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Influence of Soil and Climate Conditions on CO_2 Emissions from Agricultural Soils

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Abstract Many of the environmental problems related to agriculture will still be serious over the next 30 years. However, the seriousness of some of those problems may increase more slowly than in the past or even diminish in other cases (FAO 2002). Agriculture plays two different roles in climate change; on one hand, it suffers from the impact of climate change, on the other hand, it is responsible for 14 % of total greenhouse gases (MMA 2008). Nevertheless, agriculture is also part of the solution, as it is capable of mitigating a significant amount of global emissions, according to the FAO (2001). This paper aims to study the influence of edapho-climate conditions on soil CO_2 emissions into the atmosphere. In order to do so, we conducted three field trials in different areas in southern Spain, which have different soil textures and different climate conditions. The results show how interaction between the temperature and rainfall recorded has a greater influence on emissions than each of the factors separately. However, at the same time, the texture of the soil at each of the locations was also found to be the most dominant variable in the gas emission process.

Keywords Soil texture · Climate conditions · CO_2 flow

1 Introduction

The forecast for global warming linked to a high content of atmospheric CO_2 has generated increasing interest in the composition of the atmosphere and the changes it undergoes, particularly those brought about by humans and related to the release of sequestered carbon dioxide into the atmosphere, mainly through fossil fuels (Schlesinger 1991; Shine and Forster 1999; Sigman and Boyle 2000).

Agriculture accounts for the largest proportion of land used by humans and is an important source of emissions of these types of gases. Carbon dioxide (CO_2), methane (CH_4) and nitrogen oxide (N_2O), all of which are greenhouse gases, are related to human activity. CO_2 is produced by breathing and is also a by-product of burning fossil fuels, while N_2O losses

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related to farming are due to the utilisation of fertilisers and organic soil amendments (Dolan et al. 2006). In 2005, agriculture was estimated to be responsible for releasing a total of 6.1 Gt CO_2-eq/year, which represents between 10 % and 12 % of total anthropogenic greenhouse gases (GHGs) emissions (Smith et al. 2007).

Agriculture is also capable of removing carbon dioxide from the atmosphere and sequestering it in soils and vegetable matter. Although environmental regulations generally exclude agriculture, the capacity of this activity to offset GHG emissions from various sources means this industry can play an important role in climate policy (Claassen and Morehart 2009).

The organic carbon in the soil (SOC) is related to levels of atmospheric CO_2 through various biogeochemical processes. The reserve of C in soil is the result of the balance between that stemming from fresh organic matter and the C emitted by the soil into the atmosphere in the form of CO_2 and depends above all on two groups of factors: weather conditions and soil properties (Aguilera 2000; Swift 2001).

Similarly, CO_2 production can change depending on the quality of the organic matter added to the soil (Delaney et al. 1996; Arrigo et al. 2002) and on the seasonal variations of the climate (Swift et al. 1979).

Studies have appeared in recent times that ratify the influence of the climate on C concentration in the soil and the atmosphere. Figueroa and Redondo (2007) indicate in a study on CO_2 sinks that the fields devoted to agricultural crops are capable of sequestering between 0.1 and 1.0 tonnes of carbon per hectare, depending on the characteristics of the climate in the region. Other studies state that certain factors could restrict the efficiency of agricultural soil as a carbon sink, citing temperature and moisture as examples (Emmet et al. 2004).

The periods during which there is a shortage of rainfall, which are typical of the Mediterranean climate, limit the decomposition of organic remains. However, some papers indicate that microorganisms continue their activity in deeper layers where there is more humidity. Casals et al. (2000) observed that the flow of CO_2 into the soil of a forest of *Pinus halepensis* in a semi-arid Mediterranean climate did not decrease despite a severe summer drought. At this time of the year, microbial activity remained minimal in surface soil, suggesting that CO_2 effluxes in summer mainly came from deeper layers of soil.

Soil aggregation and texture are the soil properties that have the greatest influence on carbon sequestration and CO_2 emissions. Rothon (2000) found a positive relationship between the stability percentage of aggregates and SCO content. Chaney and Swift (1984) obtained similar results in 26 samples of British soil and Caravaca et al. (2001) in two samples of semi-arid soil in Spain.

As regards the effect of soil texture, several authors have suggested that the soil organic matter (SOM) can form various layers around particles of clay, limestone and soil aggregates. Theng et al. (1986) observed that SOM can be inserted into the interlaminar space between clay horizons.

SOM would accumulate to a greater extent in clay soils than in sandy soils due to the former having lower mineralisation rates than soils with a high content of sand (Ladd et al. 1981, 1985; Amato and Ladd 1992; Skjemstad et al. 1993). However, in other papers, authors indicate that soil texture does not affect decomposition rates (Gregorich et al. 1991; Scott et al. 1996).

In relation to CO_2 emissions, this gas, which is stored in the pore space in soil, is then released into the atmosphere following diffusion between the parts of the soil with different concentrations (Lacasta et al. 2006; Álvaro-Fuentes et al. 2008). The textural composition of a soil affects the size of soil pores. When the clay fraction is predominant, microporosity is greater. In contrast, heavy-textured soils (sand) favour microporosity. For this reason, providing a mechanical alteration does not break the structure of the soil and release the gas trapped therein (Reicosky 2002); the amount of gas emitted should be influenced by the particle fraction of the soil.

Very few studies in Spain have measured CO_2 from surface soil, and most of them compare the effect that different soil management systems have on gas flows. For this reason, the objective of this paper is to assess the influence of the weather, the evolution of organic carbon over time and soil texture on the flow of CO_2 into the atmosphere in three experimental fields in the south of Spain with different soil and climate characteristics.

2 Materials and Methods

2.1 Location of Field Trials and Climate Conditions in the Area

The experiment was conducted in three municipalities called Montoro (Cordoba), Osuna (Seville) and

Carmona (Seville), all located in the southern Spanish region of Andalusia, and the study was conducted in three consecutive farming seasons.

The three towns are located in a Mediterranean region with a Xeric moisture regime, according to the standards set by Soil Survey Staff (1999). The climate is characterised by a cold wet period in autumn and winter, which accounts for 80 % of rainfall and another very warm and dry period in spring and summer. The temperature regime is thermal. Table 1 presents the monthly average, medium temperatures and the rainfall recorded in the three areas and seasons during which data were collected.

2.2 Field Plots and Experimental Design

Initial soil samples were taken in all three sites in order to obtain some of their physicochemical characteristics. The results are shown in Table 2.

In the case of Montoro, the soil has a loamy-sandy texture in the epipedion and has a low content of OM. It is classified as Typic Haploxerept (Soil Survey Staff 1999). The Ap ranges from 15 to 30 cm thick and is a reddish-brown colour. The Bt horizon is deep red, and thickness is variable. In Osuna, the soil has a basic pH with a high percentage of carbonates and a low level of organic matter. It has a clayey-silty texture, classified as Calcic Haploxeralf (Soil Survey Staff 1999), and has developed on detritic limestone, sandstone, limestone and yellowish-white marls. Illite and kaolinite dominated the clay fraction along with many metal oxides. In Carmona, the soil has a heavy clayey texture and is classified as very fine montmorillonitic, Chromic Haploxeret (Soil Survey Staff 1999). It is naturally fertile and has a high concentration of potassium and calcium, medium levels of phosphorus and low organic matter content, while pH tends towards neutrality. It is mainly composed of clay, which accounts for over 60 %, distributed as follows: 70 % montmorillonite-type expandable clay, 20 % illite and 10 % kaolinite (Perea 2000). The high proportion of expandable clays in this soil results in retraction cracks forming during dry periods, cracks that further dry out the soil. Therefore, the availability of water is the most limiting factor when it comes to farming such soil.

The experimental design was performed using a random block design in all three field trials.

The tillage operations performed during the monitoring period at the three sites were the same as on the rest of the farm and consisted of an initial pass of disk plow and successive cultivator passes to decrease soil clod size.

2.3 Soil Sample Collection and Emission Measurements

Soil sampling was carried out monthly, except in summer when the lack of water made it very difficult to take samples. Samples were taken from the first 6 cm of soil, as many studies have reported that most

Table 1 Average temperatures (degree Celsius), accumulated rainfall (millimetre) and their standard deviation during the study period

	Montoro		Osuna		Carmona	
	MedT	Rain	MedT	Rain	MedT	Rain
Jan	7.9±2.2	24.7±16.5	8.7±1.5	52.8±26.8	9.6±1.3	45.9±12.4
Feb	10.3±2.6	35.7±23.7	11.1±1.8	57.7±25.4	12.1±1.5	66.4±8.8
Mar	12.1±2.3	76.0±65.1	12.2±0.6	31.1±25.5	13.0±1.0	31.9±15.3
Apr	15.5±0.2	38.4±17.8	15.4±1.4	74.5±75.1	14.9±1.0	81.1±84.2
May	20.0±3.3	43.5±35.4	20.2±1.8	44.9±20.4	18.5±1.3	56.7±62.9
Jun	24.8±2.9	1.5±1.4	24.2±1.7	4.2±2.5	23.5±1.1	5.2±6.2
Jul	28.7±2.2	0.0±0.0	27.7±0.6	1.5±2.5	26.9±0.5	0.0±0.0
Aug	28.7±1.0	1.9±2.4	26.7±0.7	11.1±19.0	27.1±1.2	0.1±0.2
Sep	23.6±3.1	25.3±22.9	23.2±0.5	32.5±11.9	23.4±0.8	38.1±21.3
Oct	18.5±2.3	55.3±10.5	14.8±0.7	76.8±45.5	19.6±1.3	56.8±26.7
Nov	11.8±3.1	39.4±29	13.2±1.5	43.7±44.7	13.5±1.7	60.4±46.1
Dec	8.1±2.3	30.7±14.5	9.3±0.7	26.1±10.7	9.5±0.5	34.8±20.3

Table 2 Chemical characteristics of soil for the different field trials

	Montoro	Osuna	Carmona
Sand (%)	77.0	11.4	6.3
Silt (%)	14.0	44.6	31.4
Clay (%)	9.0	44.0	62.2
pH	5.5	8.2	7.6
OC (g kg^{-1})	4.1	12.0	9.5
P (available) (mg kg^{-1})	11.4	17.0	12.7
K (available) (mg kg^{-1})	47.3	611.0	649.0
Ca (available) (mg kg^{-1})	64.0	584.3	605.0
Mg (available) (mg kg^{-1})	6.5	30.1	28.7
CEC ($mol_c kg^{-1}$)	7.70	0.29	0.52

of the organic carbon concentrates are on the surface and that is where the highest proportion of changes takes place. In this case, soil was collected in circular metallic containers with sides measuring exactly 6 cm. The containers were nailed to the ground, permitting the extraction of undisturbed samples from the soil.

Once in the laboratory, the samples were dried, put through a 2-mm sieve and their OM content analysed using the Walkley–Black method (Nelson and Sommers 1982).

A total of 36, 72 and 60 samples were collected on a monthly basis in Montoro, Osuna and Carmona, respectively. The difference in the number of samples is due to the characteristics of each experimental design with a different number of blocks, plots, etc.

Every month, as in the case of soil sampling, CO_2 emissions were measured. The measurements were made at the same point at which the soil was extracted in order to be able to evaluate the possible relationship between emissions and SOC. The number of monthly readings coincides with the number of soil samples collected.

The gas flow was estimated by a portable infrared absolute and differential gas analyser (PP-Systems EGM-4). This consists of a battery and integrated data recorder, a soil temperature sensor and is coupled with a respiration camera. This suction or respiration camera is approximately 15 cm high with a diameter of 10 cm.

The apparatus is automatically calibrated using the surrounding air before each measurement as a reference and automatically transfers the data to the computer. It is capable of measuring CO_2 ranging between 0 and 9.99 g CO_2 m^{-2} h^{-1} with a precision of ±1 SD and a resolution of 1 ppm. The analyser is based on a closed system, which calculates the increases in the CO_2 concentration of the air found on the soil surface, for which it uses fits to quadratic equations.

The analyser also has a column with space for approximately 10 ml of a silica-derived substance, which absorbs the moisture in the air circulating in the system and transforms it into dry air to prevent interferences in the detection of CO_2.

2.4 Data

Version 8.0 of the Statistix program was used to compare the means between two factors (block and plots) and was carried out by the Tukey test with $p \leq 0.05$.

Likewise, a principal components analysis was performed (Davis 1993), together with an analysis of hierarchical conglomerates, for which the programs Statistix v.8.0 and SPSS version 11 were used. The last analysis was intended to explain the process of CO_2 emissions from the soil into the atmosphere, which depends on many different factors, such as temperature and soil moisture. An initial number of variables was taken and then some final variables were obtained that were a linear combination of the previous variables, albeit less in number. These different groups of variables made it possible to assess the fraction of variance explained by the components extracted. The number of components was determined following the criterion of selecting those recording values higher than 1.

3 Results

Soil organic carbon content (SOC) should be taken into account when addressing CO_2 emissions into the atmosphere.

The dynamics of this element in the soil, due to the action of microorganisms decomposing organic matter, added to suitable temperature and moisture conditions, can influence the flow of gas into the atmosphere (Jenkinson 1992). In order to assess the relationship between soil carbon content and the atmosphere, Fig. 1 represents the SOC concentration and the CO_2 emissions readings for the different sites and sampling dates.

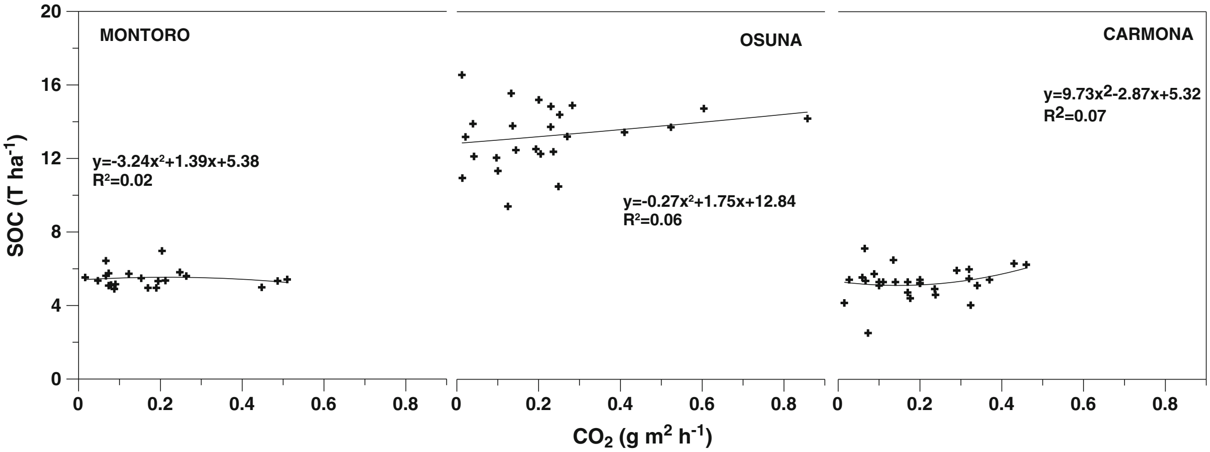


Fig. 1 Relationship between SOC and CO_2 over three seasons studied at different sites

As can be seen in Fig. 1, the evolution of SOC over time is not always correlated to CO_2 emissions into the atmosphere. In our study, other factors have a greater influence on gas flows. The results indicate that SOC content varied between 0.6–0.82, 1.49–2.63 and 0.4–1.13 and the CO_2 flow between 0.01–0.51, 0.0125–0.86 and 0.015–0.46 for the sites at Montoro, Osuna and Carmona, respectively.

These results coincide with findings of Álvaro-Fuentes et al. (2008) in a study that assessed changes in active carbon and CO_2 flows in soil for three harvesting seasons and at three different sites under semi-arid Mediterranean conditions. The results presented by those authors indicate the parameters evaluated have evolved differently and they attribute the marked differences in soil active C and CO_2 flows between the various seasons to the differences in rainfall.

Some studies have shown that rather than the content of OC in the soil, it is the environmental conditions that affect the flow of CO_2 into the atmosphere (Carbonell 2009), hence the interest in evaluating the relationship between environmental conditions and emissions into the atmosphere. Moisture and temperature are the most determinant variables (Etchevers et al. 2006) because they influence both the growth of vegetation and the activities of microorganisms, which are crucial factors in soil formation. Kononova (1975) arrives at the conclusion that decomposition of organic matter is most intense when the temperature is moderate (around 30 °C), and moisture levels are around 60 % to 80 % of the maximum water retention capacity of the soil.

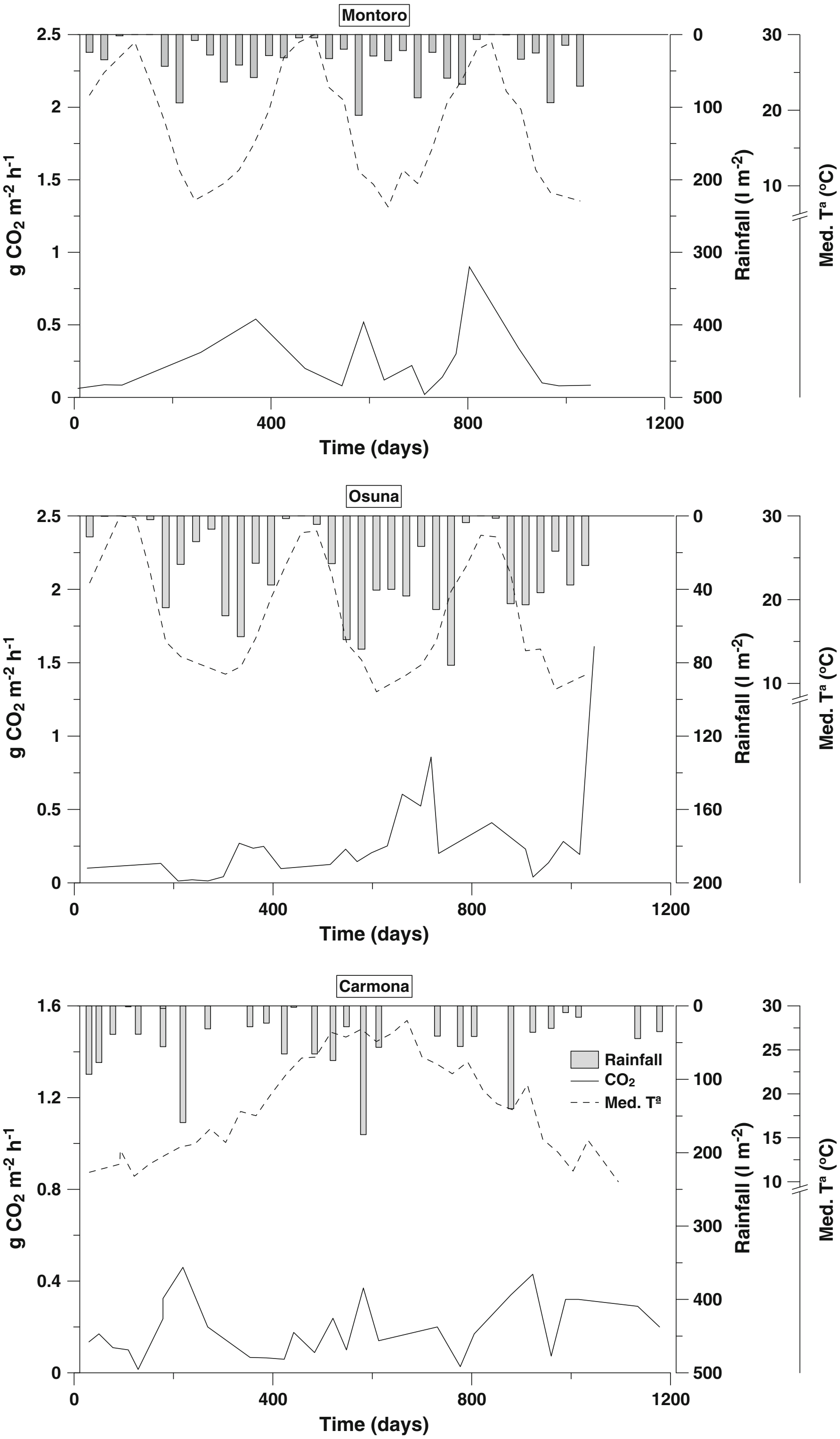
Figure 2 plots the rainfall and medium temperatures recorded in the study period and the evolution over time of CO_2 emissions for each of the fields in which the trials were carried out.

Some of the peaks observed in the figure are not only due to greater biological activity favoured by environmental conditions but also to operations carried out on the soil, which release the gas trapped in pores. This aspect has been verified by other authors such as Álvaro et al. (2004), Reicosky and Archer (2007) and Ordóñez et al. (2008), in studies evaluating the impact of agricultural tasks on CO_2 emissions into the atmosphere.

Regardless of the location, we observed how an increase or decrease in moisture beyond optimum levels had a clear effect on the evolution of organic matter, which determined increases or reductions in the amount of gas emitted. This can be seen in the figure, which shows how the months that recorded higher rainfall display the highest values, which in turn coincide with the measurements taken in spring and autumn, when in addition to the effect of rain, mild temperatures encourage the decomposition of organic residues in the soil. In general, it can be said that all the emissions accounted for were recorded in the spring period, when there was more moisture in the soil due to the rainfall during that period and, especially, the fact that temperatures were close to 20 °C. This favoured the activity of microorganisms, which degraded the organic remains protected by the soil (SoCo Project Team 2009).

Álvaro-Fuentes et al. (2007), in a study on the temporal evolution of CO_2 emissions in a Thermic

Fig. 2 Evolution of CO_2 emissions over time and rainfall and medium temperatures recorded throughout the study period



Xerollic Calciothird soil and a semi-arid climate, observed how seasonality and whether or not crops were grown had a clear influence on soil respiration.

Table 3 shows the mean emissions recorded in the different seasons of the year for the different locations and sampling years.

In the first year, the highest value was recorded in Montoro during the winter, with increases in gas emissions of 89 % and 81 % over that estimated in Osuna and Carmona, respectively. This was basically due to the large amount of rainfall in this period, which caused the decomposing activity of microorganisms. No significant data were obtained in Osuna and Carmona in that year.

In the second year, the highest values of soil respiration were observed in spring, regardless of the location considered. Montoro was again the farm that recorded the highest gas flow value, which exceeded that in Osuna and Carmona by 51 % and 33 %, respectively, in the spring period. The high rainfall rates recorded in Montoro and mild temperatures of nearly 20 °C probably provided ideal conditions for microorganism activity in the soil, resulting in an increase in respiration rates. Similar weather conditions were observed in Montoro and Osuna in the autumn, which favoured gas emissions and contrasted with the much lower values measured in this period in Carmona, as a consequence of temperatures of around 12 °C.

The seasonal behaviour of CO_2 emissions in the different locations for the third year repeated the pattern indicated previously. Consequently, the highest emission values were recorded in the spring period, and once again, Montoro displayed the highest values, albeit with no appreciable differences in comparison to that estimated in Osuna, and with an increase of 50 % over that measured in Carmona.

In order to assess the space–time variation in CO_2 readings, Fig. 3 shows the median, the first and third quartiles and maximum and minimum values of gas flows on the various sampling dates. As can be observed in Fig. 3, the majority of the data recorded display high spatial variability, the largest differences being observed in maximum values, regardless of the location considered.

Similarly, large variations are appreciated between sampling dates that cannot always be attributed to weather conditions. The results observed in Fig. 3 led us to believe that rain or high temperatures do not always determine the amount of the emissions, but that, in our case, interaction between factors could explain the behaviour of the emissions at some moments in time.

Interaction between factors has been taken into account in studies aimed at ascertaining the influence of temperature and moisture on soil microbial activity in processes such as the net mineralisation of nitrogen

Table 3 Emissions recorded throughout the different seasons at each of the sites studied

	Montoro			Osuna			Carmona		
	Mean CO_2 (g kg^{-1})	Accum. rain	Mean temp. (°C)	Mean CO_2 (g kg^{-1})	Accum. rain	Mean temp. (°C)	Mean CO_2 (g kg^{-1})	Accum. rain	Mean temp. (°C)
First year									
Spring	0.23	59.0	19.5	0.13	7.8	25.0	0.90	37.4	23.0
Summer	0.07	6.8	30.0	0.10	0.0	34.0	0.02	2.3	36.0
Autumn	0.18	61.3	18.0	0.08	49.4	18.7	0.14	209.2	15.6
Winter	0.27	148.6	4.5	0.03	132.4	13.8	0.05	92	10.7
Second year									
Spring	0.51	191.4	17.0	0.25	141.6	27.0	0.34	162.4	16.0
Summer	0.15	6.4	30.0	0.10	1.4	35.0	0.12	5.6	35.0
Autumn	0.28	182.4	20.15	0.17	156.6	24.5	0.06	90.6	12.4
Winter	0.1	156.2	8.7.0	0.15	136	12.0	0.16	139.8	8.9
Third year									
Spring	0.3	152.6	21.0	0.28	76.6	19.5	0.14	260.2	20.0
Summer	0.21	6.6	35.0	0.21	89.0	33.3	0.03	2.2	34.0
Autumn	0.07	59.2	10.0	0.22	145.8	20.4	0.21	138.2	13.2
Winter	0.16	179.2	10.0	0.13	26.20	19.0	0.26	176	12.0

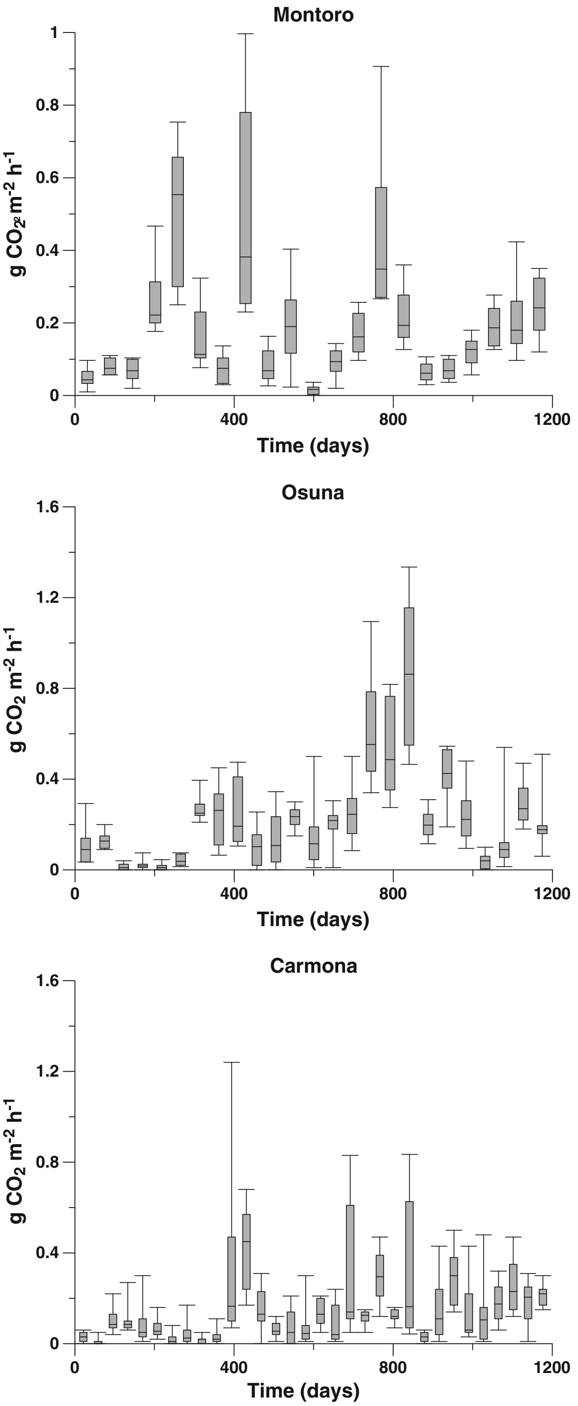


Fig. 3 Measurements of CO_2 flow throughout the study period at all locations

(Quemada and Cabrera 1997; Knoepp and Swank 2002), microbial respiration (Kowalenko et al. 1978) and nitrification (Grundmann et al. 1995).

Also, although temperature and moisture are factors that condition the activity of microorganisms that participate in the mineralisation of organic remains and thus the flow of CO_2 into the atmosphere, the proportion of soil texture with large or small grains determines whether or not the processes of emission or the retention of gas trapped in soil pore space are favoured.

Therefore, and in order to assess the influence of the different variables considered in this study on the whole set of emissions measured, a principal component analysis was performed (Davis 1993), for which a total of 2,400 CO_2 emission readings were taken into account.

The starting data taken for the study were CO_2 emission values, temperature at the time of the reading, rainfall and the content of sand, silt and clay in the soil the reading was taken from. This analysis obtained some components that were a linear combination of the parameters previously indicated and which enabled us to study their influence at all times. Each of these components had its own value, all of which are presented in Table 4, along with the correlations of all the variables intervening in the study.

As can be seen in the table, the behaviour of the different variables considered depends on only three components, such that different groups can be obtained, which share common characteristics in regard to their behaviour in terms of CO_2 emissions. The result of this study can be seen in Fig. 4, in which two different groups with the following characteristics can be distinguished.

It should be pointed out that emission data from all the measurement ranges, recorded at times of greater or lesser rainfall and all temperature ranges, were collected for both groups 1 and 2. However, the most important difference between one group and the other is that the first group includes the values obtained in Montoro, while the second group includes the values taken in Osuna and Carmona. The difference observed between the two groups could be explained by the textural composition of the different locations (Table 2) and, more specifically, by their content in clay, which is 9 % in Montoro and 44 % and 62 % in Osuna and Carmona, respectively.

When soils with a high proportion of clay receive abundant rain, they become swamped and block up, which makes the exchange of gases into the atmosphere difficult and limits emission production.

Table 4 Matrix of the characteristic values of the principal components and the correlation matrix

	Eigenvalues	Percent of variance	Cumulative percent of variance			
1	1,967.67	70.37	70.3			
2	752.439	26.99	97.1			
3	60.1892	0.19	99.3			
4	20.4829	0.7	100.0			
5	0.05924	0.0	100.0			
6	−3.525E-14	0.0	100.0			
	Clay	Sand	CO_2	Limo	T	Rainfall
Sand	−0.9657					
CO_2	0.1892	−0.1807				
Silt	0.8036	−0.9306	0.1474			
T	−0.1109	0.0165	0.0582	0.1186		
Rainfall	−0.1792	0.1908	0.2813	−0.1847	−0.1088	
PC1	0.2957	0.3107	0.2492	−0.2952	−0.1050	0.9923
PC2	0.9271	−0.9500	0.2726	0.8705	−0.0666	0.1236
PC3	−0.1281	−0.0200	0.089	0.2265	0.9659	0.0036

T temperature

This could explain the cases recorded in Table 3, where in spite of possessing favourable moisture and temperature conditions for microbial activity, no large CO_2 emissions are produced.

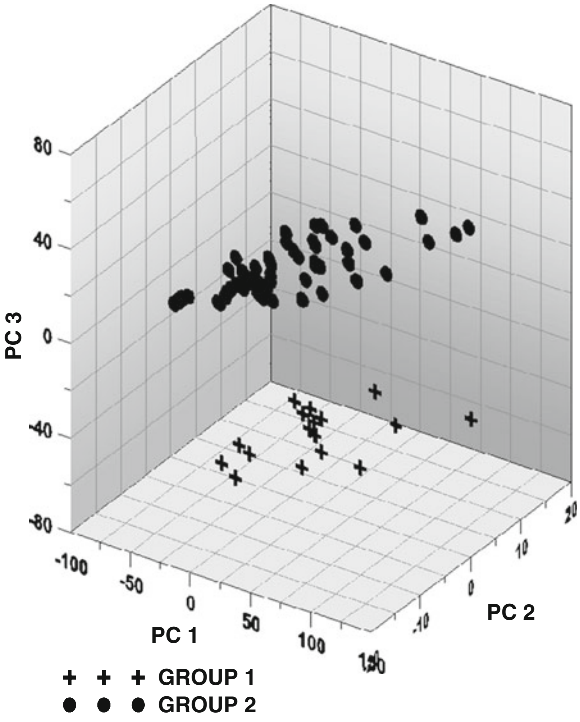


Fig. 4 Representation of the values of principal components

The sandiest soils, as in the case of Montoro, are characterized by having larger-sized pores, which retain air and where the CO_2 content in the soil is found. Conversely, the most clayey soils have smaller pores, which are responsible for the capture of water and have a smaller volume of micropores. This difference in the amount of micro- and macropores may also be the reason why the soil in Montoro retains more air and therefore produces greater specific emissions.

4 Conclusions

Considering the climatic conditions of southern Spain, the highest CO_2 emissions from soils are recorded in spring, the values during this season representing 41 %, 36 % and 57 % of total annual emissions for the locations of Montoro, Osuna and Carmona, respectively.

Although temperature and moisture exert an influence on the time variation of soil respiration, in our case, the textural composition of the soil was a determinant factor in terms of the differences in flows observed between locations. In fact, at times when rainfall was high, the soils with a high percentage of clay recorded similar CO_2 emissions to those estimated in the summer period, when the lack of rain and high temperatures limited emission production.

The temporal evolution of SOC concentration on the surface did not influence the flow of gas into the atmosphere.

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