and temperature regardless of the season (i.e., dry vs. wet). As a result, this LUC decreased the R_S, especially during the wet season [10].

Conversely, intensively managed agricultural ecosystems in an arid region of China showed a higher R_S than the natural ecosystems [11]. Likewise, the LUC from grassland to cultivated land increased the R_S by 29% [11]. In this sense, it has been shown that the LUC to agricultural sites strongly influences the R_S response. In a semi-arid ecosystem in India, the R_S increased by more than 30% due to LUC from mixed and *Prosopis juliflora* forest to agricultural sites (*Triticum aestivum* and *Phaseolus vulgaris*) and vegetables (*Capsicum annum* and *Brassica oleraceae*). Additionally, management practices such as tillage and fertilizers decrease soil C storage due to the rise of the SOM decomposition, accentuated by the presence of litter that is easier to digest by microorganisms in managed sites [12].

Semi-arid ecosystems account for as much as 30% of the net primary productivity and dominate the trend and interannual variability of the land CO_2 sink [5,13]. Together with the predicted changes associated with climate and LUC, it highlights the need to improve the modeling of the C release, weighting the multiple controlling factors of this process. This study investigates the effect of the interannual variation on the R_S and physicochemical soil properties throughout native vegetation and agricultural systems from the Chihuahuan Desert in northeastern Mexico.

2. Materials and Methods

2.1. Site Description

The research was carried out in the southeast of the Chihuahuan Desert, at General Cepeda, Ramos Arizpe, and Saltillo municipalities, in Coahuila de Zaragoza, Mexico (Figure 1). Climate conditions are arid and semi-arid. The mean annual temperature is between 18 °C and 22 °C with a maximum of 31.4 °C in the warmest month and a minimum of 3.3 °C in the coldest month [14]. The mean annual precipitation is 493 mm, with the highest rainfall during July, August, and September (Figure 2) [14]. The main soil types are leptosols, calcisols, and regosols [15]. The dominant vegetation is xeric semi-arid shrubland with *Fouquieria splendens*, *Larrea tridentata*, *Yucca carnerosana*, *Yucca filifera*, and *Dasylirion cedrosanum* as dominant species, and several species of Cactecaea family, such as *Echinocactus* spp., *Echinocereus* spp., *Mammillaria* spp., *Opuntia* spp., etc. [16].

2.2. Sampling and Measurements

Two land uses were explored: agricultural crops and native xeric shrublands. The selected agricultural plots present different management intensity gradients from fallow fields to fields with three annual crops, as well as seasonal, sprinkler, and flood irrigation systems. A more detailed description of the sites is shown in Table S1. In 2019 and 2020, six field campaigns were conducted annually every two months (February, April, June, August, October, and December). Interannual variation was analyzed by grouping sampling events in two seasons (dry and rainy). For each land use, four sites were selected within the southeastern region of Coahuila. Five sampling points (separated every 25 m) per site were established at each site (n= 40) along linear transects. At each sampling point, soil respiration (R_S), ambient temperature (Tair), relative humidity (RH), photosynthetic active radiation (PAR), temperature (Tsoil), and soil water content (SWC) were measured and recorded.

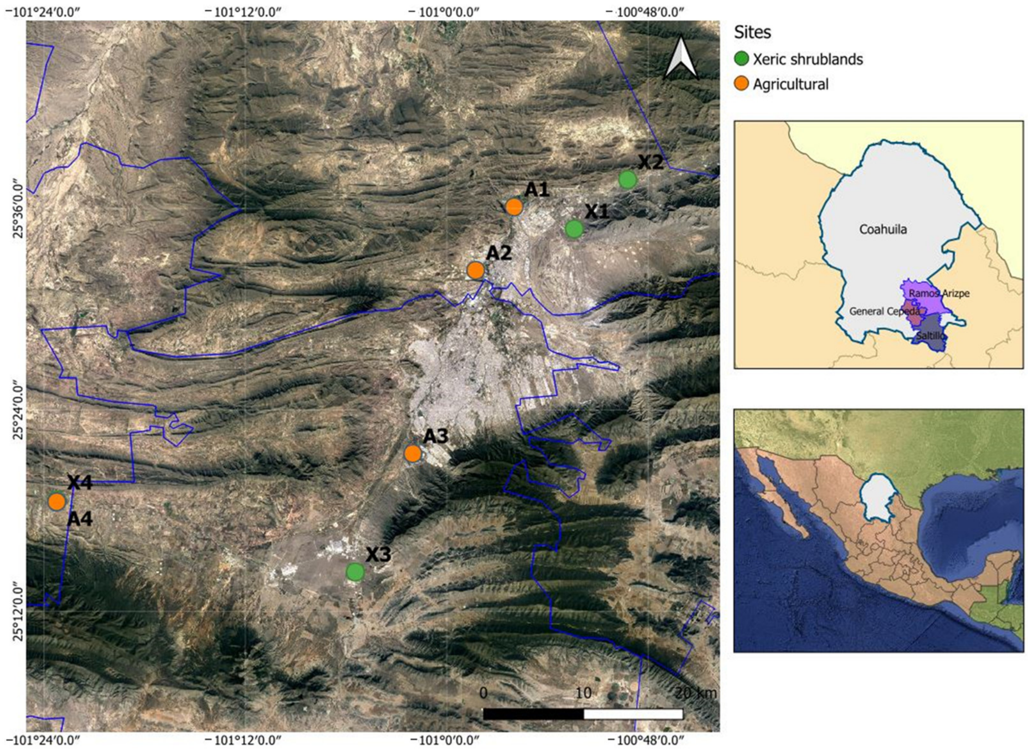

Figure 1. Location of the sites in the southeast of Coahuila by land use.

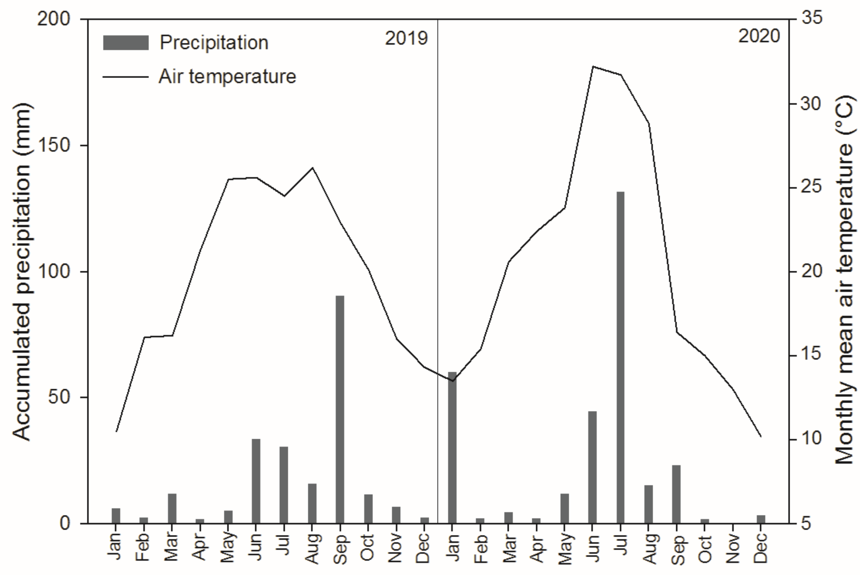

Figure 2. Precipitation and air temperature at the study sites in 2019 and 2020.

R_S was measured (60 s) with a portable dynamic closed chamber (SRC-1; PP Systems, Amesbury, MA, USA) coupled to a steady-state infrared gas analyzer (EGM-5, PP Systems). The chamber was placed on PVC rings (10 cm diameter × 5 cm height at 3 cm depth into the soil) that were inserted 24 h before the measurement and removed to minimize the impact of the soil alteration [17]. A Hydra Probe II (Stevens Water Monitoring Systems, Inc., Portland, OR, USA) was placed next to the rings at 8 cm dept to determine Tsoil and SWC. At each point, a WatchDog Micro Station (mod. 1450, Spectrum Technologies, Inc., Aurora, IL, USA) was used to determine Tair and HR, and an MQ-200 sensor (Apogee Instruments, Inc., Logan, UT, USA) was used for PAR.

A soil sample was taken at each sampling point to 0–15 cm depth. Samples were transferred and stored at 4 °C until the determinations. Electrical conductivity (EC), pH, microbial biomass carbon (MBC), and soil organic matter (SOM) were recorded once during the dry (February) and rainy (August) seasons of the two years of study.

Bulk density (BD), texture, nutrients, total carbon (TC), and nitrogen (TN) contents of soil were measured on one occasion in the first sampling. Soil pH was measured in suspension soil/water 1:2.5 using a digital pH meter (Orion Star A211, Thermo Fisher Scientific, Inc., Waltham, MA, USA), and soil electrical conductivity was measured with an Orion conductivity meter (Thermo Scientific, Inc., Waltham, MA, USA). SOM was determined using the loss on ignition method at 400 °C for 4 h [18]. MBC was determined by the fumigation-extraction method [19]. Soil texture was determined with a Particle Size Analyzer (LA 950 V2, Horiba Ltd., Kyoto, Japan). BD was determined using the volumetric method. TC and TN content were measured on air-dried soil samples using a CHNS/O elemental analyzer (Flash Smart, Thermo Fisher Scientific, Inc., Waltham, MA, USA). Soil nutrients were determined using inductively coupled plasma optical emission spectroscopy (Optima 8300, Perkin Elmer, Inc., Waltham, MA, USA).

2.3. Data Analysis

The difference between land use for soil properties measured only once (BD, sand, silt, clay, TC, and TN) was analyzed by one-way ANOVA and post hoc tests of Tukey ($\alpha = 0.05$). A one-way ANOVA was performed to analyze the seasonal variation in the chemical and biological properties (SOM, MBC, pH, and EC) over the course of two years; the data was aggregated and analyzed seasonally. To analyze the annual variability and the effect of land use change in the R_S, a one-way ANOVA in each case was performed. In all cases, the assumption of normality of residuals and homoscedasticity of the variance was fulfilled. Statistical analyses were performed using STATISTICA V10.0 software. Spearman correlation analyses were used to explore the control factors of R_S for each land use.

The relative influence of environmental variables (Tsoil, SWC, Tair, RH, and PAR) over the R_S at each land use was modeled by using structural equation models (SEM). The models considered a complete set of hypotheses based on the literature and our own previous experience [20,21]. A first set of models was proposed for each land use, considering the environmental variables that showed a higher correlation with R_S. To fully incorporate the effect of land use change over the R_S, a model that considered land use change as an exogenous variable of the system was proposed. To that, the mean metabolic coefficient, calculated as $qCO_2 = (R_S/MBC)/SOM$, was implemented as an approximation to the variable "land use" [22]. Standardized path coefficients were calculated with the maximum likelihood algorithm [23]. The root mean square error of the degree of fit between the observed and expected covariance structures (RMSEA) was computed [24]. The fit of the model to the data was assessed using the Bentler and Bonett normed fit index (NFI) and the goodness-of-fit index (GFI) [25]. The SEMs were fitted with the programs SPSS® and SPSS® AMOS 20.0 (IBM Corporation Software Group, Somers, NY, USA).

Rolling Window Correlations (RWC) were applied to analyze the time-series relationship between R_S with SWC and Tsoil, the main controlling factors. RWC was obtained via the functions rolwincor_heatmap and plot_heatmap from the R package RolWinMulCor [26,27]. The correlation method was Spearman. Window lengths (timescales) were defined as 7 days every two months across two years, 2019 and 2020.

3. Results

3.1. Soil Characteristics

The soil texture in the study sites, regardless of the land use, was silty loam. However, some differences were found between the particle sizes. The highest percentage of sand was observed in xeric shrubland sites compared to agricultural ones. Silt and clay percentages were significantly higher in agricultural plots compared to xeric shrubland sites (Table 1). The amount of TC presented significant differences between land uses, with higher percentages in xerophytic soils. Nevertheless, TN and BD did not present significant differences between sites (Table 1).

Table 1. Physicochemical properties of soil with different land uses in the southeast of the state Coahuila. Values are mean ± standard error (n = 20). Lowercase letters indicate significant differences between uses based on the one-way ANOVA.

Soil Properties	Xeric Shrubland	Agricultural	F	p	g.l.
Total carbon (%)	6.96 ± 0.52 a	5.02 ± 0.38 b	9.13	<0.05	1
Total nitrogen (%)	0.25 ± 0.02 a	0.25 ± 0.03 a	0.004	0.95	1
Bulk density (g cm^{-3})	1.14 ± 0.02 a	1.09 ± 0.02 a	3.05	0.08	1
Sand (%)	41.25 ± 3.60 a	23.56 ± 2.29 b	17.23	<0.0001	1
Silt (%)	56.33 ± 3.52 b	70.47 ± 2.16 a	11.72	<0.001	1
Clay (%)	1.54 ± 0.27 b	5.98 ± 0.38 a	90.32	<0.0001	1

Soil pH for both land uses was alkaline, presenting the highest values in xeric shrubland sites (8.14 ± 0.02) and the lowest in the agricultural plots (7.67 ± 0.04). Soil electric conductivity was significantly higher in the soils from agricultural plots regardless of the season (Table 2). The MBC (56.96 ± 2.51 mg C glucose kg^{-1} and 83.11 ± 3.07 mg C glucose kg^{-1}, respectively) and SOM (4.96 ± 0.22% and 4.51 ± 0.22%; Table 2, respectively) were significantly higher in the agricultural than the xeric shrubland plots independently of the season. Table S2 shows the statistical values of F, p, and *d.f.* of the physical, chemical, and biological properties of soil.

Table 2. Chemical and biological properties of soil and seasonal variation in different land uses in the southeast of the Coahuila state. Values are mean ± standard error (n = 20). Lowercase letters indicate significant differences between land uses for a given season.

Soil Properties	Dry Season		Rainy Season	
	Xeric Shrubland	Agricultural	Xeric Shrubland	Agricultural
Soil respiration (g CO_2 m^{-2} hr^{-1})	0.064 ± 0.003 b	0.288 ± 0.016 a	0.196 ± 0.013 b	0.483 ± 0.022 a
Soil organic matter (%)	3.90 ± 0.13 b	4.96 ± 0.22 a	3.36 ± 0.14 b	4.51 ± 0.22 a
Microbial biomass carbon(mg C glucose kg^{-1})	36.29 ± 2.23 b	56.96 ± 2.51 a	54.80 ± 3.14 b	83.11 ± 3.07 a
pH	8.14 ± 0.02 a	7.98 ± 0.03 b	7.93 ± 0.02 a	7.67 ± 0.04 b
Electric conductivity (ms/cm^{-1})	839.05 ± 23.29 b	1439.58 ± 47.73 a	509 ± 38.84 b	811.98 ± 55.25 a

3.2. Interannual Variation in Soil Respiration and Environmental Conditions

The agricultural plots exhibited the highest R_S with a mean of 0.385 ± 0.0198 g CO_2 m^{-2} hr^{-1}, and the xeric shrubland sites had the lowest CO_2 fluxes with a mean of 0.130 ± 0.0105 g CO_2 m^{-2} hr^{-1}. Consequently, agricultural soil released three times more CO_2 than the xeric shrubland (Figure 3). The R_S presented an interannual variability of 27.27% in the xeric shrubland and a variability of 2.94% for the agricultural plots.

The CO_2 flux in the dry season for xeric shrubland sites showed minimum variation. However, in agricultural plots, the variation was 3.70%. On the other hand, in the rainy season, the variability of the R_S was higher in both land uses; in the xeric shrubland, it was 40%, and in the agricultural plots, it was 7.32%. The highest R_S occurred in the rainy months (June, August, and October) in both land uses, although the R_S was particularly low in August 2019 for xeric shrubland sites. Also, the R_S in both land uses was lower in February and December (Figure 3), which corresponds to the dry season.

The environmental conditions at the time of R_S determination are presented in Figure 4. The xeric shrubland sites presented higher interannual variability of SWC and RH (17.93% and 8.23%, respectively) compared to the agricultural sites (3.37% and 0.37%, respectively; Figure 4b,d). Likewise, the mean SWC was lower in the xeric shrubland sites, with 3.87 ± 0.49%, compared to the mean of agricultural sites with 14.06 ± 1.85% (Figure 4b). On the other hand, the RH presented similar mean values between land uses but, like the SWC, they were lower in the xeric shrubland sites (29.03 ± 1.54%) compared to the agricultural plots (32.82 ± 1.73% xeric shrubland; Figure 4d).

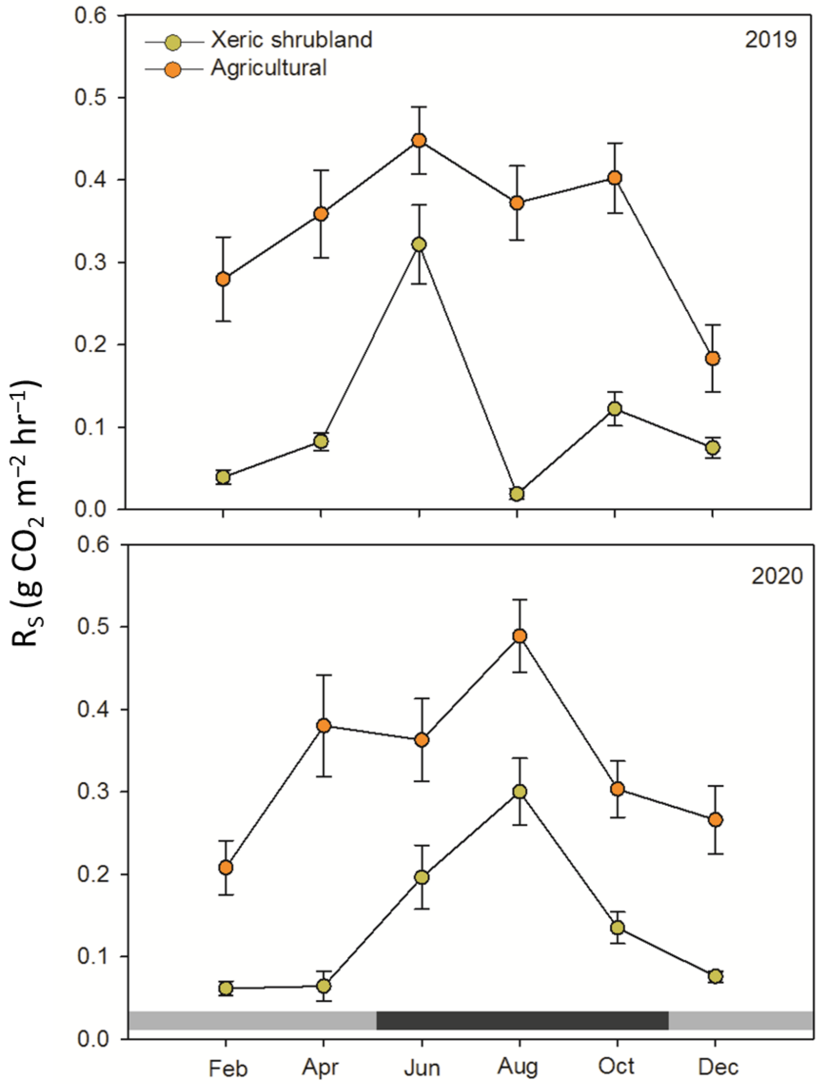

Figure 3. Soil respiration in two land uses over two years in the southeast of the Chihuahuan Desert. Values are mean ± standard error of one-way ANOVA. The light gray bars represent the dry season, and the dark gray bar represents the rainy season.

In the dry season, the SWC presented a higher seasonal variation in xeric shrubland sites at 43%, compared to agricultural plots with 17.63%. However, in the rainy season, the variation was higher in the agricultural plots (10.40%) compared to the xeric shrubland (5.89%). Soil moisture values ranged between 2% and 9% for xeric shrubland sites, with the highest percentages in June and August (rainy season) and the lowest percentages in February and April (dry season). In agricultural plots, SWC values were approximately between 9% and 24%, with the lowest values in December (dry season) and the highest in June (rainy season). The Tair and the Tsoil follow the same pattern throughout the two years of measurements for both land uses (Figure 4a,c). However, the highest temperatures were recorded in xeric shrubland sites, compared to agricultural sites, with a Tair mean of 33.74 ± 0.68 °C and 33.20 ± 0.71 °C, respectively, and a Tsoil mean of 32.79 ± 0.58 °C and 31.61 ± 0.69 °C, respectively.

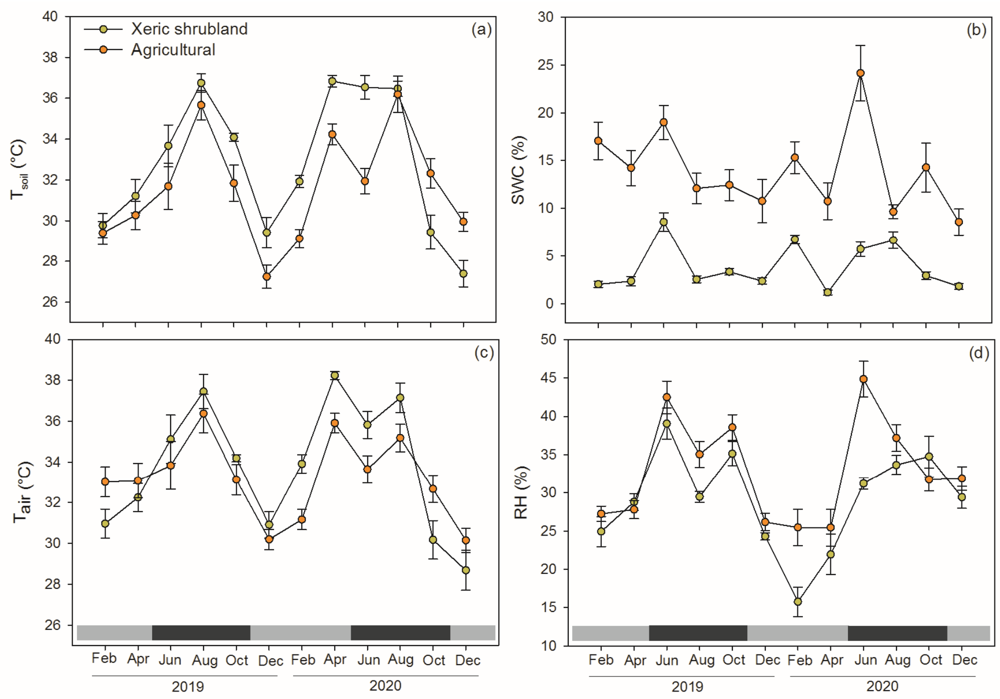

Figure 4. Soil temperature (**a**), soil water content (**b**), air temperature (**c**), and relative humidity (**d**) in two land uses over two years in the southeast of the Chihuahuan Desert. Values are mean ± standard error of one-way ANOVA. The light gray bars represent the dry season, and the dark gray bars represent the rainy season.

The interannual variation in Tsoil in both land uses was minimal, although higher in the agricultural plots (4.10%) than in the xeric shrubland sites (1.90%). The opposite occurred with the variation of the Tair; although it presented a slight variation, it was greater in the xeric shrubland sites (1.53%) than in the agricultural plots (0.45%).

The variation in the Tair in the dry and rainy seasons was higher in the sites with xeric shrubland (7.10 and 3.38%, respectively) than in the agricultural plots (0.97 and 1.78%). The opposite occurred with the Tsoil, which presented a higher variation in the dry season in the agricultural plots (7.37%) than in the xeric shrubland (6.37%). The latter presented a higher variation in the rainy season (1.98%) compared to agricultural plots (1.27%).

3.3. Control Factors of Soil Respiration

Sperman's correlation analyses for the xeric shrubland sites showed a significant correlation between the R_S and PAR > SWC > RH > TC > pH > Tair > TN (decreasing order regarding *R* values, Table S3). The R_S in the agricultural plots was correlated with SWC > TN > BD > Tair > RH > pH > PAR > Tsoil > SOM > TC (decreasing order regarding *R* values, Table S3). It is noticeable that the correlations with R_S were higher in the agricultural sites than in the xeric sites.

The SEMs used to explore the potential controls of different biotic and abiotic variables over R_S for each land use showed a good data fit (p = 0.95; NFI = 0.99; GFI = 0.99; RMSEA < 0.001 and p = 0.95; NFI = 0.99; GFI = 0.99; RMSEA < 0.05; Figure 5). These models explain a high proportion of variance of the R_S in xeric shrubland sites (R^2 = 0.43) and agricultural plots (R^2 = 0.53; Figure 5). According to the SEMs, the PAR exerted a positive influence over Tair regardless of the land use, although with a higher weight in the xeric sites (Figure 5a). The Tair positively affected the Tsoil in both land uses; however, in the xeric shrubland sites, it was more significant. SWC (0.50), PAR (0.36), and RH (0.20) had a direct and positive effect on R_S in xeric shrubland sites. This influence was maintained independently if the direct and total effects of the explanatory variables on R_S were analyzed (Figure 5a; Table S4). In the agricultural plots, SWC (0.54), RH (0.30), and PAR (0.22) had positive and direct effects on the R_S. However, unlike the xeric shrubland sites, Tsoil (0.30) strongly affected R_S (Figure 5b; Table S4).

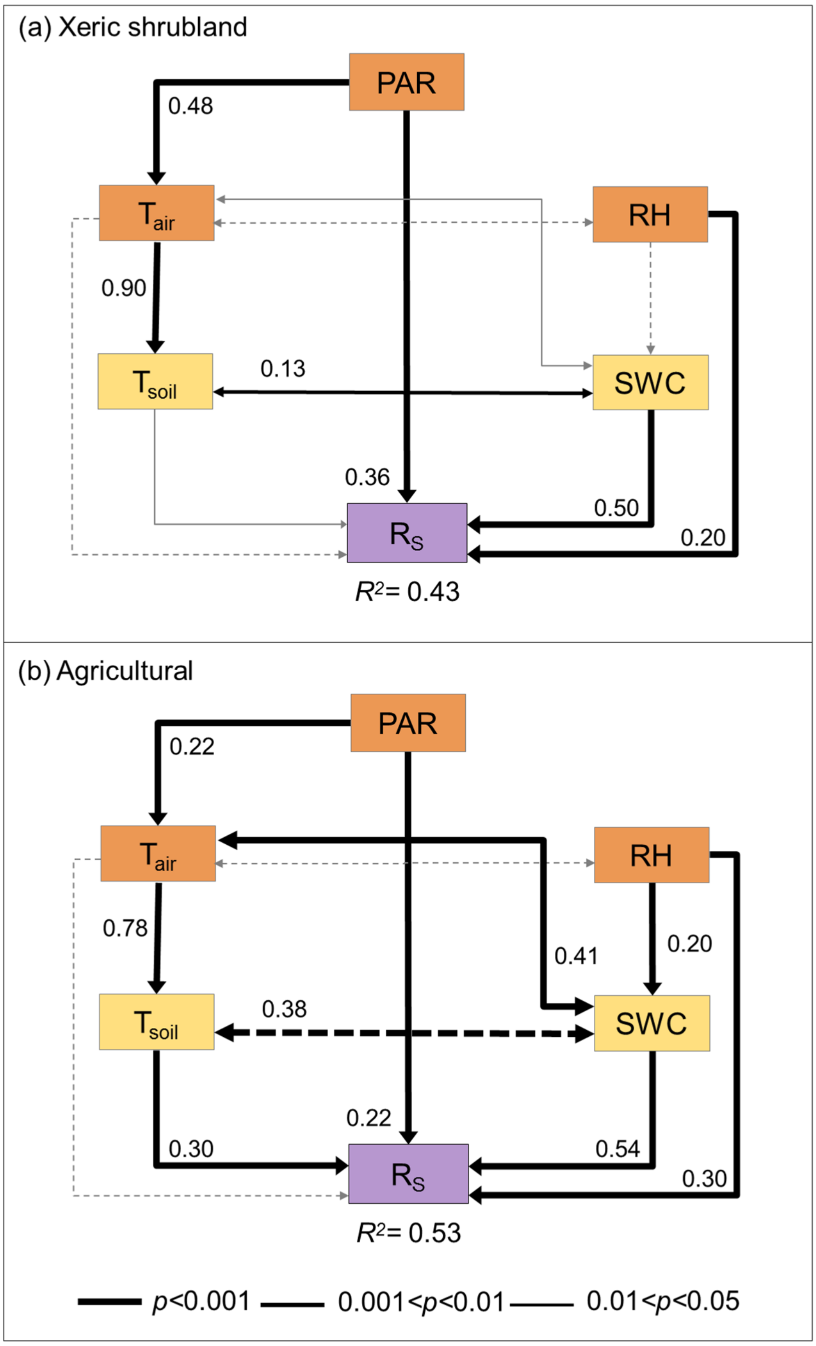

Figure 5. Path diagrams representing hypothesized causal relationships between environmental factors that control soil respiration at xeric shrubland and agricultural sites. Arrows depict causal relationships: positive (solid lines) and negative (dashed lines) effects, with numbers indicating standardized estimated regression weights (SRW). Arrow widths are proportional to significance values according to the legend. Arrows with non-significant coefficients are grey. NFI = 0.99; GFI = 0.99; RMSEA < 0.001; χ^2 = 3.47; p = 0.95; n = 240 for the first model (**a**) and NFI = 0.99; GFI = 0.99; RMSEA < 0.05; χ^2 = 5.20; p = 0.95; n = 240 for the second model (**b**).

Furthermore, the model which incorporated land use change (Figure 6) showed a good data fit (p = 0.95, NFI = 0.99, GFI = 0.99, and RMSEA < 0.001), explaining a high proportion of the effect of land use change on the R_S (R^2 = 0.60), in addition to environmental and soil variables. This model shows that land use change has a strong positive effect on SOM (0.27), a positive effect on RH (0.17), and a slight negative effect on Tsoil (0.07). However, the SWC maintains a strong positive effect over the R_S (0.60).

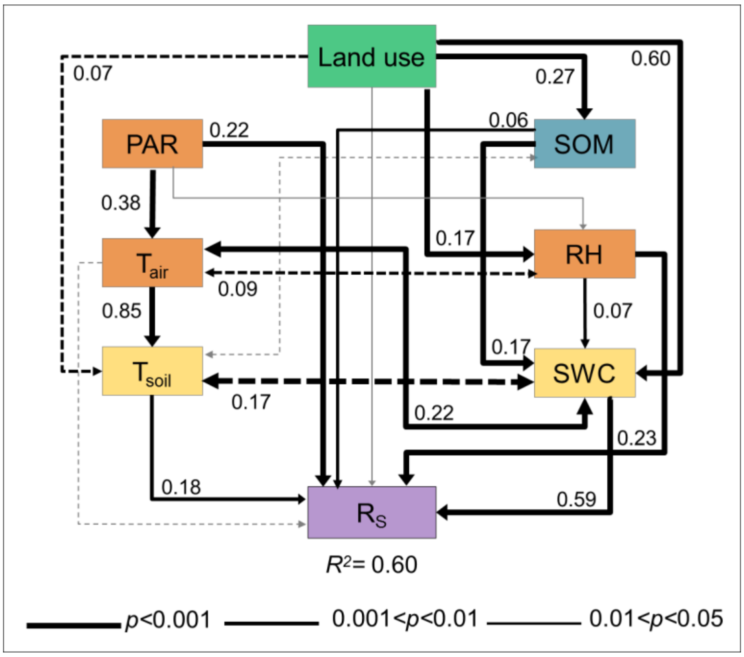

Figure 6. Path diagrams representing hypothetical causal relationships between the influence of land use and the factors that control soil respiration at xeric shrubland and agricultural sites. Arrows depict causal relationships: positive (solid lines) and negative (dashed lines) effects, with numbers indicating standardized estimated regression weights (SRW). Arrow widths are proportional to significance values according to the legend. Arrows with non-significant coefficients are grey. NFI = 0.99; GFI = 0.99; RMSEA < 0.05; χ^2 = 13.16; p = 0.95; n = 480.

The time series relationship between R_S, temperature, and soil water content was explored using heat maps of RWC. These heat maps divide the time series into two measurement periods (2019–2020). February, April, and December represent the dry season, and June, August, and October represent the rainy season (Figure 7).

In the xeric shrubland sites, the influence of SWC on R_S is temporally marked for the two measurement periods. However, in August (rainy season) of the first year, April (dry season), June, and August (rainy season) of the second year, there was a positive influence of SWC on R_S in the long term (see positive correlation marked in red for larger timescales; Figure 7a), while in the period from August to December of the first year, the SWC influences R_S after 113 days, and in February of the second year, the effect is after 20 days (see no significant correlations marked in light green in short timescales; Figure 7a). The sensitivity to SWC in R_S is evident in the plots with agricultural management during the entire time series (2019–2020). Non-significant correlations are present in very short time windows (approximately 3 to 10 days; Figure 7c).

In the shrubland sites, the Tsoil strongly influences R_S in the short term (approximately 50 days) between April and June. However, in the first year, the correlation of the Tsoil and the R_S was positive (R^2 = 0.8) (Figure 7b). In contrast, in the second year, the correlation was negative (R^2 = −0.8). For the rest of the time, a considerable number of correlation coefficients were not statistically significant (see no significant correlations $p \leq 0.05$ marked in light green; Figure 7b).

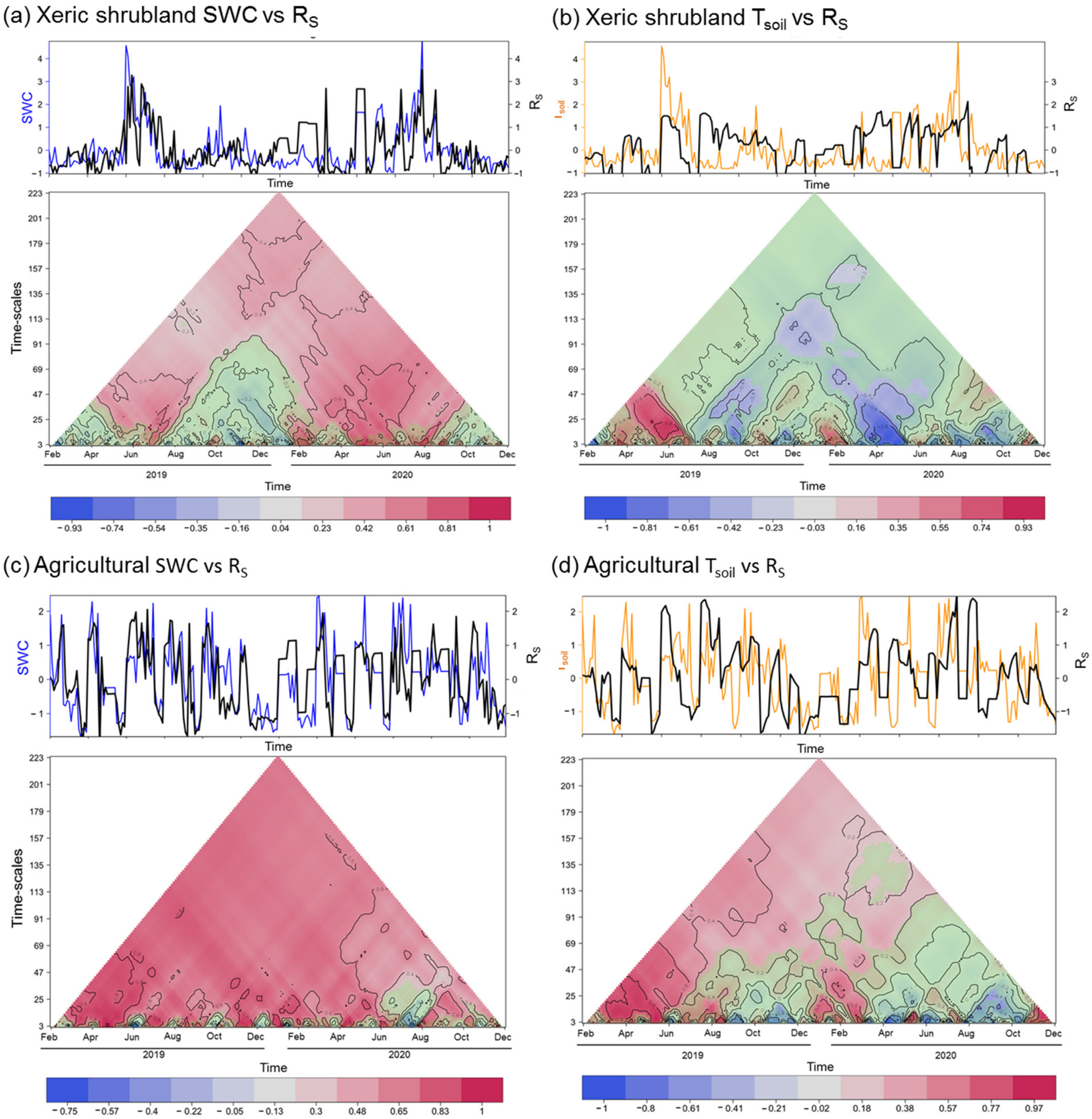

Figure 7. Heat map of rolling window correlation between soil water content (SWC) and soil temperature (Tsoil) vs. soil respiration (R_S) of the xeric shrubland and agricultural sites. Spearman's correlation coefficients that are not statistically significant (>0.05) are in light green. Line contours indicate similar values of the correlation coefficients.

The Tsoil has an evident influence on R_S in the agricultural plots in comparison to the shrubland ones (Figure 7). In agricultural plots, the correlation between Tsoil and R_S is high and positive in the long term, mainly in the first third (dry season) of the first year (R^2 = 0.8). However, the correlation coefficient decreases on the time scale. For the second half of the year, the effect of Tsoil occurs after 69 days (Figure 7d). In contrast, mainly in February (R^2 = 0.6), the influence of the Tsoil on the R_S is on a shorter time scale, with significant correlation areas but with variation in its correlation coefficient (Figure 7d). Also, there was a negative correlation (R^2 = -0.2 to -0.4) in the short term (see blue areas of the heatmap on 3 to 15 days) in the months with the lowest soil temperatures, which can be noticed in the inferior panel (Figure 7d).

4. Discussion

Land use modified the soil physicochemical properties; the higher amount of TC in the soil of the xeric shrubland could be associated with a higher content of SIC, compared to SOC, which is characteristic of the region's soils [28]. On the other hand, the concentration of TC in the soil of the agricultural plots is related to a higher content of SOC, and precisely, we can confirm it with the percentages of SOM in both land uses since, as is well known, the SOM contains about 58% organic carbon [29]. Unlike other studies [30], our results showed the SOM did not decrease from xeric shrublands to agricultural sites. The change to agricultural land use produces changes in the vegetation that raise the aerial biomass and, consequently, the content of organic matter that enters the soil. Then, the microbial biomass is increased, and the soil microclimate conditions are modified [30].

Furthermore, agricultural management as the type of tillage, irrigation, and fertilization affects the soil's physicochemical properties and the SOC content [31]. The agricultural conventional management in the study area contemplates deep tillage and fertilization, the last contributing to the increase in SOM. Additionally, for most of the year, the agricultural soils have vegetation cover [30], unlike the xeric shrubland sites with scarce vegetation and marked open areas [32].

As previously reported, the higher SOM content in the agricultural plots resulted in a lower BD (less soil compaction), less soil alkalization, and higher clay content [33,34]. The seasonal effects over the soil properties were also as expected, with a higher MBC, lower pH, and lower EC during the rainy season. It has been observed that the pH decreases during the rainy season in agricultural sites may be related to the application of fertilizers with a high nitrogen content, which is applied regularly in the study sites, mainly in the form of ammonium or ammonia, which promote rapid nitrification and release of H+ ions, lowering the soil pH [35].

Global semi-arid ecosystems dominate the positive global CO_2 sink trend (57%, 0.04 Pg C year^{-1}; global, 0.07 Pg C year^{-1}) compared with other ecosystems [5,13]. The average R_S rate observed in xeric shrublands soils reported in this study (0.12 g of CO_2 m^{-2} hr^{-1}) is comparable to the CO_2 flux of a dry valley, which oscillates between 0.1 and 0.15 g of CO_2 m^{-2} hr^{-1} [36]. In these semi-arid ecosystems, the interannual R_S variation has been mainly linked to changes in soil moisture due to variations in precipitation patterns [37]. In our two-year study, the soil moisture variability dominated the CO_2 fluxes from the soil. In contrast, the intensive agricultural management resulted in R_S variations due to these practices (tillage, fertilization, irrigation), the crop type, and the impact of environmental factors. In our study, it is notable that the observed variations in R_S were minimal, likely due to the constant irrigation of the agricultural plots throughout the year, thereby maintaining consistent soil moisture content during the two-year measurement period.

The temperature (both Tair and Tsoil) and water availability (RH and SWC) patterns coincide with the rainy and dry seasons of the study site [21,38]. However, in the agricultural plots, the patterns and levels of water availability were positively affected by irrigation throughout the period. The low-temperature values for the agricultural plots could also be explained by the irrigation and the vegetation cover, which buffered the temperature [39].

Our results showed the SWC as the main factor controlling R_S regardless of the land use. This can be attributed to the R_S responding to the most limiting factor, as shown in other arid zones [40,41]. In soils with low moisture contents, the diffusion of labile substrates (nutrients) between the soil pore spaces is slow, reducing their availability for microorganisms and, as a result, their metabolic activity [42,43]. Plants also need available water to carry out their functions; therefore, a low SWC limits their growth and, consequently, the production of aerial and root biomass [42]. When water is limited, xeric plants restrict their metabolism and reduce the inputs of labile carbon available for the activation metabolism of soil microbial communities [40]. This may explain that in the RWC analysis, SWC positively affects the long-term respiration during the dry season at both land uses. Once SWC recovers after very dry months, the undecomposed residues of the previous months are now available for decomposition by soil microorganisms. In the months with a higher SWC (i.e., rainy season), the effect on the R_S appeared rapidly due to the favorable conditions for microbial activity, especially for the shrublands. Another variable that influenced R_S in both land uses was PAR, which is directly related to the growth and development of plants and, therefore, alters the soil's aerial biomass, root growth, and organic matter content. Consequently, PAR indirectly affects soil respiration by changes in soil temperature [42]. On the other hand, RH influences R_S both directly and indirectly and is associated first with previous precipitation events or seasonality, which results in higher or lower moisture content in the soil, influencing plant growth and the metabolism of microorganisms [43]. In an agricultural system operating in a semi-arid environment, irrigation to maintain crop yield reduces the SWC control on metabolic activity. Our study consistently found that Tsoil emerges as an accurate predictor for R_S for agricultural plots in the short (i.e., SEM) and long term (i.e., RWC). Nevertheless, the SWC predominantly influences R_S, so it is a combined effect or the interaction between the SWC and the Tsoil [44,45]. The joint influence of water content and soil temperature is a typical behavior of R_S in temperate ecosystems [46,47]. When SWC reaches an optimal level to activate the soil microbial community, the Tsoil becomes a significant controlling factor for R_S. Therefore, the influence of Tsoil on R_S increases as SWC increases [45,48]. However, in the RWC, a negative impact of the SWC was observed in short periods (3 days) associated with an excessive water amount in the soil after irrigation, which temporarily limits the oxygen availability and the CO_2 transport in the soil profile [49,50].

According to Oyonarte and collaborators [42] and Cable and collaborators [51], one characteristic of arid ecosystems is a weak and negative influence of Tsoil on R_S, which agrees with the observed in our study (see RWC), where the highest temperatures were responsible for decreasing the R_S (see negative influences in blue of the RWC and negative direct influence of Tair in Table S4), regardless the land use. In different studies in semi-arid zones, the Tsoil effect on microbial activity declines above ~25 °C, limiting the R_S above this temperature in these regions [10,52].

On the other hand, it has been reported that Tsoil is a good predictor during the vegetation growth season (rainy season), where RH and SWC values are favorable [53,54]. When Tsoil and SWC increase, crop growth improves, resulting in more available substrate for soil microorganisms, activating their metabolism and reproduction [54,55], explaining the high R_S during the rainy season and its correlation with temperature, especially in the long term. Conversely, during the rainy season, the temperature influence was mainly negative in the xeric shrublands, with a short period (June 2019) with a positive influence of the Tsoil on the R_S, explained by the activation of metabolism. This period shows the higher RH and SWC in the two years studied (Figure 4), reinforcing that temperature increases in importance on the R_S control when water is not limiting. These findings indicate that converting xeric shrubland into crops enhances the sensitivity of R_S to temperature control. Consequently, according to the forecast for the region, which includes a rise in temperatures in the next decade, agricultural soils are expected to release more CO_2 into the atmosphere than xeric shrubland soils, reducing organic carbon storage [56,57].

The results presented here show that LUC does not directly affect R_S (Figure 6); however, an indirect effect of this variable is mirrored via the increase in the amount of substrate (i.e., SOM), the amount of available water (i.e., RH and SWC), and a decrease in the temperature (Tsoil). All these factors control the release of CO_2 into the atmosphere and explain 60% of its variability as modeled here. Studies have reported that R_S is influenced by LUC indirectly via changes in soil properties such as organic matter, moisture, and temperature, with moisture and temperature being the most important control factors [10,53,58]. This coincides with our study, where SWC was the primary, followed by Tsoil.

It has been shown that LUC causes changes in SOM content because of changes in plant productivity via its organic inputs to the soil [59,60]. However, an increase of more than 20% in R_S has also been reported after the LUC to agriculture and suggests that intensive management activities influence the decomposition rate of SOM at the time of breaking soil aggregates, soil aeration, and consequently, labile substrates remain available for soil microorganisms, increasing R_S [11,61]. We could also observe this effect of SOM on R_S in our study. Therefore, plant productivity and management will directly affect the SOM decomposition, influencing R_S.

In addition, SOM losses can occur in the soil, changes in the microenvironment for plant growth and microbial communities to continue with intensive management activities in agricultural plots as has already been reported [12,62], and as a consequence, agricultural ecosystems will become more susceptible to changes in environmental conditions, as is predicted to happen in the climate change scenarios, in this sense, the organic carbon stored in the soil will be lost, thus altering the carbon balance in the region.

5. Conclusions

The annual and temporal variation in the R_S in arid and semi-arid regions under different land uses, such as xeric shrubland and agricultural areas, confirms that alteration in management practices and changes in environmental and soil microclimatic conditions play a pivotal role in modulating microbial activity. Consequently, these factors influence the release of carbon (C) into the atmosphere. SWC was the main predictor of R_S regardless of land use. However, when vegetation cover is changed from shrublands to agricultural use, the increase in SWC due to irrigation increases the R_S temperature sensitivity. Even slight alterations in the R_S following the conversion of xeric shrubland to agricultural plots can have significant implications on CO_2 emissions from the soil into the atmosphere. Therefore, in a scenario of increased temperatures expected in the region, an increase in the release rate of C is expected.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12111961/s1. Table S1. Description of the agricultural and xeric shrubland sites in the southeast of the Coahuila state. Table S2. Analysis of variance soil properties of land use for a given season in the southeast of the Coahuila state. Table S3. Spearman correlation between the physical, chemical, and biological properties soil. The values in bold represent significant correlations between the variables. R_S= soil respiration (g CO_2 m^{-2} hr^{-1}), Tsoil= soil temperature (°C), SWC= soil water content (%), Tair= soil temperature (°C), RH= relative humidity (%), PAR= photosynthetically active radiation (mmol m^{-2} s^{-1}), SOM= soil organic matter (%), EC= electrical conductivity (µS cm^{-1}), BD = bulk density (g cm^{-3}), TN= total nitrogen (%) and TC = total carbon (%). Significances are indicated by asterisk: * $p < 0.05$; ** $p < 0.001$; *** $p < 0.0001$. Table S4. Total, direct and indirect standardized effects (based on standardized regression weights) on soil respiration for each structural equation model (SEM) (Figure 4a, b). Significant direct effects are noted in bold.

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