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The Effect of Conservation Agriculture and Environmental Factors on CO_2 Emissions in a Rainfed Crop Rotation

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Abstract: There are many factors involved in the release of CO_2 emissions from the soil, such as the type of soil management, the soil organic matter, the soil temperature and moisture conditions, crop phenological stage, weather conditions, residue management, among others. This study aimed to analyse the influence of these factors and their interactions to determine the emissions by evaluating the environmental cost expressed as the kg of CO_2 emitted per kg of production in each of the crops and seasons studied. For this purpose, a field trial was conducted on a farm in Seville (Spain). The study compared Conservation Agriculture, including its three principles (no-tillage, permanent soil cover, and crop rotations), with conventional tillage. Carbon dioxide emissions measured across the four seasons of the experiment showed an increase strongly influenced by rainfall during the vegetative period, in both soil management systems. The results of this study confirm that extreme events of precipitation away from the normal means, result in episodes of high CO_2 emissions into the atmosphere. This is very important because one of the consequences for future scenarios of climate change is precisely the increase of extreme episodes of precipitation and periods extremely dry, depending on the area considered. The total of emission values of the different plots of the study show how the soils under the conventional system (tillage) have been emitting 67% more than soils under the conventional agriculture system during the 2010/11 campaign and 25% for the last campaign where the most appreciable differences are observed.

Keywords: soil management; climate change; mitigation; conventional tillage; conservation agriculture; GHG emissions

1. Introduction

In a world in which the concern for food security is increasing, there are important questions to be addressed about the impact of climate change on the production and availability of food [1–3]. According to the Food and Agriculture Organization (FAO), in 2050 there will be more than 9 billion people on the planet. Therefore, feeding the growing population, without exhausting natural resources will be a challenge, especially when even today about 795 million people are undernourished globally [4].

The agricultural sector is one of the most affected by climate change, as a result of the close relationship between agricultural activities and the climate. However, it is also a net source of greenhouse gases emissions (GHG), as evidenced by the fact that, at European level, agriculture currently ranks third in the GHG set of issuing activities (EEA Report 5/2018: Annual European Union greenhouse gas inventory 1990–2016 and inventory report 2018).

The different management systems in agriculture regulate soil nitrogen and carbon dynamics and affect the emissions of nitrous oxide (N_2O) and carbon dioxide (CO_2) [5,6].

For many developing countries, food security, economic development and the impact of climatic change are the main concerns related to agriculture. A significant proportion of these countries have expressed interest in mitigating GHG in the agriculture sector and two-thirds of them are developing strategic plans to mitigate GHG emissions from agriculture [7].

Both political and social concerns are currently focused on understanding and predicting the effects of the interaction between human activity, the carbon cycle and the expected climate change impact [8,9]. This coincides with growing scientific evidence that continued global warming is due (in part) to the rates of GHG emissions such as CO_2, methane (CH_4) and N_2O from the earth [10]. Land-use may have direct and indirect effects on carbon stocks in the soil and these may be associated with changes in the use of land conditioned to meet social needs such as the production of foods, energy and water supply and the management of crop residues.

Since the COP 21 celebrated in Paris at the end of 2015, agriculture has been assigned three roles in the context of climate change: on the one hand, it is an issuing activity (14% of the total GHG that could reach 25% if we include forest land) secondly, agriculture itself suffers from the consequences of global warming, as demonstrated by the IPCC reports for 2013; but it is also a mitigating activity, which is undoubtedly an opportunity to alleviate the negative consequences of climate change. Soil management systems account for 25% of total anthropogenic emissions [11].

Anthropogenic activities have affected 40% of the Earth's surface. Land-use conversion has depleted the terrestrial ecosystem carbon stock with a big loss of soil organic carbon and future climate change scenarios can affect this carbon stock by increasing the rate of decomposition of organic matter (OM) [12]. In the specific case of agriculture, the use of ploughs for tilling the soil in conventional farming provokes the mineralization of soil organic matter (SOM) while increasing the release of CO_2 into the atmosphere due to oxidation [13]. Likewise, the tillage operation can incorporate crop residues from the surface into deeper soil layers where microorganisms and moisture conditions favour their decomposition and, thus, carbon oxidation [14]. Furthermore, soil tillage physically disrupts aggregates and leaves the soil unprotected from the action of microorganisms which were encapsulated within the soil. Soil tillage practices are also conducted by farmers to alleviate soil compaction, but only temporarily [15]. These practices also promote the decomposition of OM and losses of carbon (C) to the atmosphere in the form of CO_2 [16–18].

According to FAO [19] and many other authors [20], Conservation Agriculture (CA) is an agricultural system based on three interlinked principles:

(i) Minimum mechanical soil disturbance (which is not minimum tillage, i.e., no tillage) through direct seeding and/or fertilizer placement.

    Minimum tillage is a tillage method that does not turn the soil over, while no tillage is a way of farming without disturbing the soil.

(ii) Permanent soil organic cover, (at least 30 percent) with crop residues and/or cover crops.

(iii) Species diversification through varied crop sequences and associations involving at least three different crops.

Whereas CA is an agricultural system, no-tillage (NT) is an agricultural technique needed for performing CA (Principle 1). The adoption of CA has significant environmental benefits [21]. The accumulation of soil organic carbon (SOC), i.e., due to the sequestration of carbon in the soil, is certainly one of the major benefits, making CA systems be considered as being effective in helping to mitigate the increase in atmospheric CO_2 concentration in annual, perennial and mixed cropping systems [22], whether rainfed or irrigated. At the same time, NT systems are acknowledged for being more profitable for farmers [23].

There are international initiatives, such as the United Nations Framework Convention on Climate Change (the 21st Conference of the Parties agreements reached in Paris), where growth of the "4 per 1000" initiative that aims to demonstrate that agriculture and agricultural soils, in particular, play a crucial role where food security and climate change are concerned. This initiative fosters implementing practical programs for carbon sequestration into the soil. Reviewing the available literature on climate change and agricultural soil management systems, it can be concluded that agricultural operations have different effects on CO_2 emissions depending on the activity, soil type, and climate conditions in the area. Different authors [24] suggested that crops managed under CA could capture between 0.1 and 1 tonne of carbon per hectare annually depending on the climate characteristics of the area; the lower figure applicable for dry areas and the higher for humid areas. In Spain, several studies corroborate the findings that different types of tillage practices strongly increase short-term CO_2 emissions [25–27]. These studies suggest that under different tillage and soil management practices, a range of interactions between the crop and soil quality clearly has an influence on CO_2 emissions, and that these relations are even more complex under the influence of climate change in the Mediterranean area [28,29]. The global climate variabilities are estimated to be responsible for 32% to 39% of yield variability [30].

The climate conditions in the study area are characterized by long and hot dry summers, high inter-annual and intra-annual variations in rainfall, which, in combination with the high temperatures during the summer period, greatly limit biomass production. However, depending on the management practices, soil quality and land productivity potential could be enhanced or reduced by affecting soil physical, hydrological, chemical and biological properties. Good agricultural practices can reduce soil erosion and degradation, decrease greenhouse gases emissions from the soil, and help maintain or even improve production under changing climate conditions in the Mediterranean basin.

The objectives of the study reported in this paper were (a) to quantify the short-term and long-term impacts of different management systems on CO_2 fluxes from the soil; and (b) to determine the influence of climatic conditions of the area and of crop phenology on soil CO_2 fluxes. The variability in the data obtained is presented from both a spatial and a temporal perspective.

2. Material and Methods

2.1. Experimental Sites

A field experiment was conducted to study the dynamics of CO_2 emissions from the soil as influenced by soil management and weather conditions.

For this purpose, a farm in the cereal-growing area of Andalusia (southern Spain) situated in the municipal area of Las Cabezas de San Juan (Seville): 36°56′37,8″ N 5°55′13,6″ W was selected to carry out the trial during four agricultural seasons 2009/10, 2010/11, 2011/12 and 2012/13. Figure 1 presents the location of the study area.

Once the farm was selected, a first sampling was carried out in order to characterize the soil where the trials were going to be conducted. Table 1 presents the soil properties of the study site.

Since 2003, the techniques of Conservation Agriculture were implemented in part of the farm, concretely in the NT. The trial plots under this technique were established in those areas and the plots where traditional management systems were used in areas where NT is not practised.

Traditionally the farmer would make a wheat/sunflower rotation and every 4 years a legume was included in that rotation. In our trial, and as can be seen in next point Section 2.2, the rotation was cereal (wheat), sunflower, legume. The dates of the carried out operations are also included in the next section.

The farm is located in the Mediterranean area with a Xeric moisture regime, according to the standards set [31]. The region is characterized by a typical Mediterranean climate pattern with a mild rainy autumn and winter season, which accounts for 80% of the annual rainfall, and warm to hot and dry springs and summers.

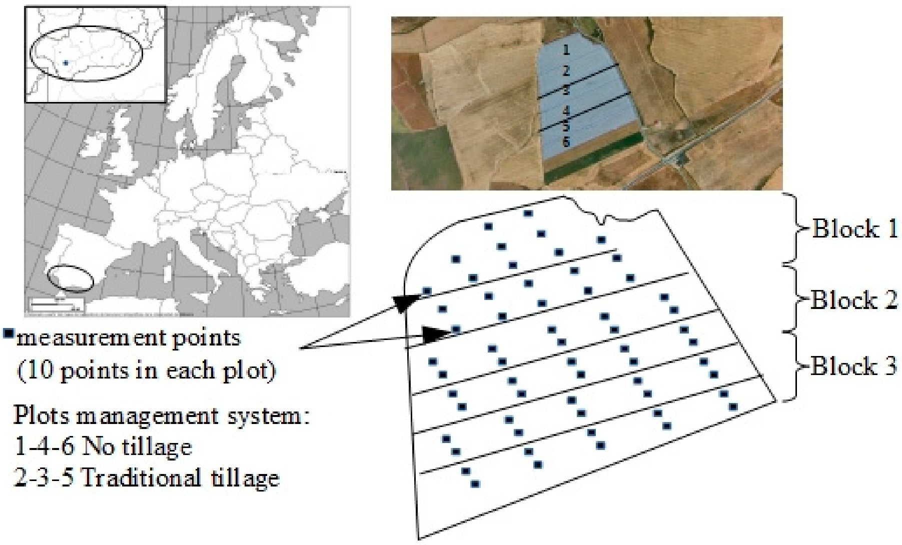

Figure 1. The location of the study area.

Table 1. The physical and chemical characteristics of several soil layers (0.2, 0.4 and 0.6 m) at the study sites.

System	Depth	Ntotal	OC	OM	$CO_3^=$	pH	CEC	K	P	Sand	Lime	Clay	Texture
	cm			*%*			*meq/100 gr*	*ppm*			*%*		
BLOCK 1													
NT	0–20	0.13	0.91	1.55	11.87	8.56	36.2	482.6 b	6.40 b	16.10	23.40	60.50	Clayey
	20–40	0.11	0.88	1.48	11.11	8.62	35.3	433.94 b	6.0 b	16.00	22.60	61.40	Clayey
	40–60	0.10	0.80	1.36	11.46	8.43	37.2	358.58 b	5.0 b	16.00	23.70	60.30	Clayey
T	0–20	0.10	0.98	1.66	13.45	8.32	39.3	674.04 a	13.05 a	16.90	30.80	52.30	Clayey
	20–40	0.10	1.00	1.70	13.17	8.46	42.4	625.16 a	11.21 a	19.20	32.70	48.10	Clayey
	40–60	0.10	0.99	1.69	13.30	8.68	43.3	689.36 a	13.10 a	14.90	32.90	52.20	Clayey
BLOCK 2													
NT	0–20	0.12	1.17	1.99	6.3 a	8.25	31.36 b	481.82	23.19 b	20.60	22.80	56.60	Clayey
	20–40	0.12	1.15	1.96	5.0a	8.33	29.53 b	407.64	17.03 b	20.40	22.40	57.20	Clayey
	40–60	0.11	0.99	1.69	7.1 a	8.36	30.23 b	344.58	30.36 a	20.90	23.90	55.20	Clayey
T	0–20	0.11	1.21	2.07	3.2 b	8.23	41.08 a	432.06	32.89 a	13.40	26.10	60.50	Clayey
	20–40	0.10	1.13	1.92	4.7 b	8.25	40.40 a	375.62	28.92 a	13.60	24.60	61.80	Clayey
	40–60	0.10	1.10	1.87	2.18 b	8.29	40.56 a	424.2	13.57 b	14.10	24.70	61.20	Clayey
BLOCK 3													
NT	0–20	0.13	1.12	1.90	24.52 a	8.57	27.20	802.87 a	12.23 b	17.60	27.60	54.80	Clayey
	20–40	0.10	0.97	1.65	24.53 a	8.63	25.90	682.60 a	10.77 b	19.90	34.30	45.80	Clayey
	40–60	0.10	0.89	1.51	23.32 a	8.69	23.57	459.88 b	10.17 b	23.10	34.50	42.40	Clayey
T	0–20	0.10	1.16	1.98	10.74 b	8.46	29.30	663.36 ab	16.66 a	16.10	23.40	60.50	Clayey
	20–40	0.10	1.09	1.86	11.26 b	8.53	30.50	547.38 b	11.66 b	16.00	22.60	61.40	Clayey
	40–60	0.10	1.00	1.70	9.36 b	8.49	34.27	531.00 b	22.34 a	16.00	23.70	60.30	Clayey

Table 2 shows the statistical analysis of the main climatic variables with data from the last ten years. The data have been obtained from a climatic station located in the same municipality.

Table 2. The descriptive statistics of the main climatic variables.

	Max. Temp.	Min. Temp	Med. Temp	Humidity (máx.)	Humidity (min.)	Radiation	Rainfall	ET_0
Number of values	3816	3816	3816	3816	3816	3816	3816	3816
Minimum	8.2	−7.9	2.5	53	0	0.9	0	0.34
Maximum	44.9	26.8	33.3	100	100	32.5	80.2	10.05
Mean	25.49	10.85	17.94	92.78	41.56	18.25	1.47	3.93
Median	24.9	11.6	17.9	95.4	38.9	18.2	0	3.72
Standard error	0.1218	0.0951	0.1022	0.1347	0.2936	0.1330	0.0856	0.03
Variance	56.62	34.55	39.87	69.21	329	67.49	27.99	4.83
Standard deviation	27.5	5.87	6.31	8.31	18.14	8.21	5.29	2.19

Data from the Climatic station situated in Las Cabezas de San Juán; UTM coord: X: 243351.0; Y: 4100490.0; Latitude: 37°00′56″ N; Longitude: 05°53′04″ W; Altitude: 13.0.

2.2. Soil Management Systems and Experimental Design

The experimental design is a randomized complete block (see Figure 1), in order to compare NT with conventional tillage (T), the experimental area consisted of three blocks with two plots inside of each one. In one plot of each block was CA, more specifically, NT with a soil mulch cover, was applied, whereas T with bare soil was the soil management system followed in the other plot of the different blocks. Each plot was approximately five hectares in size. Inside each plot, 10 point samples were taken initially in order to characterize the soil. As a result, it was possible to grow all three crops of the wheat-sunflower-legume rotation simultaneously every year (See Table 3). One reason why these crops have been chosen is due to the fact that the common agricultural policy framed within the European strategy called Horizon 2020 addresses economic, environmental and territorial challenges, including a mandatory "green" component in the aid (Regulation (EU) 1307/2013) and simplifying conditionality. The green component or "greening" which makes 30% of the basic payment (Royal Decree 1075/2014 and Royal Decree 1076/2014), includes measures that should provide environmental benefits, where crop diversification and the area of ecological interest are considered beneficial agricultural practices:

- Crops diversification: Whenever the cultivation land covers more than 30 hectares, there must be at least 3 different crops.
- Count on Ecological Focus Area (EFA) on the agricultural surface. Farms with more than 15 ha should allocate 7% of the arable land to EFA. The main EFAs chosen by the European countries are N-fixing crops such as grain and forage legumes.

Table 3. The crop rotation in each block of the study. NT: no-tillage; T: conventional tillage.

Block	Soil Management System	Area (ha)	Season 2009/2010	Season 2010/2011	Season 2011/2012	Season 2012/2013
1	T	5	Wheat *Triticum durum*	Sunflower *Helianthus annus*	Legume *Pisum sativum*	Wheat *Triticum durum*
	NT	5				
2	T	5	Sunflower *Helianthus annus*	Legume *Cicer arietinum*	Wheat *Triticum durum*	Sunflower *Helianthus annus*
	NT	5				
3	T	5	Legume *Cicer arietinum*	Wheat *Triticum durum*	Sunflower *Helianthus annus*	Legume *Pisum sativum*
	NT	5				

The sowings of the crops were carried out by the farmer who owns the farm. The doses of the used seeds are those used in the rest of the farm since our intention is to reproduce what happens in the field and not recreate situations that do not occur (Table 4).

In the case of NT, all crop residues were left on the soil surface. As soil cover is one of the principles of CA, an NT seeder equipped with cutting disks in the seeding line was used for sowing in NT plots, whereas a conventional tine seeder was used for sowing in the T plots. Both machines are well adapted to the study area and are the same as those used by local farmers. Table 5 shows the agricultural operations performed throughout the study in both soil management systems.

Table 4. The seed doses and working widths of the different crops in the study.

Crop	Seed Doses	Working Width (m)
Sunflower	75,000 plants/ha	3.9
Wheat	220 kg/ha	2.85
Legume (chickpea)	120 kg/ha	3.9
Legume (pea)	250 kg/ha	3.2

With the aim of obtaining representative data, each of the five-hectare experimental plots has ten points marked and all of them were geo-referenced. Knowing the precise location of each sampling point made it possible to evaluate the seasonal variability of the CO_2 emissions of the specific area.

In order to evaluate the production and quality of each crop and soil management system, data provided by a harvester equipped with a Ceres 8000 i RSD yield monitor were used.

Soil cover was measured in order to relate the production and soil moisture to the soil management. The percentage of soil cover was calculated following the sector evaluation method, which takes pictures using a frame of 1 m^2 divided into 100 0.01 m^2 squares. The frame was placed in the points marked out for soil samples and soil moisture. Along the study period, 1480 points were measured for soil cover by taking two pictures per point.

2.3. Emission Measurements

The emission measurements were made monthly over four seasons (2009/10, 2010/11, 2011/12, 2012/13), with an infrared portable EGM-4 absolute and differential gas analyser, coupled with a soil respiration chamber. The respiration chamber was approximately 15 cm high with a diameter of 10 cm and a CO_2 flow measurement capacity ranging between 0 and 9.99 g CO_2 m^{-2} h^{-1}. The measurement accuracy was ± 1 SD (standard deviation), with a resolution of 1 ppm. The measurement procedure consisted of placing the chamber over the soil surface for a period of 2.5 min. The measurements were taken automatically every 4 s during that 2.5 min period, the final value being the mean of the whole period. The technique principle is based on calculating the CO_2 concentration in the air present inside the chamber using fits to quadratic equations. The gas analyser is equipped with a column with space for approximately 10 mL of a silica-derived substance, which absorbs the moisture in the air circulating within the closed system, preventing interferences. The use of static or automatic chambers and gas analysers has been widely recommended by other authors [32–35].

We estimated the soil respiration as the flux emitted from the soil surface that represents the sum of the CO_2 produced by the heterotrophic decomposition of root exudates, plant litter, soil organic matter decomposition and root respiration. The influence of autotrophic soil microorganisms is small in most situations [36] as well as non-biological reactions (precipitation or dissolution of soil carbonates and biological reactions).

During the study period, CO_2 measurements were conducted simultaneously in both plots: NT and T. Two gas analysers were used at the same time in order to work with similar conditions, making the measurements comparable.

2.4. Temperature and Soil Moisture Measurements

At the same time that the gas emission measurements were performed, the soil temperature was recorded at a depth of 5 cm using a thermometer. Soil moisture measurements were taken using a Diviner 2000 capacitance probe (Sentek Pty Ltd.) that was inserted into tubes positioned in each CO_2 measurement point (ten points in each plot) at ± 1 m of distance. Those tubes, in permanent contact with the soil, were previously introduced into a hole made in the soil. The probe automatically records the soil moisture at 10 cm intervals and saves the data in internal memory, from which it could be downloaded later onto a computer using the appropriate software. The probe took measurements to an effective depth of 80 cm, although manual measurements could be taken directly by recording the reading on the built-in screen on the probe. Rainfall data were obtained from nearby agro-climatic stations.

Table 5. The field operations performed each season per crop and per soil management system. NT: no-tillage; T: conventional tillage.

SEASON 2009/10								
LEGUME			**SUNFLOWER**			**WHEAT**		
Date	**T**	**NT**	**Date**	**T**	**NT**	**Date**	**T**	**NT**
14/10/09		Herbicide Glyphosate (42%) Vol. 1.5 L/ha	14/09/09		Herbicide Glyphosate (42%) Vol. 1.5 L/ha	14/10/09		Herbicide Glyphosate (36%) Vol. 1.5 L/ha
29/10/09	Disk harrow		29/10/09	Disk harrow		30/10/09	Disk harrow	
07/11/09	Disk harrow		06/11/09	Chisel plough		05/11/09	Chisel plough	
20/11/09	Disk harrow		11/11/09	Disk harrow		10/11/09	Disk harrow	
22/03/10	Herbicide Glyphosate (42%) Vol. 4 L/ha Seeding		14/05/10	Herbicide Granstar (50%) Vol. 37.5 g/ha		04/12/09	Spring tine cultivator	
28/04/10	Fungicide Clortaronil Vol. 1 L/ha		15/03/10	Spring tine cultivator		04/12/09	Seeding	Seeding
13/05/10	Fungicide Clortaronil Vol. 1 L/ha		03/04/10	Seeding	Seeding	24/01/10	Fertilizer	Fertilizer
						16/03/10	Fertilizer	Fertilizer
						19/03/10	Herbicide Topik + sekator Vol. 250 cc y 300 g/ha	
						28/04/10	Fungicide Topik + Lovit Vol. 250 cc y 1 L/ha	
SEASON 2010/11								
LEGUME			**SUNFLOWER**			**WHEAT**		
Date	**T**	**NT**	**Date**	**T**	**NT**	**Date**	**T**	**NT**
19/01/11	Herbicide Pulsar Vol. 1 L/ha		27/09/10	Disk harrow		08/10/10	Disk harrow	
27/04/11	Fungicide Clortaronil Vol. 1 L/ha		07/10/10	Chisel plough		19/11/10	Fertilizer	Fertilizer
20/05/11	Fungicide Clortaronil Vol. 1 L/ha		14/03/11	Spring tine cultivator		20/11/10	Spring tine cultivator	
07/07/10	Disk harrow		21/03/11	Seeder	Seeder Herbicide Glyphosate (42%) + Oxifluorfen (24%) Vol. 1.5 + 0.15 L/ha	24/01/11	Spring tine cultivator Herbicide Glyphosate (36%) + U46combi Vol. 1.5 L/ha	

Table 5. *Cont.*

<table>
<tr><th colspan="9">SEASON 2010/11</th></tr>
<tr><th colspan="3">LEGUME</th><th colspan="3">SUNFLOWER</th><th colspan="3">WHEAT</th></tr>
<tr><th>Date</th><th>T</th><th>NT</th><th>Date</th><th>T</th><th>NT</th><th>Date</th><th>T</th><th>NT</th></tr>
<tr><td>20/11/10</td><td>Spring tine cultivator</td><td></td><td>31/03/11</td><td colspan="2">Herbicide
Glyphosate (36%) + Granstar (50%)
Vol. 1 L/ha + 40 g/ha</td><td>25/01/11</td><td>Seeder</td><td>Seeder</td></tr>
<tr><td>17/03/11</td><td>Spring tine cultivator</td><td></td><td>25/05/11</td><td colspan="2">Herbicide
Granstar (50%) + Ceres
Vol. 40 g/ha y 1 L/ha</td><td>24/02/11</td><td>Fertilizer</td><td></td></tr>
<tr><td>18/03/11</td><td>Seeder</td><td>Seeder</td><td></td><td></td><td></td><td>19/03/11</td><td colspan="2">Herbicide
U46combi + Sekator
Vol. 0.75 L/ha y 0.225 L/ha</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>19/04/11</td><td></td><td>Fertilizer</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>25/04/11</td><td colspan="2">Fungicide
Lovit
Vol. 1 L/ha</td></tr>
<tr><th colspan="9">SEASON 2011/12</th></tr>
<tr><th colspan="3">LEGUME</th><th colspan="3">SUNFLOWER</th><th colspan="3">WHEAT</th></tr>
<tr><th>Date</th><th>T</th><th>NT</th><th>Date</th><th>T</th><th>NT</th><th>Date</th><th>T</th><th>NT</th></tr>
<tr><td>24/09/11</td><td>Disk harrow</td><td></td><td>26/10/11</td><td>Chisel plough</td><td></td><td>12/08/11</td><td>Disk harrow</td><td></td></tr>
<tr><td></td><td></td><td></td><td>30/11/11</td><td></td><td>Herbicide
Glyphosate + U46ombi
Vol. 1.15 L/ha y 150 cc</td><td>17/11/11</td><td></td><td>Herbicide
Glyphosate + U46combi
Vol. 1.5 L/ha y 750 cc</td></tr>
<tr><td></td><td></td><td></td><td>14/01/12</td><td colspan="2">Herbicide
Glyphosate + Oxifluorfen
Vol. 1.5 L/ha y 300 cc</td><td>18/11/11</td><td>Spring tine cultivator
Seeder</td><td>Seeder</td></tr>
<tr><td></td><td></td><td></td><td>30/01/12</td><td>Disk harrow</td><td></td><td>13/01/12</td><td>Fertilizer</td><td>Fertilizer</td></tr>
<tr><td></td><td></td><td></td><td>09/02/12</td><td>Spring tine cultivator</td><td></td><td>26/01/12</td><td colspan="2">Herbicide
Sekator + Topik
Vol. 300 cc + 250 cc</td></tr>
<tr><td>22/12/11</td><td></td><td>Herbicide
Glyphosate
Vol. 3 L/ha</td><td>05/04/12</td><td>Seeder</td><td>Seeder</td><td>19/04/12</td><td>Fertilizer</td><td>Fertilizer</td></tr>
<tr><td>25/12/11</td><td>Spring tine cultivator
Fertilizer</td><td>Fertilizer</td><td>07/04/12</td><td colspan="2">Herbicide
Glyphosate + Oxifluorfen
Vol. 3 L/ha y 300 cc</td><td></td><td></td><td></td></tr>
</table>

Table 5. *Cont.*

SEASON 2011/12								
LEGUME			**SUNFLOWER**			**WHEAT**		
Date	**T**	**NT**	**Date**	**T**	**NT**	**Date**	**T**	**NT**
24/12/11	Seeder	Seeder	18/05/12	Herbicide Pulsar Vol. 1 L/ha				
15/02/12	Herbicide Pulsar Vol. 1 L/ha							
EASON 2012/13								
LEGUME			**SUNFLOWER**			**WHEAT**		
Date	**T**	**NT**	**Date**	**T**	**NT**	**Date**	**T**	**NT**
10/11/12	Disk harrow		04/10/12	Chisel plough		11/10/12	Disk harrow	
			04/12/12	Herbicide Glyphosate + Oxifluorfen Vol.2 L/ha + 150cc				
21/12/12	Herbicide Glyphosate + Pulsar Vol. 3 L/ha + 0.75 L/ha		04/02/13		Herbicide Glyphosate + Oxifluorfen Vol.2 L/ha + 150cc	15/11/12		Herbicide
24/12/12	Seeder	Seeder	27/02/13	Vibro-cultivator		21/11/12	Vibro-cultivator	
12/05/13	Herbicide Glyphosate + Oxifluorfen Vol. 2.5 L/ha + 250 cc		16/04/13	Herbicide Glyphosate + Oxifluorfen Vol. 3 L/ha + 250 cc		04/12/12	Seeder	Seeder
			22/04/13	Seeder	Seeder	16/01/13	Fertilizer	Fertilizer
						14/02/13	Herbicide Sekator + U46Combi Vol.1.8 L/ha + 750 cc	
						03/04/13	Fertilizer	Fertilizer
						10/04/13	Herbicide Traxos + Lovit Vol. 300 g + 1 L/ha	

NT: no-Tillage; T: conventional tillage; DH: Disk harrow; S: Seeding; CP: Chisel plough; C: Cultivator.

2.5. Data Analysis

The data obtained from the EGM-4 CO_2 emission analyser throughout the different campaigns of the study have been the object of different statistical analyses. First, an analysis of variance was carried out, which allows us to test the null hypothesis that the means of the two populations (T, NT) are equal.

The emission values of CO_2 are related and are affected by multiple variables, such as temperature, precipitation collected during measurement periods, soil moisture, etc. In order to be able to study the relationship that each of them has over the emitted gas, a Pearson correlation analysis was made. The null hypothesis $\rho = 0$, from which we start, states that the values of r must be compared with the probability tables for n-2 degrees of freedom. The calculation of the correlation coefficient requires that the population follow a normal distribution of two variables. Therefore, it has been previously studied whether the variables' object of the correlation analysis complies with this premise of linearity, which is our case. The result of this correlation analysis is found in Table 6, which is presented in the Section 3.

Table 6. The yield (kg ha^{-1}) and environmental cost (kg CO_2 /kg production) during the four seasons in each soil management system. NT: no-tillage; T: conventional tillage. Different letters indicate statistically different results at $p < 0.05\%$ $p^{*} < 0.01\%$, $p^{**} < 0.001\%$ Test Tuckey.

Season	**2009/10**		**2010/11**		**2011/12**		**2012/13**		**Average**	
	NT	**T**	**NT**	**T**	**NT**	**T**	**NT**	**T**	**NT**	**T**
					Yield (kgha^{-1})					
Wheat	2620a	2972a	4060a	2922b	870b	1378a	3040a	3144a	2648a	2604a
Legume	492b**	1282a**	558a	833a	860a	980a	420a	620a	583a	928a
Sunflower	1312a	1140a	907a	1265a	466a	394a	1190a	684b	969a	871a
					kg CO_2 /kg yield					
Wheat	4.4	40.2	1.6	36.0	13.9	82.0	4.8	35.4	6.2	48.4
Legume	15.7	92.2	2.6	63.3	6.4	51.6	19.3	80.3	11.0	71.8
Sunflower	10.7	54.2	12.6	88.4	26.4	341.1	6.6	170.6	14.1	163.6

As we have already mentioned, soil CO_2 emissions are related to the moisture present in the soil at the time of emission, while the moisture content is influenced by soil management. For this reason, a map of the distribution of gas emissions has been carried out. The distribution maps allowed us to represent the spatial variability of any variable measured in the experimental plots. CO_2 emission distribution maps were prepared using ordinary kriging for points, with intervals of 1 m in both directions to evaluate the spatial variability of the CO_2 emissions. As mentioned before, the sample points were georeferenced, therefore, their coordinates in the area are known. For the geostatistical analysis, the Surfer 10 program was used, while the data was analysed using the Statistix v.9 program.

3. Results

Figure 2 shows the evolution of CO_2 emissions for the two soil management systems studied in the different test periods and crops.

The annual rainfall ranged from 815 mm registered in 2009/10 to 268 mm in 2011/12. None of the agricultural years showed values close to the average annual rainfall which, in this area, and considering the 10-year average, is 552 mm. Not only did this rainfall variability affect CO_2 emissions during different crop phenological stages, but it also affected the field operations carried out.

Figure 3 depicts the accumulated daily rainfall, the total accumulate over all the different farming periods, and the average annual rainfall over the last 10 years and shows the water content in the soil over the different periods and soil management systems.

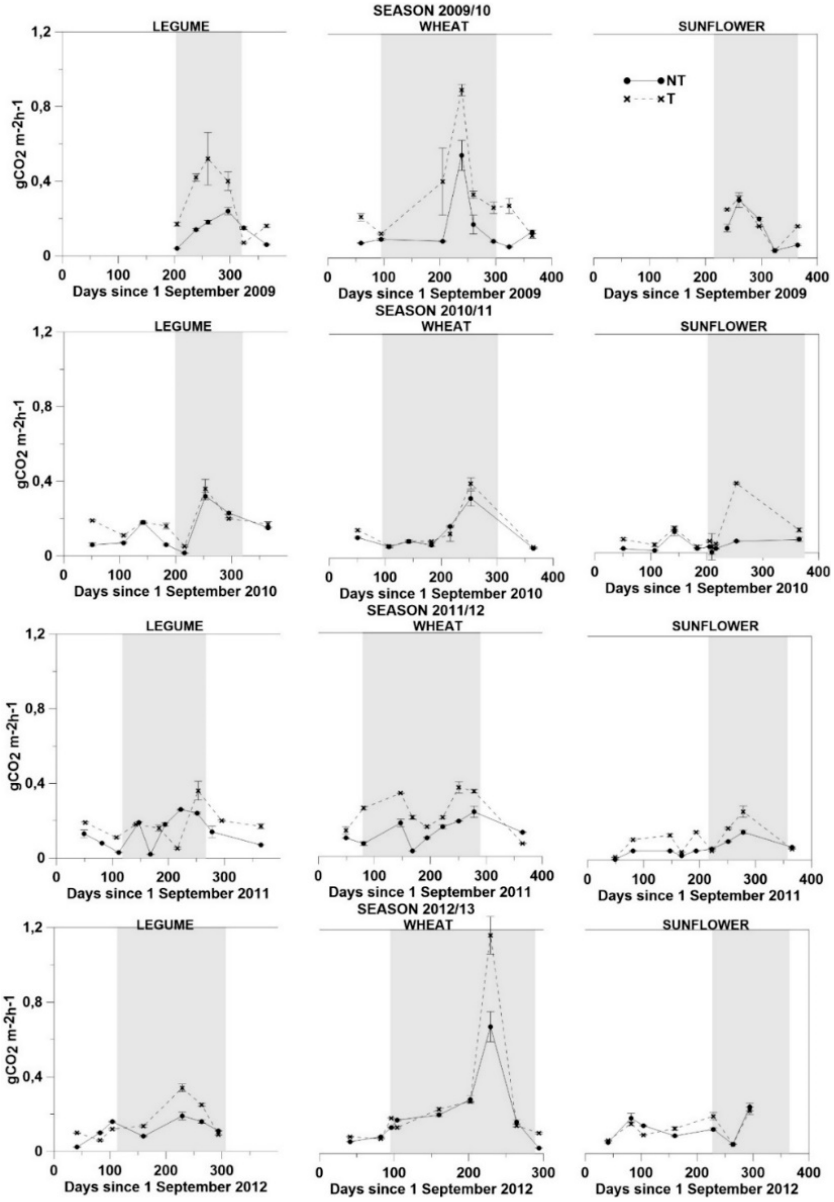

Figure 2. The evolution of CO_2 emissions for the two soil management systems studied in the different test periods and crops. Each line corresponds to a management system. Every point shows the average of 20 readings. The highlighted (grey) zones correspond to the time period during which the crop is on the field. The vertical lines denote the standard error of the data obtained in the field samplings.

In Figure 3, a series of maximum and minimum values can be seen, corresponding to times of recharge due to rainfall and drying of the soil profile. Worthy of highlight is the fact that NT soils always had a larger amount of water than T soils, and these differences have been larger during periods of low rainfall.

Soil moisture data shown in Figure 4 indicate the total value for the entire profile assessed by the probe (1 m).

With regards to the crops, if root respiration emits CO_2 when the plant is growing, then the yield would have a direct relationship with the amount of gas emitted. Thus, the yield collected in each soil management system (NT vs. T) may explain the differences found in the respiration processes presented in Figure 2. To assess this effect, Table 5 shows the yields obtained in the test farm for different crops during the four seasons studied. Additionally, Table 6 presents the CO_2 emitted per unit of production, which has been named the environmental cost.

As can be seen in Table 6, there are no significant differences in production among T and NT, except in the legume in the first season, wheat in the second season and sunflower in the third season. As an example and considering the case of the sunflower, the largest difference in the amount of CO_2 emitted between NT and T is shown in the third season and yet, in this period, the yield is similar without statistical differences.

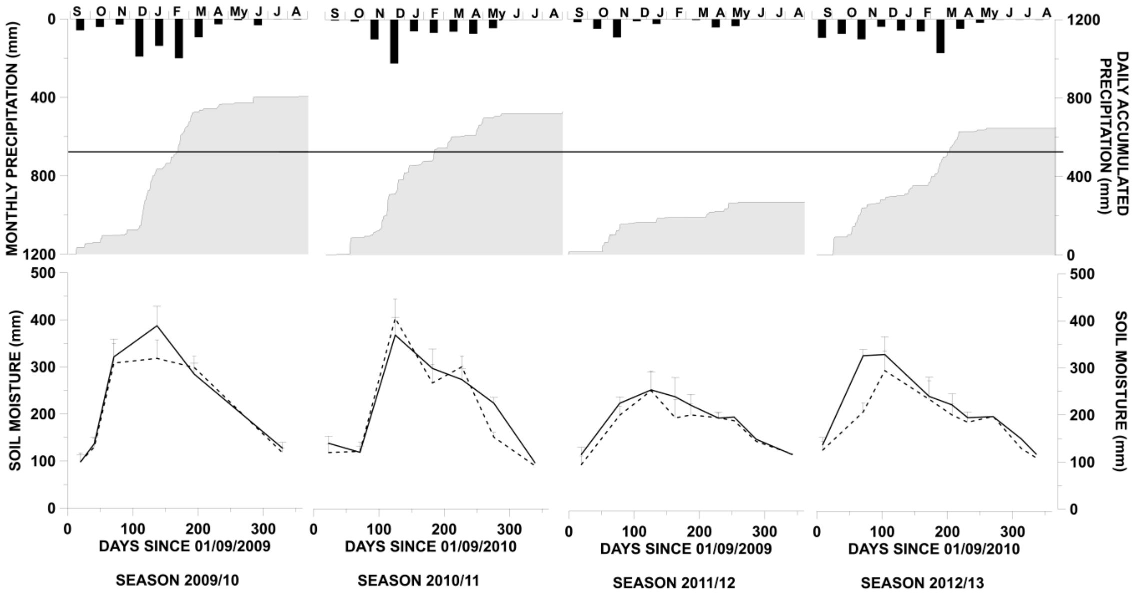

Figure 3. The accumulated daily rainfall, the total accumulate over all the different farming periods and the average annual rainfall over the last 10 years (horizontal line). Changes in soil moisture content during the test period for both soil management systems. NT = no-tillage; T = tillage.

Irrespective of the agricultural season and crop considered in the rotation, the production entails a higher environmental cost in T than in NT. Considering the average of the four agricultural seasons, for each kg produced in T, 42.2 kg more CO_2 is emitted in wheat, 60.8 kg more CO_2 in legume and 149.5 kg more CO_2 in sunflower, than those emitted in NT.

In this sense, CA fulfils the challenges of sustainability that are demanded by agriculture nowadays, which are used to improve yields and the efficiency in the use of inputs, whilst mitigating the environmental impact of conventional agriculture, better than tillage agriculture [37].

The emissions produced in the main phenological stages of the different crops analysed during the four seasons studied are shown in Table 7.

In most of the cases, there is a clear relationship between CO_2 emissions and the phenological stage of the crop. In the case of wheat and legumes, the highest percentage of emissions took place during the flowering period and this coincides across all four growing seasons. However, in the case of sunflower, no single stage can be specified as being that of maximum emission, a fact which can be explained due to the crop developing entirely during the summer months when high temperatures are recorded and the soil contains relatively little moisture, which results in the emissions not following a defined pattern as in the other cases.

To assess the influence of climatic and productive conditions in the area of study on the flux of CO_2 gas to the atmosphere, we analysed the Pearson correlation between these variables and the results are shown in Table 8.

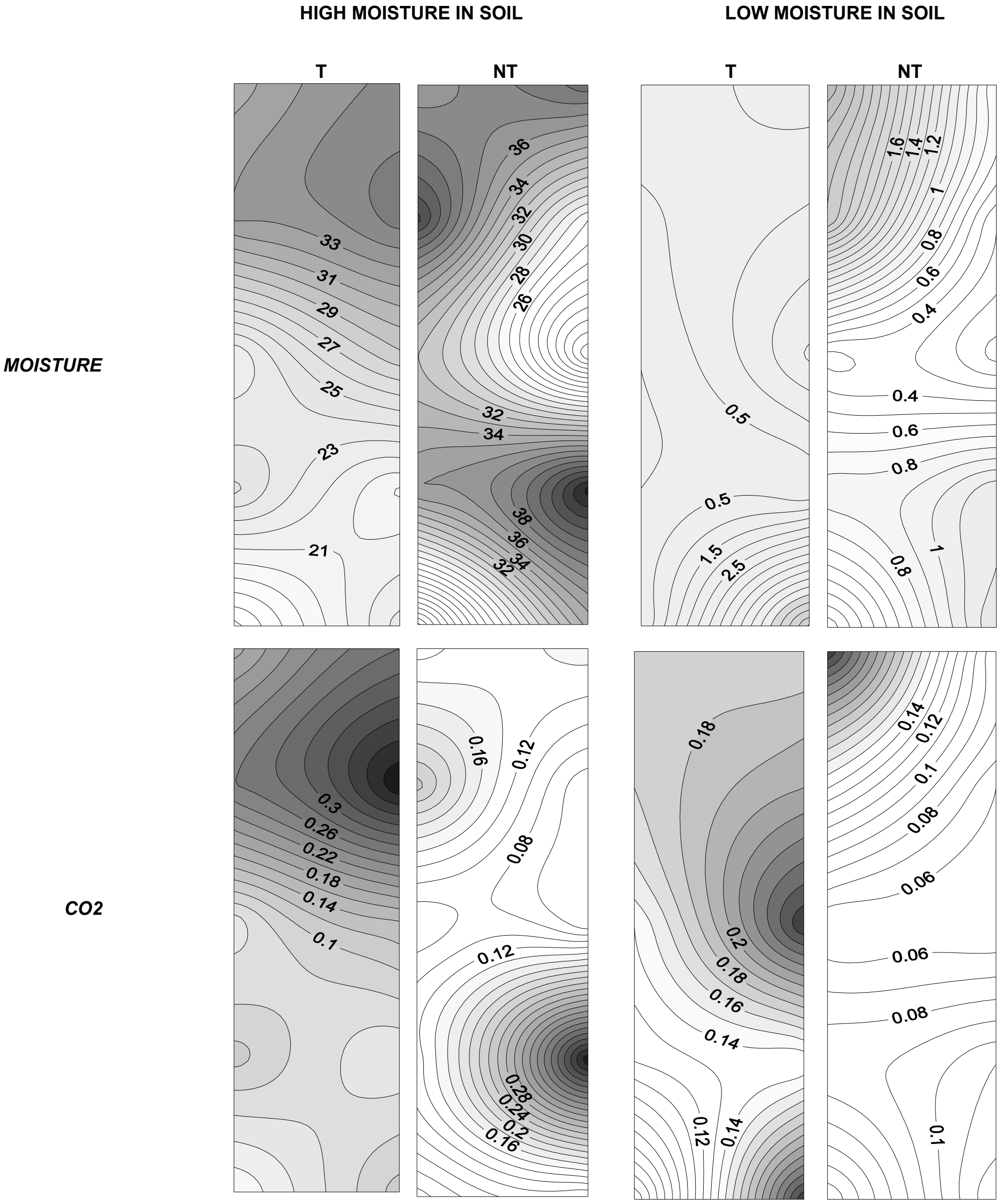

Figure 4. The spatial distribution of soil moisture and CO_2 emissions into the atmosphere.

As can be seen in the correlation matrix, CO_2 emissions are highly correlated with precipitation (approximately 58.6%) and with the presence or absence of crops at the time of measurement of the emissions (41.5%). It also shows a correlation with temperature, but with a lower percentage. The correlation matrix also shows that soil moisture is one of the variables with the highest correlation with the measured emissions. In order to assess this relationship, spatial distribution maps that reflect the data of both parameters were drawn.

In Figure 4, the result of the spatial distribution is given, specifically for the first season in the wheat plot, when one of the largest CO_2 emissions was recorded. This case is referred to as "high moisture in soil". On the other hand, for the third season, when the lowest amount of annual precipitation and one of the lowest volumes of emissions was recorded at a time of very low moisture in the soil during the cultivation of wheat, is referred to as "low moisture in soil".

It can be observed for the two moisture conditions studied, at the time the measurements of gas flows were carried out, that the areas of the plots which registered greater water content coincided with the areas where a higher value of emissions was registered, which corresponds to the darker areas of the maps. There is evidence that the soil moisture content at the time when the measurements of CO_2 emissions were made was decisive in the volume of CO_2 emitted.

Table 7. The breakdown in the percentage (%) of CO_2 emissions in each of the main phenological stages of the crop rotation for the seasons 2009/10, 2010/11, 2011/12 and 2012/13.

	2009/10	**2010/11**	**2011/12**	**2012/13**
PhenologicalStage		**Wheat**		
Stage 0	13	31	18	21
Stages 1 to 4	18	24	18	24
Stage 5 and 6	54	39	24	43
Stage 7 to 9	15	6	22	15
		Legume		
Stage 0	8	31	22	17
Stages 1 to 4	51	40	41	30
Stage 5 and 6	28	15	16	30
Stage 7 to 9	13	14	21	23
		Sunflower		
Stage 0	23	34	37	51
Stages 1 to 4	36	18	26	17
Stage 5 and 6	21	34	26	5
Stage 7 to 8	20	14	11	27

Note: the different phenological states based on the BBCH-scale (Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie [38], are the following.

*Stage 0: Germination
*Stage 1: Leaf development
*Stage 2: Tillering
*Stage 3: Stem elongation
*Stage 4: Booting
*Stage 5: Inflorescence emergence
*Stage 6: Flowering
*Stage 7: Development of fruit
*Stage 8: Ripening

Table 8. The correlation matrix.

	CO_2	**CROP**	**MAX. T**	**MED. T**	**MIN. T**	**RAINFALL**
CROP	0.4149					
p-value	0.0000					
MAX. T	0.2476	0.1556				
	0.0007	0.0339				
MED. T	0.2043	0.1077	0.9562			
	0.0052	0.1435	0.0000			
MIN. T	0.1135	0.0264	0.7477	0.9021		
	0.1228	0.7202	0.0000	0.0000		
RAINFALL	0.5859	0.0128	−0.4622	−0.3504	−0.1189	
	0.0002	0.8619	0.0000	0.0000	0.1061	
SOIL MOISTURE	0.6987	0.3435	−0.2123	−0.1321	−0.1118	0.7879
	0.0005	0.1359	0.0001	0.0002	0.0001	0.0000
SOC	−0.2890	0.4243	0.1211	0.2204	0.0891	0.4124
	0.0000	0.0033	0.0012	0.0121	0.0009	0.0011

4. Discussion

CO_2 emissions are closely related to soil moisture and temperature throughout the several growing seasons of the study period.

There are several studies that show the relationship between environmental conditions and the flux of CO_2 into the atmosphere [39,40]. Soil moisture and temperature are the most influential factors [41,42] since both affect crop growth and microorganism activity, which are crucial factors in soil formation.

Figure 2 shows that the CO_2 emissions were higher during the first season (2009/10) when the highest rainfall events were recorded. SOM and CO_2 emissions are influenced by weather conditions. In that season (2009/10), the higher rainfall and soil moisture boosted the gases emissions.

In the season of 2010/2011, differences in the amount of gas emitted between NT and T were obtained and the latter system showed a larger CO_2 flux. Considering all emissions measurements, T produced 67% more CO_2 than the NT system. The different increment percentages of emissions for the several seasons are due to weather conditions that affect the soil respiration regardless of the soil management system. As is shown in Figure 3, precipitation was dramatically different in the third season; it was the factor that varied more widely. Productions were also affected by the scarce precipitation in the third season (Table 5), which was also reflected in the environmental cost. In any case, the T system had a substantially greater environmental cost than NT (Table 5).

There are studies that give more relevance to the soil temperature, showing a strong relationship with the daily CO_2 emissions [43] whereas others show a high correlation between soil moisture content and CO_2 emissions [44]. The decomposition of OM and, with it, soil respiration is more intense when the temperature is moderate (about 25 °C) and soil moisture is in the range between 60% to 80% of the maximum retention capacity [3,40,45]. Indeed, moisture is a key factor in the activity of soil biota that breaks down OM, the process by which CO_2 is emitted into the atmosphere.

Regarding the results of the correlation matrix [46], in a study on the evolution of CO_2 over time from Thermic Xerollic Calciothird soil and with a semi-arid climate, the authors also observed how climatic variables and the presence or absence of crops in development had a clear influence on soil respiration. These authors suggest that a precipitation event of 22 mm induced increments of about 0.10–0.15 g CO_2 m^{-2} h^{-1} in the three soil management systems studied; NT, T and minimum tillage.

In Mediterranean areas, soil respiration during summers, characterized by being very dry, is limited by scarce soil moisture, while in the remainder of the growing season, respiration is more controlled by temperature [47]. This affirmation is consistent with our results in which the lowest gas emission values occurred in summer. Conversely, in very wet soil, aeration is restricted because a large proportion of pore space is filled with water and CO_2 flux to the atmosphere decreases [48]. Related to that, some authors [39] found more specific emissions from soil with larger-sized pores since it lets a greater flux of air that oxidised the organic matter.

A high correlation was obtained in almost all cases between CO_2 emission and soil moisture content (Table 7). Comparing the data obtained for the different variables studied, it must be highlighted how CO_2 values presented a higher correlation with moisture than with temperature [49]. It suggests that these small changes in soil water content and temperature allow interpreting differences in CO_2 fluxes between tillage treatments. Conservationist practices such as NT also have influence in the water storage capacity, improving the biopores and soil structure.

Furthermore, in most of the sampling dates, the values of CO_2 fluxes were higher in T soils than in NT soils, especially in those areas where mechanical cultivation activity was carried out on the soil. Under NT, the minimum soil disturbance produces changes in soil conditions that benefit the physical soil properties and reduce the rate of decomposition of SOM and, with it, the flux of CO_2 into the atmosphere [50].

5. Conclusions

Conservation Agriculture fulfils the challenges of sustainability that are demanded to nowadays agriculture better than tillage-based agriculture. In productivity terms, Conservation Agriculture has improved yields in the crop rotation studied, whilst mitigating the environmental impact of agriculture.

Carbon dioxide emissions from agricultural soils comprise complex processes. Among them, soil tillage has a great influence on CO_2 emissions, as the deeper the soil is ploughed, the more emissions it releases. In this article, Conservation Agriculture where mechanical soil tillage is avoided is presented as a feasible alternative to mitigate climate change in Mediterranean areas. In our case, in all crops studied, conventional tillage increased the CO_2 emissions compared to Conservation Agriculture. Conservation Agriculture not only reduces CO_2 net emissions, but also reduces the emissions related to yield. Additionally, the presence or absence of crops also significantly influences the emission of CO_2, which is increased when a crop is set. In our study in most of the cases, there is a clear relationship between CO_2 emissions and the phenological stage of the crop.

Carbon dioxide emissions are closely related to the soil moisture and temperature of the area. In the Mediterranean region, annual rainfall variability is a major characteristic of the agricultural environment. This variability has a strong influence on the changes in soil moisture content and in soil microbial activity. Consequently, the CO_2 emitted into the atmosphere and the CO_2 stored within soil pores vary between cropping seasons. In this regard, carbon dioxide emissions have been found to be positively correlated to the moisture content of the soil. It must be highlighted that the results were obtained in a specific period and area.

To contextualise for a bigger scale, reference values are necessary to take into account the spatial and temporal variability of the agro-ecosystems [23]. Even if the deliverables of Conservation Agriculture are promising, in terms of adoption, the Mediterranean region lags behind other regions in the world. Proper policies supporting the shift from conventional tillage to a more sustainable system are considered essential.

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Abbreviations

GHG	(greenhouse gases)
CO_2	(carbon dioxide)
N_2O	(nitrous oxide)
CH4	(methane)
SOM	(soil organic matter)
OM	(organic matter)
C	(carbon)
CA	(Conservation Agriculture)
NT	(no-Till)
SOC	(soil organic carbon)
T	(conventional tillage/tillage)

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