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CO_2 EFFLUX IN VERTISOL UNDER DIFFERENT LAND USE SYSTEMS

[EMISIONES DE CO_2 EN VERTISOL BAJO DIFERENTES SISTEMAS DE USO DEL SUELO]

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SUMMARY

Determinations of CO_2 efflux, soil temperature and soil-water content in vertisols were monitored at least twice a week between July 2001 and January 2002. At each sampling date, two daily measurements (at 08:00 and 14:00 h local time, named as morning and afternoon, respectively) were carried out. A dynamic closed chamber with a portable system EGM employing a infrared gas analyzer (IRGA) and a soil chamber (SRC-1) were used to assess soil CO_2 efflux throughout the experimental period from vertisols under different land uses in northeastern Mexico: Pasture (*Dichanthium annulatum*), *Leucaena leucocephala* in an alley cropping system, a native and undisturbed shrubland plot, a *Eucalyptus microtheca* plantation, and a *Sorghum bicolor* field. Results showed for the *Eucalyptus* and Pasture plots a highly significant and positive linear relationship between morning and afternoon soil respiration rate and soil temperature, while no significant relationship was found between soil temperature and soil respiration for the *Leucaena*, *Sorghum* nor the Shrubland plots. Soil temperature alone explained 68% of the variation in the CO_2 efflux rate in *Eucalyptus* and 33% in Pasture. During the study period, average morning soil respiration rates for all land uses ranged from 0.7 (October) to 8.4 µmol CO_2 m^{-2} s^{-1} (August), while afternoon soil respiration rates ranged from 0.6 to 14.4 µmol CO_2 m^{-2} s^{-1}. Average morning and afternoon soil respiration rates showed the following decreasing CO_2 efflux order among the five investigated land uses: Pasture>Shrubland>*Leucaena*>*Eucalyptus*>*Sorghum*; thus, the pasture plot showed the highest average morning and afternoon soil respiration rates; 3.5 and 5.0 µmol CO_2 m^{-2} s^{-1}, respectively. In contrast, the *Sorghum* plot showed the lowest average morning (1.9) and afternoon (2.5 µmol CO_2 m^{-2} s^{-1}) soil respiration rates. The Pasture and Shrubland, which are common livestock management practices in this region, contribute to more CO_2 emissions than agriculture and forestry systems. The dry period had a significant influence in the vertisol structure, since the soil shrinks and swells noticeably in response to soil moisture content and this affects the reliability of the CO_2 efflux measurements by the close dynamic chamber. Our field observations have also illustrated the need of research efforts in vertisols under dry periods, especially when soil water content drops below 15%, in order to explain the dynamics of the characteristic CO_2 balance in different land uses.

Key words: Soil respiration; Vertisol; CO_2 efflux; Shrubland; *Leucaena; Dichanthium* Grass; *Eucalyptus; Sorghum;* Land use systems.

RESUMEN

Determinaciones del flujo de CO_2, temperatura del suelo y contenido gravimétrico de agua en el suelo fueron investigados entre julio de 2001 y enero de 2002, al menos dos veces por semana. En cada fecha de muestreo, dos mediciones diarias (a las 08:00 y 14:00 h, denominadas mañana y tarde, respectivamente) se llevaron a cabo. Una cámara dinámica cerrada con un sistema portátil EGM que emplea un analizador de gas infrarrojo (IRGA) y una cámara de suelo (SRC-1) se utilizaron para medir el flujo de CO_2 en un suelo vertisol bajo diferentes usos en el noreste de México: Pastizal (*Dichanthium annulatum*), *Leucaena leucocephala* en cultivo de callejones, Matorral nativo, plantación de *Eucalyptus microtheca* y un cultivo de *Sorghum bicolor*. Los resultados indican que la plantación de Eucalipto y el terreno con pastizal mostraron una relación lineal positiva y altamente significativa entre la respiración del suelo (mañana y tarde) y la temperatura del mismo, mientras que una relación no significativa entre la temperatura y la respiración del suelo para los usos del suelo con *Leucaena*, Sorgo y Matorral. La temperatura del suelo por sí sola explica el 68% de la variación de la tasa del flujo de CO_2 en el Eucalipto y el 33% en pastizal. Durante el periodo estudiado, el promedio de la tasa de respiración del suelo por la mañana para todos los usos del suelo varió de 0.7 (Octubre) y 8.4 μmol CO_2 m^{-2} s^{-1} (Agosto); mientras que por la tarde la tasa de respiración del suelo varió de 0.6 a 14.4 μmol CO_2 m^{-2} s^{-1}. Promedios de las tasas de respiración del suelo en la mañana y tarde mostraron el siguiente orden de disminución en el flujo de CO_2 entre los cinco usos del suelo investigados: Pastizal>Matorral>*Leucaena*>Eucalipto>Sorgo, lo que indica que la parcela de pastizal mostró el promedio de respiración más alto por la mañana y la tarde; 3.5 y 5.0 μmol CO_2 m^{-2} s^{-1}, respectivamente. Por otra parte, el cultivo de Sorgo presentó el promedio más bajo de respiración por la mañana y la tarde; 1.9 y 2.5 μmol CO_2 m^{-2} s^{-1}, respectivamente. El Pastizal y el Matorral, los cuales son prácticas comunes de ganadería en esta región, contribuyeron con mayores emisiones de CO_2 que los sistemas agrícolas y forestales. El período seco tiene una influencia relevante en la estructura del vertisol, ya que el suelo se contrae y se expande considerablemente en respuesta a las variaciones en el contenido de humedad del suelo, alterando la confiabilidad de la medición del flujo de CO_2 en la cámara dinámica. Estas observaciones también han mostrado la necesidad de investigar con mayor precisión al vertisol en épocas secas; especialmente cuando el contenido gravimétrico del agua en el suelo está por debajo del 15%, con el fin de explicar la dinámica del balance del CO_2 de los diferentes usos del suelo.

Palabras clave: Respiración del suelo; Vertisol; Emisiones de CO_2; Matorral; *Leucaena;* Pasto *Dichanthium; Eucalyptus; Sorghum;* Sistemas de uso del suelo.

INTRODUCTION

Soil respiration is an important component of the terrestrial carbon budget and is considered the second-largest factor in the flux of carbon between the earth's ecosystems and the atmosphere (Bohn 1982; Eswaran *et al*., 1993 and 1995). It has been pointed out that any increase in soil CO_2 emissions in response to environmental change have the potential to substantially increase atmospheric CO_2 levels and to provide a positive effect to global warming (Schleser, 1982; Jenkinson *et al*., 1991; Kirschbaum, 1995). Soil respiration is widely accepted as the most representative manifestation of the biological activity in the soil, and a good understanding of the variation occurring in the CO_2 fluxes due to land use changes could help explain the soil fluxes of other biogenic gases such as N_2O, NO, CO, and CH_4 (Sanhueza and Santana, 1993). Identifying the key environmental factors that control soil CO_2 emissions and their effects on emission rates is a fundamental step in assessing the potential impacts of environmental change. Soil respiration rates vary significantly among major biomes, suggesting that vegetation type influences the rate of soil respiration, soil microclimate and structure, the quantity and quality of detritus supplied to the soil, and the overall rate of root respiration (Raich and Tufekcioglu, 2000). Previous studies have indicated that the terrestrial biosphere is acting as a carbon sink (Valentini *et al*., 2000; Schimel *et al*., 2001), attenuating the potential global warming by anthropogenic gaseous emissions (mostly CO_2 and CH_4). It has been well documented that rates of soil respiration are dependent upon soil temperature and soil-water content (Carlyle and Than, 1988; Simmons *et al*., 1996; Raich and Tufekcioglu, 2000; Scott-Denton *et al*., 2003; Subke *et al*., 2004) and land uses (Priess and Fölster, 1994; Raich and Tufekcioglu, 2000; Saviozzi *et al*., 2001; Mendham *et al*., 2002; Lohila *et al*., 2003; Luo and Zhou, 2006). Other soil factors potentially influencing rates of soil respiration *in situ* include the availability of C substrates for microorganisms (Seto and Yanagiya, 1983), plant root densities and activities (Ben-Asher *et al*., 1994), soil organism population levels (Singh and Shukla, 1977; Rai and Srivastava, 1981), soil physical and chemical properties (Boudot *et al*., 1986; Bouma and Bryla, 2000; Lohila *et al*., 2003) and soil drainage (Moore and Knowles 1989; Freeman *et al*., 1993). Based on the importance of the increasing anthropogenic emissions of greenhouse gases in northeastern Mexico (SEMARNAT *et al*., 2005) and in an attempt to understand the contribution of different land uses in CO_2 efflux from the predominant vertisol type of soil in this region into the atmosphere, the objective of the present study was to assess the different seasonal trends in soil respiration rates among different land use systems and their relationship to environmental variables.

MATERIAL AND METHODS

Research site description

The present study was carried out at the Experimental Research Station of the Faculty of Forest Sciences of the Universidad Autónoma de Nuevo León (24º47' N; 99º32' W; 350 m elevation) located 8 km south of Linares county, in Nuevo Leon state of Mexico. The climate is typically subtropical and semi-arid with a warm summer. Mean monthly air temperature ranges from 14.7°C in January to 22.3°C in August, although daily high temperatures of 45°C are common during the summer. Average annual precipitation is 805 mm with a bimodal distribution. Peak rainfall months are May, June and September. Annual potential evapotranspiration is about 2200 mm. The native Shrubland vegetation is known as the Tamaulipan Thornscrub or subtropical Thornscrub woodlands (SPP-INEGI, 1986). The dominant soils are deep, dark gray, lime gray, lime clay vertisols, with montmorillonite. These alluvial soils shrink and swell noticeably in response to changes in soil moisture content. Some physical and chemical properties of the soil at profile depths of 0-20 and 20-40 cm are shown in Table 1.

Land uses experimental plots

Five experimental plots with different land uses were selected at the research site to evaluate the contribution of CO_2 efflux: Pasture (*Dichanthium annulatum*), *Leucaena leucocephala* in an alley cropping system, a native and undisturbed shrubland plot, a *Eucalyptus microtheca* plantation, and a *Sorghum bicolor* field. A brief description of each land use is as follows: a) The pasture plot was identified as an intensive livestock system, mainly for meat production, with a rotation grazing system. The perennial grass species established is *Dichanthium annulatum*_(Bluestem), which is a tufted up to 60 cm; ninety-six percent of its roots is found within a depth of 100 cm. This species is widely adapted, it is tolerant to alkaline soils and it also helps in preventing soil erosion. b) The *Leucaena leucocephala* plot was planted in an agroforestry system (alley cropping) established 15 years ago for experimental purposes. *Leucaena* is a thornless long-lived multipurpose shrub or tree, which may reach heights between 7 and 20 m. This tree is a deep-rooted perennial plant and its roots have been found to a depth of 5 m. It is partially dependent on endomycorrhizal fungi of the genera *Glomus* and *Microspora*. c) The Shrubland plot is composed of native vegetation dominated by diverse, dense, and spiny shrubs. These woodlands are characterized by a wide range of growth patterns, diverse leaf life spans, textures, and growth dynamics with contrasting taxonomic and phenological developments. In terms of productivity of the vegetation, average above-ground biomass and yearly biomass production has been estimated at 22 Mg ha^{-1} and 3.2 Mg ha^{-1} year^{-1} on a dry weight basis, respectively (Villalón, 1989). d) the *Eucalyptus microtheca* plot was established 25 years ago for research purposes and was planted (3 m x 3 m) under the Taungya's system. The *Eucalyptus* plant is an evergreen tree of 6 to 20 m high, usually crooked or irregular, 30 to 100 cm in diameter. It is used for erosion control, shade and soil conservation in hot arid climates. e) The *Sorghum bicolor* plot was established in a crop rotation field under rainfed conditions and managed in a non-tillage system. This dry land agriculture under sustainable production criteria, due to the protective layer of crop residues, results in several environmental benefits for soil management, such as stabilization of soil temperature and moisture levels.

Table 1. Some physical and chemical properties of the vertisols at each land use system at two soil profile depths.

Soil	Land Use System									
	Pasture		*Leucaena*		Shrubland		*Eucalyptus*		*Sorghum*	
Property	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm
Sand (g kg^{-1})	130	80	70	85	70	90	100	100	130	130
Silt (g kg^{-1})	490	480	480	370	490	440	420	400	360	355
Clay (g kg^{-1})	380	440	450	545	440	470	480	500	510	515
pH	7.16	7.36	7.40	7.44	7.46	7.51	7.36	7.39	7.35	7.18
EC (μS cm^{-1})	113.50	107.30	114.10	104.60	114.20	102.50	110.10	110.00	130.40	161.30
OM (%)	2.34	2.20	3.41	3.14	3.17	2.39	3.52	3.01	3.06	3.09
N (%)	0.15	0.14	0.21	0.18	0.23	1.73	0.22	0.17	0.23	0.21
K (mg kg^{-1})	55.02	275.52	562.60	423.48	506.32	393.92	449.24	525.32	536.12	437.90
P (mg kg^{-1})	3.67	1.78	1.78	0.94	2.11	2.11	2.73	3.36	13.66	11.45
C : N	9 : 1	9 : 1	9 : 1	10 : 1	8 : 1	6 : 1	9 : 1	10 : 1	8 : 1	8.5 : 1

Soil respiration measurements

A closed chamber method for measuring soil respiration was described by Parkinson (1981), in which a chamber of known volume is placed on the soil and the rate of increase in CO_2 within the chamber is monitored. Thus, soil CO_2 efflux in each plot was obtained by means of a dynamic closed chamber which is a portable system EGM (PP-Systems, U.K.) employing an infrared gas analyzer (IRGA) and a soil chamber (SRC-1) equipped with a fan. With this system, the air is continuously sampled in a closed circuit through the EGM, and the soil respiration rate is calculated, displayed and recorded by the analyzer. The air within the chamber is carefully mixed to ensure representative sampling without generating pressure differences which would affect the evolution of CO_2 from the soil surface. Once the SRC-1 chamber has been placed on the soil, the rate of increase in CO_2 in the system should be linear, although any exchange with the outside air will cause it to decline with time. Approximately 120 seconds after the chamber has been placed on the soil, the EGM records CO_2 efflux.

Sampling procedures

Determinations of CO_2 efflux in each plot were made twice a week between July 3, 2001 and January 29, 2002. At each sampling date, two daily measurements (at 08:00 and 14:00 h local time, named herein as morning and afternoon sampling time, respectively) were carried out. At each sampling time, four (replications) random measurements of soil CO_2 efflux (μmol CO_2 m^{-2} s^{-1}) were taken. Simultaneously, soil temperature (^oC) and soil water content (%, dry mass basis) were registered. Soil respiration in the *Sorghum* and *Leucaena* plots was measured between plant rows.

Environmental data

Air temperature (^oC) and precipitation data (mm) were obtained from a meteorological station located 100 m from the study site. Gravimetric soil water content on each sampling date was determined in soil cores at depths of 0-20 cm by using a soil sampling tube (Soil Moisture Equipment Corp.). Soil water content was determined by drying soil samples in an oven at 105^oC for 72 h, and was expressed on a dry mass basis. Soil temperature was measured by means of a geothermometer (Fisher Scientific) at 10-15 cm soil depth.

Statistical analysis

Since the null hypothesis of normality for soil respiration data at each land use and sampling time was rejected at $p<0.05$ according to the Kolmogorov-Smirnov test, data were subjected to logarithmic transformation in order to achieve assumptions of normality (Steel and Torrie, 1980). To detect significant differences in soil respiration rates among land uses, sampling time and the interaction land uses x sampling time, CO_2 efflux rate data were subjected to a two-way analysis of variance (ANOVA) at each sampling date. The differences were validated using the Tukey's honestly significant differences (HSD) test and were considered statistically significant at $p\leq0.05$ for all pairwise comparisons (Steel and Torrie, 1980). On a seasonal basis, correlation coefficients between morning and afternoon soil respiration rates and environmental variables (soil temperature, soil water content, absolute maximum air temperature, maximum mean air temperature, monthly mean air temperature, minimum mean air temperature, absolute minimum air temperature and monthly precipitation) at each land use were quantified by the Spearman's rank order correlation analyses since the null hypothesis of normality was rejected at $p<0.05$ (Steel and Torrie, 1980; Ott, 1993). Linear regression analyses were performed between soil respiration rate and morning and afternoon soil temperature at each land use. All statistical methods were applied according to the SPSS (Statistical Package for the Social Sciences) software package (standard released version 9.0 for Windows, SPSS Inc., Chicago, IL).

RESULTS

Environmental conditions during the experimental period

Seasonal trends of monthly mean, minimum and maximum air temperatures and total precipitation are shown in Fig. 1. During the experimental period, mean maximum air temperatures ranged from 18.8^oC (January, 2002) to 36.4^oC (July, 2001), whereas mean minimum air temperatures varied between 6.3^oC (January, 2002) and 24.3^oC (July, 2001). Total rainfall registered at the study site was 592 mm.

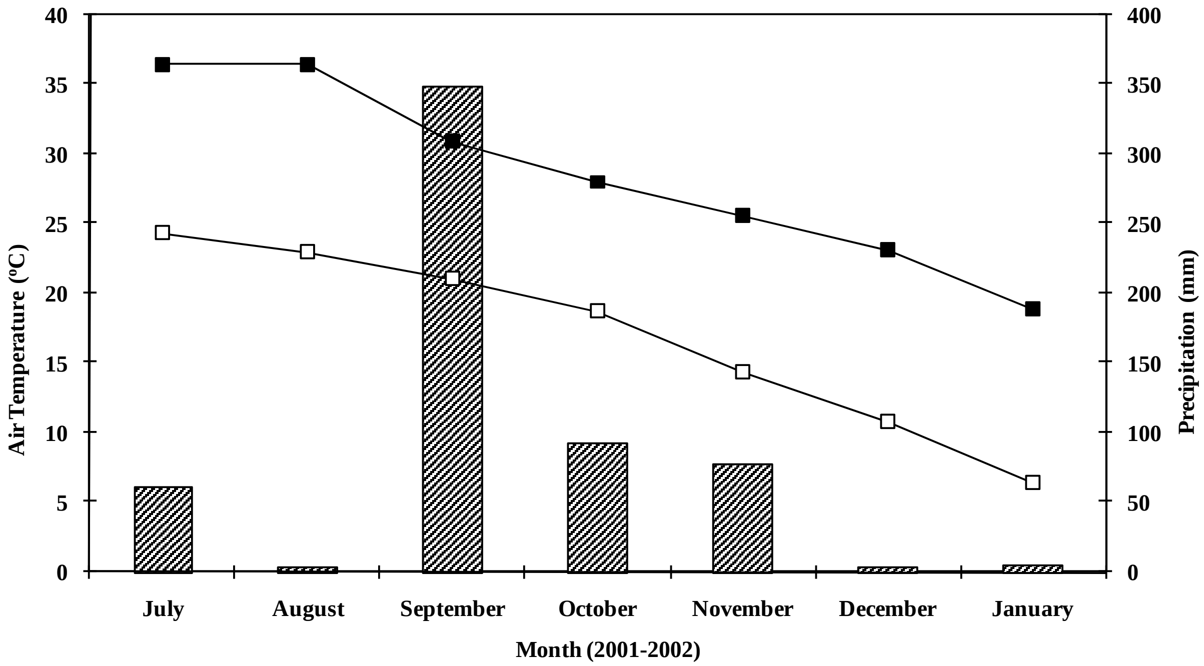

Figure 1. Monthly mean, minimum and maximum air temperatures, and monthly precipitation between July, 2001 and January, 2002 at the research site. Precipitation (▨) Mean Maximum Air Temperature (■); Mean Minimum Air Temperature (☐).

The seasonal trend of morning and afternoon soil temperature during the study period are shown in Fig. 2. Maximum morning soil temperature values ranged between 28°C (*Eucalyptus*) to 32°C (Pasture), whereas minimum morning soil temperature varied from 10.5°C in Shrubland to 13°C in *Sorghum* (Fig. 2(a)). In general, afternoon soil temperature prevails during July to August in all land use systems after which, it shows a gradual decrease reaching to minimum in December and January. Maximum afternoon soil temperature ranged from 40°C (Shrubland) to 32°C (*Eucalyptus*), while minimum afternoon soil temperature varied between 17.8 °C (*Sorghum*) and 14.2 °C (*Eucalyptus*) (Fig. 2(b)). Seasonal soil water content trends at each land use were similar between morning (Fig. 3(a)) and afternoon (Fig. 3(b)) sampling times. It is clearly observed that soil water content was maximum in early July (coinciding with precipitation) which decreased to minimum in August; this reached to peaks in late August. The large variability is observed in different land use systems for example *Sorghum* and *Eucalyptus* had maximum soil water content while Pasture showed minimum soil water content during late July to early August.

Seasonal variation in soil respiration

According to the two-way ANOVA statistic analysis for differences among land uses (LU), sampling time (ST) and the interaction (LU*ST) in soil respiration rates (Table 2), in the case of LU, for only one sampling date (Dec-18, 2001) out of thirty, there were no significant differences (p>0.05); however, there were significant differences (p<0.05) among LU in the remaining twenty nine sampling dates. With respect to sampling time, seventeen sampling dates out of thirty showed no differences (p>0.05); however, there were significant differences (p<0.05) between ST in the remaining thirteen sampling dates. In relation to the interaction LU*ST, eleven sampling dates out of thirty showed no significant differences (p>0.05). The seasonal variation in morning and afternoon soil respiration rate at each land uses is shown in Figs. 4 (a) and (b), respectively.

During the study period, average morning soil respiration rates ranged from 0.01 (Shrubland and *Sorghum*) to 8.46 (*Leucaena*) µmol CO_2 m^{-2} s^{-1}. With respect to afternoon soil respiration rates values ranged from 0.01 (Pasture, *Eucalyptus* and *Sorghum*) to 14.4 (*Leucaena*) µmol CO_2 m^{-2} s^{-1} throughout the experimental period. In general, average morning and afternoon soil respiration rates showed the following decreasing CO_2 efflux order among the five investigated land uses Pasture>Shrubland>*Leucaena*>*Eucalyptus*>*Sorghum*; thus, the pasture plot showed the highest average morning and afternoon soil respiration rates 3.5 and

5.0 μmol CO_2 m^{-2} s^{-1}, respectively. In contrast, *Sorghum* consistently showed the lowest average morning and afternoon soil respiration rates with values of 1.9 and 2.5 μmol CO_2 m^{-2} s^{-1}, respectively. Conversely, *Leucaena* showed the absolute maximum morning and afternoon CO_2 efflux rate during the study period; 8.4 μmol CO_2 m^{-2} s^{-1} and 14.4 μmol CO_2 m^{-2} s^{-1}, respectively.

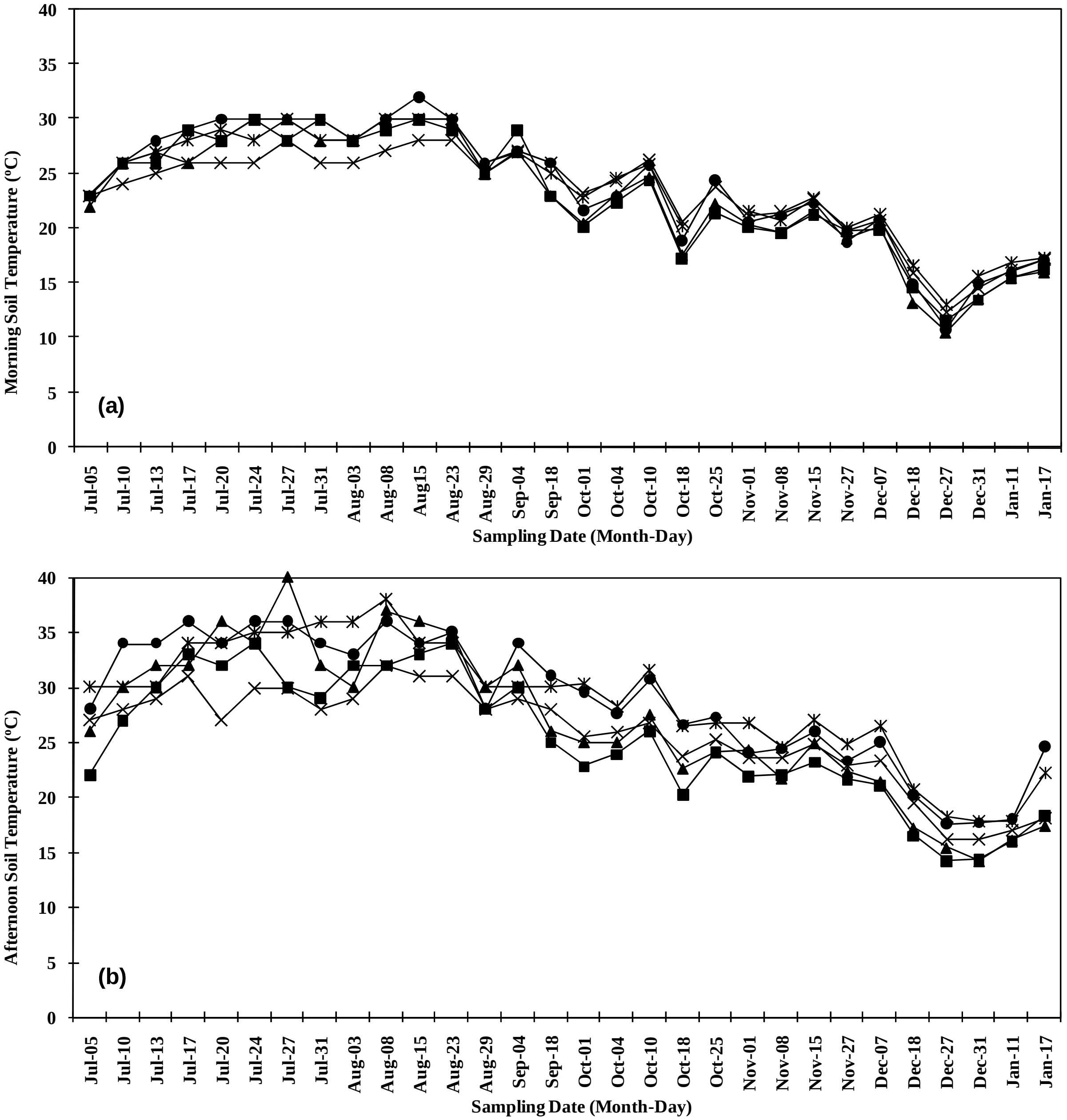

Figure 2. Seasonal variation in morning (a) and afternoon (b) soil temperature at five different land uses. Pasture (•); *Leucaena* (■); Shrubland (▲); *Eucalyptus* (×) and *Sorghum* (✱).

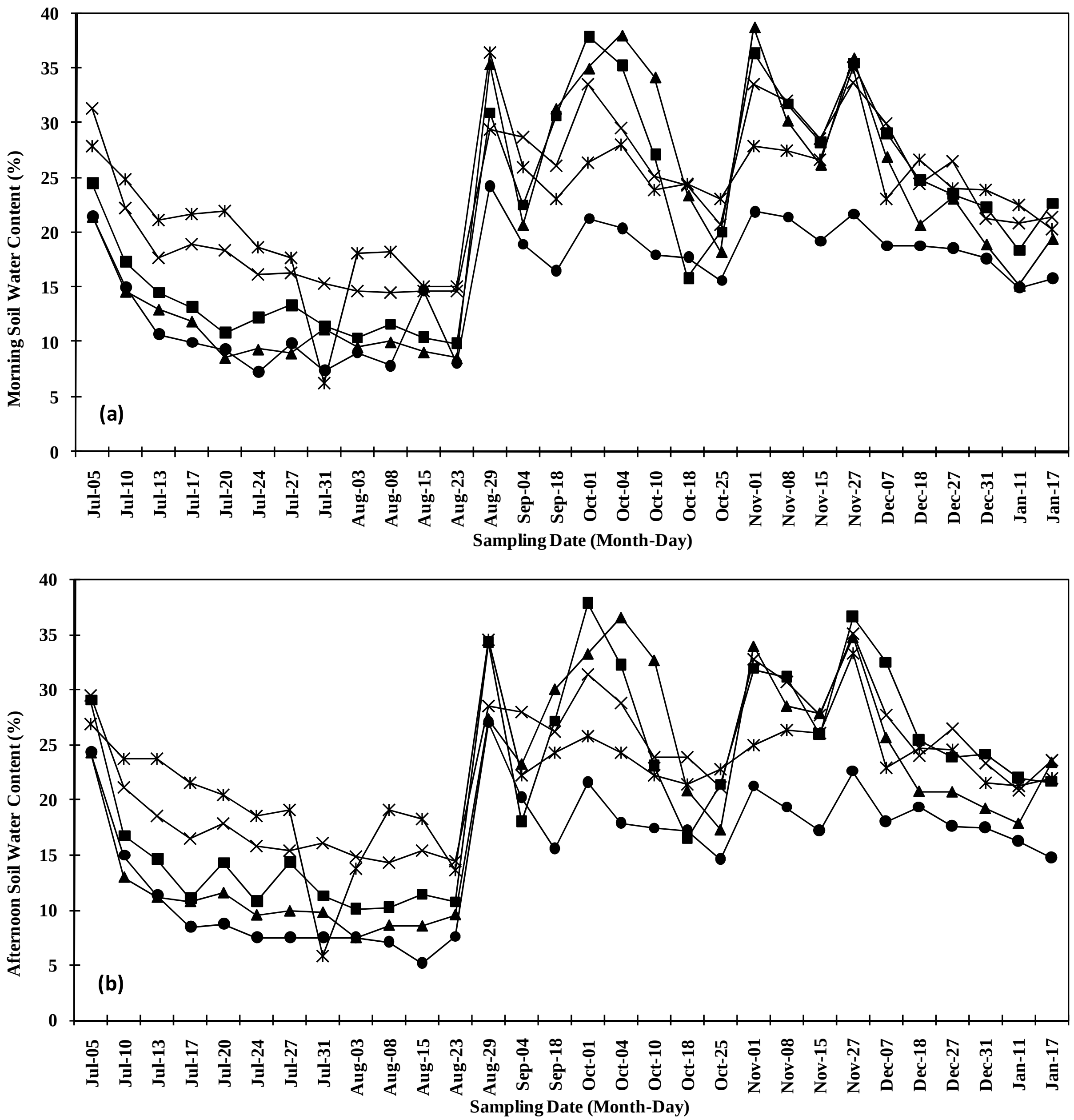

Figure 3. Seasonal variation in morning (a) and afternoon (b) soil water content (%) at 20 cm soil profile depths at five different land uses. Pasture (•); *Leucaena* (■); Shrubland (▲); *Eucalyptus* (×) and *Sorghum* (✱).

Soil temperature and soil respiration relationships

The relationship between soil respiration rate and soil temperature for all land uses at each sampling time is illustrated in Fig. 5. Least square statistics for this relationship is shown on Table 3. Results suggest that only in the Pasture and *Eucalyptus* land uses there was a highly significant ($p<0.01$) and positive linear relationship between soil respiration rate and morning and afternoon soil temperature, whereas for the remaining land uses (*Leucaena*, *Sorghum* and Shrubland) the relationship was not significant (Table 3). For the Pasture and *Ecucalyptus* land use, morning soil temperature explains soil respiration rate between 33 and 57%, respectively. Similarly, afternoon soil temperature in theses land uses explains soil respiration rate between 32 and 68%, respectively. In addition, according to the slopes of the linear model, an increase in morning soil temperature of 1°C in the Pasture and *Eucalyptus* land use will induce an increase of 0.212 and 0.189 μmol CO_2 m^{-2} s^{-1}, respectively; likewise, an increase in afternoon soil temperature of 1°C in the Pasture and *Eucalyptus* land use will induce an increase of 0.225 and 0.261 μmol CO_2 m^{-2} s^{-1}, respectively.

Relationships between soil respiration and environmental variables

In general, morning and afternoon soil respiration rate in all land uses showed a significant ($p<0.05$) and positive correlation with absolute maximum and minimum air temperature, mean maximum and minimum air temperature, and mean monthly air temperature. Similarly, morning and afternoon soil respiration rate in Pasture and *Eucalyptus* showed a significant ($p<0.01$) and positive correlation with both morning and afternoon soil temperature. In contrast, only morning and afternoon soil respiration rate in Pasture showed a significant ($p<0.01$) and positive correlation with both morning and afternoon soil water content (Table 4).

Table 2. Two-way ANOVA results for land use, sampling time and interaction at each sampling date for soil respiration rate.

Sampling	Land Use (LU)		Sampling Time (ST)		Interaction (S*ST)		Adjusted	
Date	*F* value	*p*-value	*F* value	*p*-value	*F* value	*p*-value	R^2	CV(%)
Jul-05	46.30	<0.001	183.84	<0.001	9.42	<0.001	0.931	5.6
Jul-10	4.18	0.010	12.10	0.002	5.36	0.003	0.512	10.9
Jul-13	14.63	<0.001	0.80	0.381	1.23	0.331	0.686	13.1
Jul-17	7.52	0.001	2.99	0.102	4.46	0.017	0.572	11.3
Jul-20	12.76	<0.001	0.01	0.905	7.85	0.001	0.781	14.2
Jul-24	7.88	<0.001	2.67	0.115	15.89	<0.001	0.720	14.3
Jul-27	3.17	0.037	2.82	0.110	2.28	0.099	0.412	21.9
Jul-31	15.12	<0.001	3.34	0.085	16.31	<0.001	0.807	19.3
Aug-03	33.29	<0.001	1.55	0.224	18.23	<0.001	0.850	11.6
Aug-08	7.31	0.001	0.62	0.442	3.02	0.045	0.466	26.2
Aug-15	19.14	<0.001	0.03	0.876	6.98	0.018	0.826	13.2
Aug-23	10.40	<0.001	0.48	0.496	1.62	0.210	0.602	14.4
Aug-29	6.78	0.002	1.46	0.242	1.37	0.283	0.492	12.6
Sep-04	12.52	<0.001	39.67	<0.001	2.63	0.055	0.707	10.4
Sep-18	20.11	<0.001	52.90	<0.001	5.42	0.002	0.815	14.5
Oct-01	8.15	0.001	0.99	0.331	1.85	0.174	0.548	15.1
Oct-04	11.22	<0.001	2.79	0.024	3.50	0.021	0.631	16.0
Oct-10	19.14	<0.001	3.47	0.074	2.58	0.062	0.711	13.8
Oct-18	6.38	0.001	1.34	0.257	1.19	0.340	0.390	15.2
Oct-25	13.27	<0.001	0.46	0.505	1.47	0.245	0.602	12.0
Nov-01	50.93	<0.001	75.64	<0.001	4.74	0.010	0.890	9.6
Nov-08	36.46	<0.001	49.19	<0.001	9.55	<0.001	0.854	8.9
Nov-15	51.61	<0.001	0.17	0.683	24.63	<0.001	0.886	8.4
Nov-27	42.22	<0.001	74.50	<0.001	2.15	0.107	0.875	10.1
Dec-07	26.78	<0.001	42.84	<0.001	11.73	<0.001	0.855	10.7
Dec-18	2.63	0.059	9.14	0.006	7.13	0.001	0.531	14.8
Dec-27	8.70	<0.001	29.77	<0.001	6.01	0.002	0.778	12.4
Dec-31	33.93	<0.001	0.01	0.949	5.23	0.004	0.841	11.0
Jan-11	3.70	0.019	14.49	0.001	2.77	0.066	0.536	12.9
Jan-17	20.13	<0.001	12.05	0.002	3.96	0.014	0.782	10.3

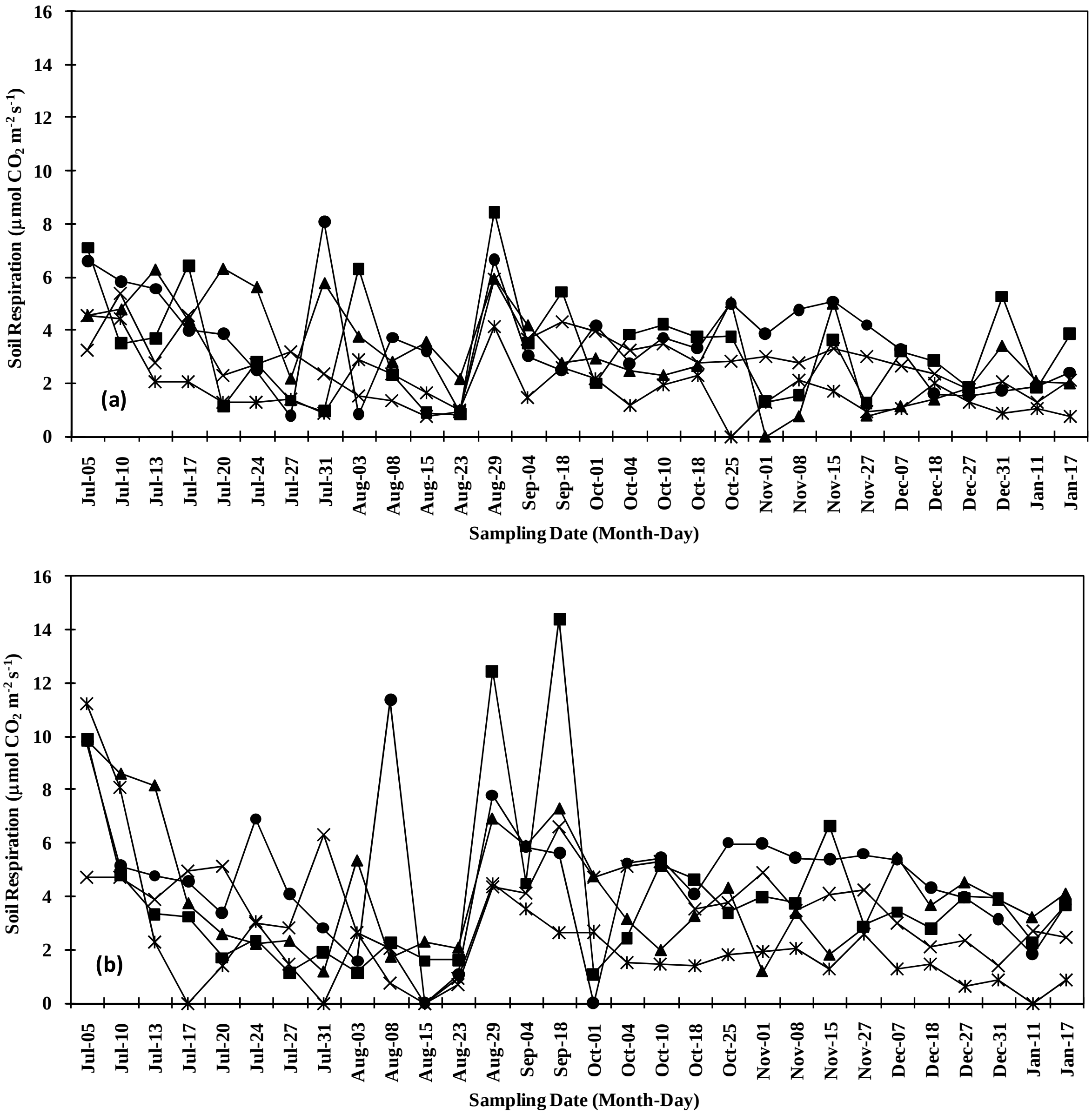

Figure 4. Seasonal variation in morning (a) and afternoon (b) soil respiration rate at five different land uses. Pasture (●); *Leucaena* (■); Shrubland (▲); *Eucalyptus* (×) and *Sorghum* (✳).

DISCUSSION

Northern Mexico has been characterized by its industrial development; this has induced remarkable changes of land use, which together with the exploitation of forest resources, has altered the hydrology of the region, recharging of the groundwater, wildlife habitats and it has contributed to soil erosion (Cantú and Gonzalez, 2001). Intensive forest management alters significantly soil properties and environment, which may influence microorganism soil activity and therefore, soil organic matter (SOM) decomposition and soil CO$_2$ dynamics (Brumme, 1995). The production of CO$_2$ within the soil is basically a biochemical process and thus responds strongly to variations in temperature. This dependence may change with the age of the SOM and also with the availability of water for biochemical reactions. In this study, there was a decreasing trend of air temperature from July onwards to minimum in January. Higher afternoon soil temperatures were observed during the study period in *Sorghum* and Pasture land use systems. Such results may be expected, as the low vegetation density of these land uses will allow higher solar radiation impinging at soil level, compared with other land uses involving trees (*i.e. Leucaena* and *Eucalyptus*), which showed lower soil temperatures as a result of radiation interception by vegetation cover. However, the trend of morning soil temperature during the study period was similar in the five land uses. Although Pasture and *Sorghum* showed higher afternoon soil temperatures, only Pasture showed higher soil respiration rate, while *Sorghum* presented the lowest soil respiration rates. Maybe the accumulated mulch in the *Sorghum* plot due to the non-tillage system management, helps to maintain the SOM for longer time and to some extent influence in soil respiration. Also, root respiration may play an important role, since annual sorghum fields, due to the short root life span and the relatively low root biomass production, could generally promote lower soil respiration rates. Studies in the United States have demonstrated that the tilling process in the conventional system (a highly mechanized cropping process) results in a loss of organic matter and emission of carbon dioxide, thus contributing to the greenhouse effect. A more extensive use of the Non-Tillage System could absorb up to 16% of CO_2 emissions by fossil fuels and Non-Tillage has been responsible for a reduction between 64 to 74% of CO_2 emissions (Fontes and Hermann, 2000). A positive relationship between soil temperature and soil CO_2 efflux rate has been established (Singh and Gupta, 1977; Raich and Schlesinger, 1992). On the other hand, Mariko *et al.* (2000) and Davidson *et al.* (2000) have recognized the limitations of using a simple temperature function from one soil depth only, to describe a complex process operating throughout the profile under the influence of the heterogeneity of substrate and many diverse environmental factors. Splitting the temperature response function into several components to represent the flux contribution from different soil layers is one step towards a better understanding of the origin of CO_2 within the soil. However, this would increase the number of variables in a regression model, thus requiring significantly more data to yield a significant regression pattern. In this study, soil respiration was conducted using a manually operated closed chamber, which cannot easily provide a sufficient number of observations to allow a regression model of this type.

Table 3. Least-squares coefficients for soil respiration in relation to morning and afternoon soil temperature in five different land uses.

Land	Environmental	Least-square Statistics						
		y-axis intercept			Slope of the regression model			Adjusted
Uses	Variable	$\hat{\beta}_0$	E.S.E	*p*-value	$\hat{\beta}_1$	E.S.E	*p*-value	R^2
Pasture	MST	-0.804	1.411	0.576	0.212	0.067	0.006	0.334
	AST	-0.410	1.910	0.833	0.225	0.075	0.008	0.322
Leucaena	MST	0.146	2.036	0.944	0.174	0.100	0.100	0.101
	AST	-2.276	3.957	0.573	0.337	0.179	0.078	0.123
Shrubland	MST	-0.530	1.468	0.723	0.171	0.073	0.031	0.212
	AST	1.523	2.309	0.518	0.122	0.099	0.237	0.027
Eucalyptus	MST	-0.950	0.807	0.255	0.189	0.038	<0.001	0.576
	AST	-2.255	0.993	0.036	0.261	0.042	<0.001	0.679
Sorghum	MST	-0.545	1.300	0.680	0.115	0.061	0.077	0.131
	AST	-4.463	3.389	0.207	0.263	0.128	0.056	0.160

Least squares estimates (n=19) have indicated that the best fitted model to relate soil respiration as a function of soil temperature corresponded to a linear mathematical function. β_0 and β_1 are the y-axis intercept and slope of the estimated regression model, respectively. Estimated standard errors (E.S.E.), *p*-values and adjusted coefficient of determination (R^2) values are provided. MST, Morning Soil Temperature; AST, Afternoon Soil Temperature.

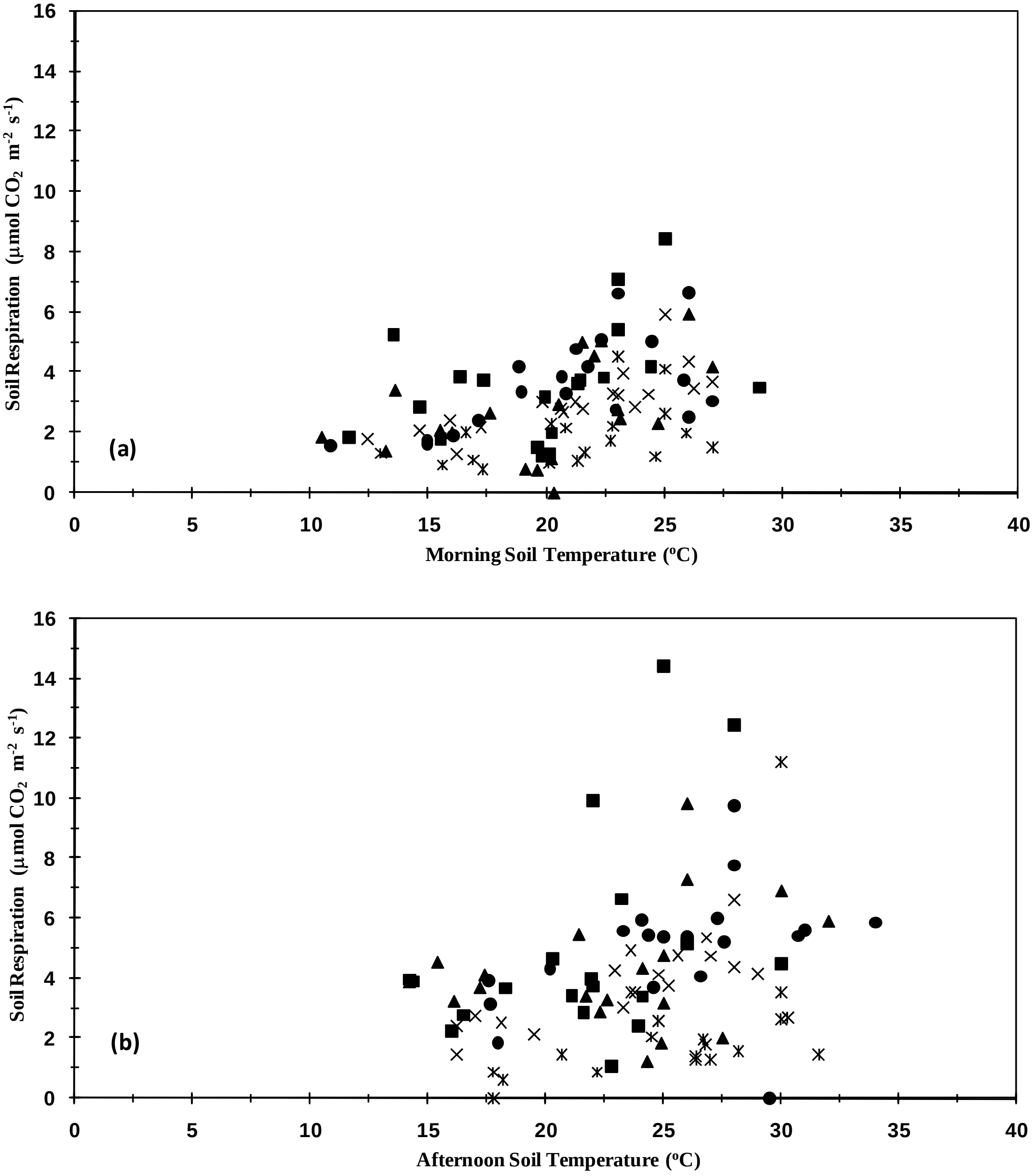

Figure 5. Relationship between soil respiration and morning (a) and afternoon (b) soil temperature. Data are from all land uses and selected sampling dates (soil water content >15%) during the study period. Pasture (•); *Leucaena* (■); Shrubland (▲); *Eucalyptus* (×) and *Sorghum* (✱).

Table 4. Spearman's correlation coefficient values (n=17 selected data with soil water content > 15%) for morning and afternoon soil respiration in relation to environmental variables in five different land uses.

	Land Use				
Environmental Variable	Pasture	*Leucaena*	Shrubland	*Eucalyptus*	*Sorghum*
	Morning Soil Respiration				
Morning Soil Temperature	0.609**	0.389	0.508*	0.570**	0.303
Morning Soil Water Content	0.607**	-0.175	-0.111	0.234	0.235
Absolute Maximum Air Temp.	0.758**	0.446	0.563*	0.614**	0.555**
Maximum Mean Air Temp.	0.707**	0.673**	0.629**	0.550**	0.583**
Mean Monthly Air Temp.	0.680**	0.620**	0.608**	0.564**	0.575**
Minimum Mean Air Temp.	0.644**	0.558*	0.579*	0.572**	0.561**
Absolute Minimum Air Temp.	0.420	0.730**	0.611**	0.525**	0.552**
Monthly Precipitation	-0.014	0.072	0.177	0.319	0.035
	Afternoon Soil Respiration				
Afternoon Soil Temperature	0.602**	0.414*	0.285	0.646**	0.261
Afternoon Soil Water Content	0.675**	0.040	-0.208	0.074	0.246
Absolute Maximum Air Temp.	0.787**	0.582**	0.358	0.666**	0.480*
Maximum Mean Air Temp.	0.861**	0.672**	0.617**	0.521**	0.520**
Mean Monthly Air Temp.	0.836**	0.626**	0.565**	0.564**	0.517**
Minimum Mean Air Temp.	0.796**	0.566*	0.502*	0.603**	0.503*
Absolute Minimum Air Temp.	0.664**	0.695**	0.762**	0.493*	0.491*
Monthly Precipitation	0.218	0.372	0.255	0.513**	0.097

Correlations are on a seasonal basis. * and ** indicate significant correlation at p<0.05 and p<0.01, respectively.

Factors such as temperature, moisture availability, and substrate properties that simultaneously influence the production and consumption of organic matter are more important in controlling the overall rate of soil respiration than vegetation type in most cases. However, coniferous forests had ~10% lower rates of soil respiration than did adjacent broad-leaved forests growing on the same soil type, and grasslands had, on average, ~20% higher soil respiration rates than did comparable forest stands, demonstrating that vegetation type does indeed, in some cases, significantly affect rates of soil respiration (Raich and Tufekcioglu, 2000).

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Soil moisture and soil respiration relationships

The exact relationship between soil water content (SWC) and the soil CO_2 efflux rate differs from one soil type to another (Howard and Howard, 1993), and is also likely to depend on adaptations by the soil microbial communities to local climatic conditions. Severe soil CO_2 efflux limitations in more arid ecosystems, for example, do not occur until SWC drops below about 0.1 $m^3 m^{-3}$ (Carlyle and Than, 1988; Janssens *et al.*, 2000; 2003). Apparently, during the dry period (Jul-10 to Aug-23), soil respiration rate was not SWC dependent, since Pasture and Shrubland, which showed the lowest SWC (<10%) during this dry period (Figs. 3(a) and (b)), also attained highest respiration rates in comparison with *Eucalyptus* and *Sorghum,* which presented the highest SWC (>15%). However, the dry period has a substantial influence in the vertisol structure, since the soil shrinks and swells noticeably in response to variations in soil moisture content and that affects the reliability of the CO_2 efflux measurement by the instrument. Field observations have also illustrated the need for research efforts in vertisols under dry periods, especially when soil water content drops below 15%, in order to explain the dynamics of the CO_2 balance of different land uses.

CONCLUSIONS

According to ANOVA statistic analysis of differences among land uses (LU), sampling time (ST) and the interaction (LU*ST) in soil respiration rates, one sampling date of thirty (Dec-18, 2001) for LU factor was not different ($p>0.05$); however, there were significant differences ($p<0.05$) among LU in the remaining twenty nine sampling dates. With respect to sampling time, seventeen sampling dates out of thirty were not different ($p>0.05$); however, there were significant differences ($p<0.05$) between ST in the remaining thirteen sampling dates. In relation to the interaction LU*ST, eleven sampling dates out of thirty were not significantly different ($p>0.05$).

During the study period, average morning soil respiration rates for all land uses ranged from 0.7 to 8.4 μmol CO_2 m^{-2} s^{-1} (in Oct. and Aug., respectively), while afternoon soil respiration rates ranged from 0.6 to 14.4 μmol CO_2 m^{-2} s^{-1} throughout the experiment. Average morning and afternoon soil respiration rates showed the following decreasing CO_2 efflux order among the five investigated land uses Pasture>Shrubland>*Leucaena*>*Eucalyptus*>*Sorghum*; thus, the pasture plot showed the highest average morning and afternoon soil respiration rates: 3.5 and 5.0 μmol CO_2 m^{-2} s^{-1}, respectively. In contrast *Sorghum* showed the lowest average morning and afternoon soil respiration rates: 1.9 and 2.5 μmol CO_2 m^{-2} s^{-1}, respectively. *Leucaena* and Pasture achieved the absolute maximum CO_2 efflux rates. In *Eucalyptus,* morning and afternoon soil temperature explained about 58 and 68%, respectively, of the variation in soil respiration rate, while in Pasture this relationship reached around 32%. An increase in morning soil temperature of 1°C in the Pasture and *Eucalyptus* land use will induce an increase of 0.212 and 0.189 μmol CO_2 m^{-2} s^{-1}, respectively; likewise, an increase in afternoon soil temperature of 1°C in the Pasture and *Eucalyptus* land use will induce an increase of 0.225 and 0.261 μmol CO_2 m^{-2} s^{-1}, respectively. Morning and afternoon soil respiration rate in all land uses showed a significant ($p<0.05$) and positive correlation with absolute maximum and minimum air temperature, mean maximum and minimum air temperature, and mean monthly air temperature. Similarly, morning and afternoon soil respiration rate in Pasture and *Eucalyptus* showed a significant ($p<0.01$) and positive correlation with both morning and afternoon soil temperature. In contrast, only morning and afternoon soil respiration rates in Pasture showed a significant ($p<0.01$) and positive correlation with both morning and afternoon soil water content.

Finally, the Pasture and Shrubland, which are common livestock management practices in this region, contribute to more CO_2 emissions than agriculture and forestry systems.

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