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Journal of
Water & Climate Change

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Journal of Water and Climate Change Vol 00 No 0, 1 doi: 10.2166/wcc.2022.190

Deficit irrigation with wastewater in direct sowed silage maize reduces CO_2 emissions from soil by providing carbon savings

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ABSTRACT

Direct sowing and deficit irrigation practices can reduce the effect of wastewater on CO_2 emissions from soil by providing carbon savings. Therefore, the effect of domestic recycled wastewater uses at different levels in irrigation under conventional tillage and direct sowing practices on the CO_2 emission from soil at the end of the vegetation period of silage maize was investigated by comparing it with full irrigation of fresh water. Both organic carbon and CO_2 emissions in the second year in fully irrigated treatments were higher than those in the first year. The CO_2 emission in the full irrigation with wastewater (0.263 g m^{-2} h^{-1}), compared to full irrigation with fresh water and 33 and 67% deficit irrigations with wastewater, was higher at 23.4, 25.0, and 59.3%, respectively. Direct sowing practice also (0.193 g m^{-2} h^{-1}) resulted in 17.0% less CO_2 emission as compared to conventional tillage. The positive linear relationships of H_2O emission and the soil moisture content at different depths (5, 10, and 20 cm) with CO_2 emission were significant, and the negative relationships with the soil temperatures were also found. It has been concluded that deficit irrigation and direct sowing applications can be practical for reducing CO_2 emissions from soil in wastewater irrigation conditions.

Key words: CO_2 emissions, conventional tillage, direct sowing, silage maize, wastewater

HIGHLIGHTS

- Wastewater irrigation increases soil organic carbon content and thus CO_2 emission.
- Direct sowing and deficit irrigation are the practices for declining CO_2 emissions.
- Soil moisture content positively affects CO_2 emission in irrigated conditions.

INTRODUCTION

Agriculture is the sector that fresh water resources are consumed the most compared to other sectors (FAO 2020). For this reason, it is very important to use marginal water resources instead of fresh water in agriculture for the sustainability of fresh water resources. Wastewater, one of the marginal water resources (Cakmakci & Sahin 2021), can be defined as water that has been polluted as a result of various uses, and the properties have changed partially or completely. Wastewater increases soil and crop productivity with irrigation in terms of its rich nutrient content. In addition, the wastewater, which reduces the need for fertilizers, contributes to environmental sustainability through disposal also.

While the nutritive properties of wastewater are considered as positive advantages, the high organic matter contribution of wastewater to the soil may increase CO_2 emissions from soil (Rosso & Stenstrom 2008). It is estimated that about 10% of the amount of CO_2 in the atmosphere is released from the soil (Raich & Potter 1995). Although CH_4 and N_2O cause global warming 21 times and 310 times more than CO_2, respectively (Forster *et al.* 2007), the 82% share of CO_2 among greenhouse gases makes it the most important greenhouse gas. It is very worrying that the amount of CO_2, around 280 ppm in the atmosphere in the 1700 s, reached 406 ppm in 2017 (WMO 2019). It is thought that if the amount of CO_2 continues to increase at this rate, it would reach 450 ppm in 2050, and as a result, agricultural, social, and economic life would be adversely affected (Aksay *et al.* 2005).

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The agricultural sector causes 25% of global warming (Tubiello *et al.* 2015; Vurarak & Bilgili 2015). Many factors such as soil temperature, soil water content, and O_2 level have an effect on CO_2 emission from soil. Soil tillage has a significant share in increasing agricultural greenhouse gases (Abdalla *et al.* 2016). Soil tillage provides a suitable environment for microbial activities and increases the speed of these activities by increasing the oxygen level of the soil and by ensuring that the surface residues come into closer contact with the soil particles (Vurarak & Bilgili 2015). However, direct sowing or minimum tillage contributes to both reducing emissions and increasing soil and crop productivity by providing moisture and carbon sequestration in the soil (Kocyigit 2008). In addition, considering the possibility of increased CO_2 emissions with soil moisture, CO_2 emissions can be reduced with an easy and practical approach in deficit irrigation (Hou *et al.* 2020).

It has been determined that not any findings from previous studies about the effect of deficit wastewater irrigation in direct sowed silage maize on the CO_2 emissions during the harvesting period were reported. In this context, the effect of using domestic treated wastewater at different levels (100, 67, and 33%) in the irrigation of silage maize under conventional tillage and direct sowing on the CO_2 emission from soil at the end of the vegetation period was investigated. In addition, the relationship of CO_2 emission with H_2O emission, soil moisture, and soil temperature at this period was evaluated. Therefore, the hypothesis of this study was that (1) direct sowing would be decreased CO_2 emission from soil by providing carbon savings, (2) deficit irrigation might increase the benefit to reduce CO_2 emission, and (3) CO_2 emission would show a strong correlation with H_2O emission, soil moisture content, and soil temperature.

MATERIAL AND METHODS

This study was conducted at the Experimental Field of the Faculty of Agriculture, Van Yuzuncu Yil University for 2 years. The experimental area is a semi-arid region and located at an altitude of 1,670 m near Lake Van (38° 34′35″ N and 43° 17′26″ E). The total precipitation amount measured in the experimental area in the vegetation period of silage maize in 2020 and 2021 was 37.0 and 52.1 mm, respectively. The mean air temperature during the vegetation period was 22.4 °C in 2020 and 22.8 °C in 2021.

Each plot was planned with five rows, 70 cm×15 cm row spacing, and with a measuring 3.5 m×7.2 m. The experiment was carried out according to the split plots design. The main plot factor of the experiment was conventional tillage and direct sowing, and sub-plot factors include full irrigations with fresh water and wastewater (FW100 and WW100), and 33% (WW67) and 67% (WW33) deficit irrigations with wastewater, in three replications. Therefore, 24 plots were arranged in the experimental field.

The seeds of silage maize (cv 'OSSK 644') in trial years were sown in May and harvested in September. The conventional tillage plots were plowed, then the clods were broken down by using a cultivator-rotary harrow combination and the plots were leveled. The seeds were sowed with a precision sowing machine on the same day after soil tillage. In the direct sowing treatment, the seeds were sowed with a direct sowing machine on the same day as conventional tillage. The hoeing in conventional tillage plots in both years was done for two times as crop heights reach 15–20 and 40–50 cm.

Irrigation applications were carried out with a surface drip irrigation system placed one lateral to each crop row at 70 cm intervals. Laterals with in-line drippers with a flow rate of 2.3 l h^{-1} and 33 cm spacing were used. The fresh water used in the study was obtained from tap water in the university campus. Recycled wastewater was collected from the Van city Edremit Domestic Wastewater Treatment Plant and transported before each irrigation and brought to the experimental area. The average values of soil reaction (pH), electrical conductivity (EC), biological oxygen demand (BOD), chemical oxygen demand (COD), and total N of the domestic wastewater throughout the irrigation periods in trial years were 7.58, 1.124 dS m^{-1}, 23.2 mg l^{-1}, 37.5 mg l^{-1}, and 10.9 mg l^{-1}, respectively. The pH and EC values for fresh water were 8.15 and 0.353 dS m^{-1}.

In all plots, the crops were irrigated with fresh water equally with a 30% wetting percentage considering 30 cm soil depth until they get 40–50 cm height. After this stage, irrigation with wastewater at different water deficit levels was started and continued until the harvest with a 65% wetting percentage considering 90 cm soil depth. A total of 13 and 12 irrigations were made in the first and second years of the experiment, respectively. The plots fully irrigated reached the seasonal irrigation quantities of 351.3 mm in the first year and 327.3 mm in the second year in the conventional tillage practice. In the direct sowing practice, the irrigation quantities of 318.7 and 294.1 mm were applied in the first and second trial years.

The soil texture in the experimental area was sandy clay loam. While the soil organic carbon contents in the 0–30 cm soil layer at the harvest were determined at 1.0, 1.15, 1.05, and 0.88% in the FW100, WW100, WW67, and WW33 treatments in the first year, respectively, and the second year values were 1.04, 1.24, 1.07, and 0.91%. The carbon contents in the first year

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were found at 1.0% in direct sowing and 1.03% in conventional tillage practice, and 1.06 and 1.07% in the second year. Organic matter determined with the Walkley-Black method was converted to organic carbon using the standard coefficient (Nelson & Sommers 1982; Setyanto *et al.* 2004; Avramidis *et al.* 2015).

The CO_2 emissions from the soil in all plots were measured at the time of silage maize harvest in September. The measurements were made by an infrared gas analyzer device (EGM-5, PPSystems, Stotfold, UK) from three different points randomly selected from each plot with three replicates between two crops, approximately 15–20 cm far from the dripper. In addition, soil temperatures and moisture contents at 5, 10, and 20 cm soil depths and the H_2O emissions were measured simultaneously with CO_2 emission measurement. The measurement of H_2O emission was provided automatically by the device, and a temperature probe connected to the CO_2 measurement device was used in soil temperature measurements. Soil moisture contents were determined using the TDR probe (Trime-Pico, IPH/T3, IMKO) calibrated to the experimental field.

The data were evaluated by variance analysis (ANOVA) using SPSS software (v23.0). Correlograms with a scatterplot, correlation coefficient, and variable distribution were built using the RStudio package to determine the relationships of CO_2 emission with H_2O emission and soil moisture and temperatures.

RESULTS AND DISCUSSION

The results indicated that the effects of irrigation and soil tillage-sowing practices on CO_2 emission were significant (Figure 1 and Table 1). In both years, full irrigation with wastewater and conventional tillage had the highest CO_2 emission (Figure 1). While the CO_2 emissions in the second year were found higher than the first year values in all irrigation treatments in conventional tillage practice, the CO_2 emissions higher than the first year were determined under fully irrigated conditions in the direct sowing practice. It could be said that the high organic carbon contents in the second year can appear in this finding. However, deficit irrigation treatments in direct sowing conditions probably resulted in less CO_2 emissions in the second year due to a change in the organic matter dynamics by affecting soil biology (Li *et al.* 2010). On a 2-year average, the CO_2 emission in the WW100 treatment (0.263 g m^{-2} h^{-1}) was found 23.4, 25.0, and 59.3% higher, respectively, compared to FW100, WW67, and WW33 treatments. Direct sowing (0.193 g m^{-2} h^{-1}) practice resulted in 17.0% less CO_2 emissions than the conventional tillage.

The higher CO_2 emission in the WW100 treatment and the decrease in emission values under deficit irrigation can be explained by the rich nutrient content of the wastewater and by the less entering of nutrients from the wastewater to the soil under decreased irrigation conditions. In particular, the high amount of organic carbon with wastewater earned to the soil can be considered as the main cause of CO_2 emissions. The content of organic carbon in the WW100 treatment was 16.5, 13.2, and 34.8% higher than the FW100, WW67, and WW33 treatments, respectively. The organic carbon accumulated in the soil encounters O_2, and it turns into CO_2 form and leaves the soil, and spreads to the atmosphere (Yerli *et al.* 2019). Similarly, Rosso & Stenstrom (2008) and Kudal & Muftuoglu (2014) reported that irrigation with wastewater increases the amount

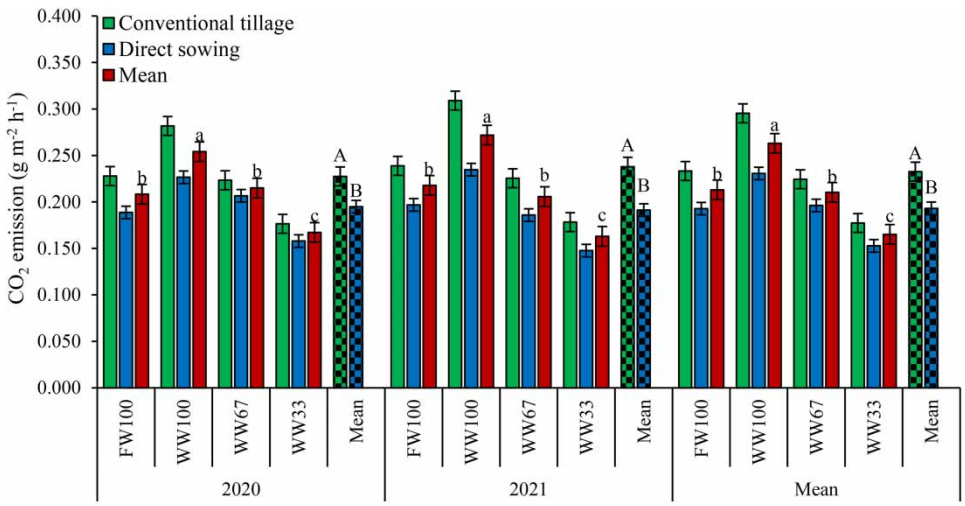

Figure 1 | CO_2 emissions in 2020, 2021, and the mean of two years. FW100, full irrigation with fresh water; WW100, full irrigation with wastewater; WW67, wastewater irrigation with 33% water deficit; WW33: wastewater irrigation with 67% water deficit. Different lowercase or uppercase letters in each trial year indicate a difference at the level of 0.05.

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Table 1 | The variance analysis results for CO_2 and H_2O emissions, and soil moisture and temperature values in trial years

2020

		CO_2		H_2O		Moisture (5 cm)		Moisture (10 cm)	
Source	**df**	**Mean square**	***P***	**Mean square**	***P***	**Mean square**	***P***	**Mean square**	***P***
Tillage (T)	1	0.006	0.021	1.870	0.141	0.403	0.496	0.271	0.209
Irrigation (I)	3	0.008	0.002	13.249	0.000	3.126	0.032	0.099	0.609
T×I	3	0.001	0.674	1.374	0.194	0.106	0.942	0.074	0.708
Error	16	0.001		0.779		0.829		0.158	
		Moisture (20 cm)		**Temperature (5 cm)**		**Temperature (10 cm)**		**Temperature (20 cm)**	
Source	**df**	**Mean square**	***P***	**Mean square**	***P***	**Mean square**	***P***	**Mean square**	***P***
Tillage (T)	1	0.810	0.214	3.682	0.172	2.802	0.147	0.510	0.596
Irrigation (I)	3	2.657	0.009	3.921	0.131	3.712	0.057	6.478	0.033
T×I	3	0.044	0.964	0.194	0.954	0.536	0.724	1.097	0.606
Error	16	0.484		1.804		1.203		1.741	

2021

		CO_2		H_2O		Moisture (5 cm)		Moisture (10 cm)	
Source	**df**	**Mean square**	***P***	**Mean square**	***P***	**Mean square**	***P***	**Mean square**	***P***
Tillage (T)	1	0.013	0.000	0.020	0.908	1.777	0.155	0.311	0.242
Irrigation (I)	3	0.012	0.000	17.779	0.000	19.726	0.000	24.909	0.000
T×I	3	0.001	0.390	0.235	0.923	0.033	0.988	0.006	0.993
Error	16	0.001		1.482		0.797		0.211	
		Moisture (20 cm)		**Temperature (5 cm)**		**Temperature (10 cm)**		**Temperature (20 cm)**	
Source	**df**	**Mean square**	***P***	**Mean square**	***P***	**Mean square**	***P***	**Mean square**	***P***
Tillage (T)	1	0.670	0.353	8.760	0.003	3.227	0.024	0.920	0.344
Irrigation (I)	3	29.392	0.000	6.714	0.001	9.741	0.000	12.668	0.000
T×I	3	0.239	0.806	0.889	0.311	1.408	0.080	0.918	0.440
Error	16	0.731		0.688		0.519		0.966	

2020–2021

		CO_2		H_2O		Moisture (5 cm)		Moisture (10 cm)	
Source	**df**	**Mean square**	***P***	**Mean square**	***P***	**Mean square**	***P***	**Mean square**	***P***
Tillage (T)	1	0.009	0.000	0.540	0.371	0.976	0.188	0.288	0.099
Irrigation (I)	3	0.010	0.000	15.141	0.000	9.453	0.000	6.831	0.000
T×I	3	0.000	0.131	0.154	0.865	0.037	0.974	0.013	0.933
Error	16	0.000		0.637		0.516		0.094	
		Moisture (20 cm)		**Temperature (5 cm)**		**Temperature (10 cm)**		**Temperature (20 cm)**	
Source	**df**	**Mean square**	***P***	**Mean square**	***P***	**Mean square**	***P***	**Mean square**	***P***
Tillage (T)	1	0.746	0.250	6.202	0.007	3.010	0.019	0.770	0.264
Irrigation (I)	3	12.370	0.000	5.241	0.002	6.358	0.000	9.274	0.000
T×I	3	0.118	0.877	0.287	0.727	0.280	0.607	0.850	0.258
Error	16	0.522		0.652		0.446		0.575	

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of organic carbon in the soil. Shakeel *et al.* (2021) determined that the highest CO_2 emission in maize cultivation was obtained from the raw wastewater plots and the lowest CO_2 emission was obtained from the plots irrigated with fresh water. Nosalewicz *et al.* (2013) stated that CO_2 emissions from the soil increased in wastewater irrigation conditions and this increase was related to the high organic matter contribution provided to the soils depending on the nutrient content of the wastewater.

The increased CO_2 emissions in conventional tillage can be explained with intensive soil tillage increasing the O_2 entry into the soil, thereby accelerating the oxidation of organic carbon. Therefore, in the direct sowing practice, organic carbon content was 2.0% higher than in conventional tillage, showing that the increasing carbon stock in the soil reduced CO_2 emissions. It is also thought that less emission under direct sowing practice is related to the direct sowing of the seed and thus to the more superficial intervention in the soil. Vurarak & Bilgili (2015) reported that soil tillage creates a suitable environment for microbial activities both by increasing the O_2 level of the soil and by enabling the surface residues to come into closer contact with the soil particles. Altikat *et al.* (2012) expressed that organic carbon decomposition increased with increased soil tillage due to physically breaking up the soil and providing better aeration. Akbolat *et al.* (2016) determined that the CO_2 emissions in direct sowing conditions were 30.6% lower than the conventional tillage, and pointed out that CO_2 emission from the soil in direct sowing is less due to less O_2 entry into the soil.

It was thought that insignificant effects of tillage-sowing practices on soil moisture content resulted in similar H_2O emissions. However, the irrigation practices had a significant effect on soil moisture contents and thus H_2O emissions (Figure 2, and Tables 1 and 2).

In the average trial years, while the WW100 and FW100 treatments provided similar H_2O emissions and soil moisture contents, H_2O emissions in the WW100 treatment (12.6 g m^{-2} h^{-1}) compared to the WW67 and WW33 treatments were found 16.7 and 34.0% higher, respectively (Figure 2). The soil moisture at 5, 10, and 20 cm soil depths in WW100 (0.237–0.260 m^3 m^{-3}) also were 5.3–8.2% and 13.4–14.0% higher compared to WW67 and WW33 treatments, respectively (Table 2). It was concluded that the proportion of reduction in H_2O emission with the water deficit was greater than the proportion of reduction in soil moisture content, and this indicated that high soil moisture contents contributed more to H_2O emission. The increased H_2O emissions in high irrigation conditions due to increased soil moisture content were also determined in previous studies. Akbolat & Senyigit (2012) reported that H_2O emissions decreased due to the decrease in the occupancy rate of the pores with increasing deficit irrigation levels. Senyigit & Akbolat (2010) also, in their study examining the effects of varying amounts of irrigation water on H_2O emissions, stated that the lowest H_2O emissions were obtained from the lowest amount of irrigation quantity.

The correlations of CO_2 emissions with H_2O emissions and soil moisture contents measured at 5, 10, and 20 cm soil depths were significantly positive linear in both conventional tillage and direct sowing practices (Figures 3 and 4). Similarly, Buragiene *et al.* (2019) reported that CO_2 emissions from the soil showed a positive linear change in the soil moisture content. It

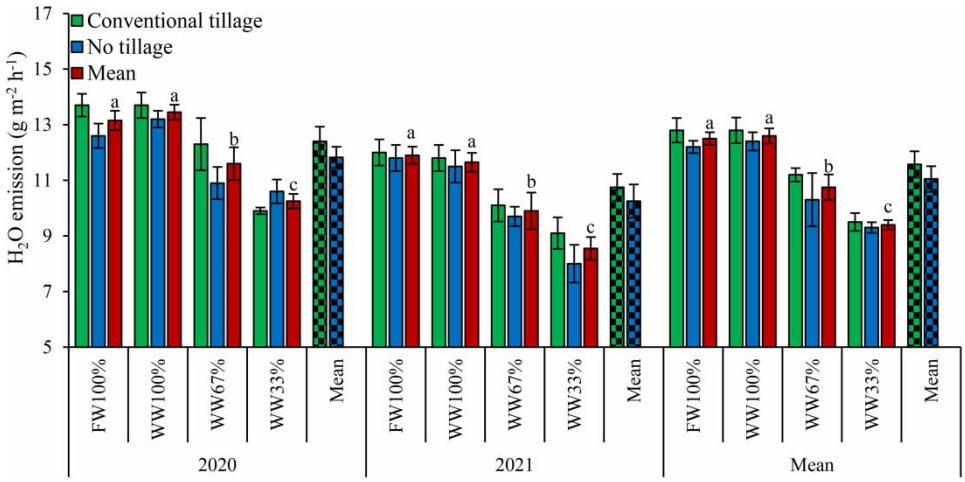

Figure 2 | H_2O emissions in 2020, 2021, and the mean of two years. FW100, full irrigation with fresh water; WW100, full irrigation with wastewater; WW67, wastewater irrigation with 33% water deficit; WW33, wastewater irrigation with 67% water deficit. Different lowercase letters in each trial year indicate a difference at the level of 0.05.

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Table 2 | Soil moisture contents and soil temperatures measured at 5, 10, and 20 cm soil depths in trial years

		2020			2021			2020–2021		
Treatments		**CT**	**DS**	**Mean**	**CT**	**DS**	**Mean**	**CT**	**DS**	**Mean**
Soil moisture content at 5 cm ($m^3\ m^{-3}$)	FW100	0.224	0.228	0.226 AB	0.233	0.239	0.236 A	0.228	0.233	0.231 A
	WW100	0.230	0.235	0.232 A	0.239	0.245	0.242 A	0.234	0.240	0.237 A
	WW67	0.219	0.220	0.219 B	0.217	0.221	0.219 B	0.218	0.220	0.219 B
	WW33	0.216	0.216	0.216 B	0.198	0.205	0.202 C	0.207	0.211	0.209 C
	Mean	0.222	0.225		0.222	0.227		0.222	0.226	
Soil moisture content at 10 cm ($m^3\ m^{-3}$)	FW100	0.233	0.237	0.235	0.242	0.244	0.243 B	0.238	0.240	0.239 B
	WW100	0.237	0.236	0.237	0.247	0.250	0.249 A	0.242	0.243	0.243 A
	WW67	0.233	0.235	0.234	0.232	0.234	0.233 C	0.232	0.234	0.233 C
	WW33	0.232	0.236	0.234	0.202	0.204	0.203 D	0.217	0.220	0.219 D
	Mean	0.234	0.236		0.231	0.233		0.232	0.234	
Soil moisture content at 20 cm ($m^3\ m^{-3}$)	FW100	0.251	0.256	0.254 A	0.258	0.265	0.262 A	0.255	0.261	0.258 A
	WW100	0.253	0.256	0.255 A	0.263	0.266	0.265 A	0.258	0.261	0.260 A
	WW67	0.245	0.250	0.247 AB	0.245	0.250	0.247 B	0.245	0.250	0.247 B
	WW33	0.239	0.241	0.240 B	0.217	0.215	0.216 C	0.228	0.228	0.228 C
	Mean	0.247	0.251		0.246	0.249		0.246	0.250	
Soil temperature at 5 cm (°C)	FW100	22.1	21.1	21.6	23.9	21.7	22.8 C	23.0	21.4	22.2 B
	WW100	22.1	20.9	21.5	23.0	22.6	22.8 C	22.6	21.8	22.2 B
	WW67	22.5	21.9	22.2	24.7	23.3	24.0 B	23.6	22.6	23.1 B
	WW33	23.4	23.0	23.2	24.4	24.6	24.5 A	23.9	23.8	23.9 A
	Mean	22.5	21.7		24.0 A	23.1 B		23.3 A	22.4 B	
Soil temperature at 10 cm (°C)	FW100	21.0	20.7	20.9	23.6	21.4	22.5 C	22.3	21.1	21.7 C
	WW100	21.7	20.4	21.1	22.3	22.4	22.3 C	22.0	21.4	21.7 C
	WW67	22.2	21.1	21.7	23.7	23.3	23.5 B	23.0	22.2	22.6 B
	WW33	22.6	22.6	22.6	24.7	25.0	24.8 A	23.6	23.8	23.7 A
	Mean	21.9	21.2		23.6 A	23.0 B		22.7 A	22.1 B	
Soil temperature at 20 cm (°C)	FW100	20.9	19.8	20.4 B	22.8	21.3	22.0 C	21.9	20.6	21.2 C
	WW100	20.6	20.5	20.5 B	21.8	22.1	22.0 C	21.2	21.3	21.3 C
	WW67	21.5	22.4	22.0 AB	23.6	23.6	23.6 B	22.6	23.0	22.8 B
	WW33	22.8	22.1	22.5 A	24.2	24.0	24.1 A	23.5	23.0	23.3 A
	Mean	21.5	21.2		23.1	22.7		22.3	22.0	

CT, conventional tillage; DS, direct sowing; FW100, full irrigation with fresh water; WW100, full irrigation with wastewater; WW67, wastewater irrigation with 33% water deficit; WW33, wastewater irrigation with 67% water deficit.
Different uppercase letters indicate a difference at the level of 0.05.

was thought that increased microbial activity with increased soil moisture causes decomposition of organic matter and thus increases CO_2 emission. Similarly, Jabro *et al.* (2008) reported that CO_2 emission increases with the increased moisture in the soil due to increased organic matter oxidation. Soil moisture balance and processes greatly influence the amount of organic carbon oxidation in the soil (Shi & Marschner 2014). Especially in arid and semi-arid regions, re-wetting the dried soil can increase emissions by triggering microbial activities (Lamparter *et al.* 2009). Entry *et al.* (2008) determined that the continuous supply of water to the soil provides more organic carbon to the soil from crop roots and crop residues, and thus, the emission increases. Mancinelli *et al.* (2015), in their study in which they examined the CO_2 emissions in 100, 75, and 50% irrigation water levels, stated that the CO_2 emission from the soil decreased with the decrease in the amount of irrigation.

In the average trial years, while soil temperatures at 5 and 10 cm soil depths changed significantly by the tillage-sowing practices, the significant effects of irrigation treatments were determined in all measuring depths (Table 2). Soil temperatures at 5 and 10 cm soil depths in direct sowing practice (22.1–22.4 °C) were 3.9 and 2.6% less than the conventional tillage. Soil temperatures in all depths were similar in FW100 and WW100 treatments. The soil temperatures at 5, 10, and 20 cm soil depths under WW100 treatment (21.3–22.2 °C) were 3.9–6.6%, 7.1–8.6%, and 6.6–8.6% lower than the values in WW67 (22.6–23.1 °C) and WW33 (23.3–23.9 °C) treatments, respectively. The higher soil temperature in deficit irrigation can be explained by the lower moisture content in the soil considering significant negative correlations between soil moisture and temperatures (Figures 2 and 3). High moisture content in the soil can reduce the soil temperature by creating a cooling effect in the soil with increased evaporation (Mancinelli *et al.* 2015). The soil temperature in direct sowing is lower than in conventional tillage

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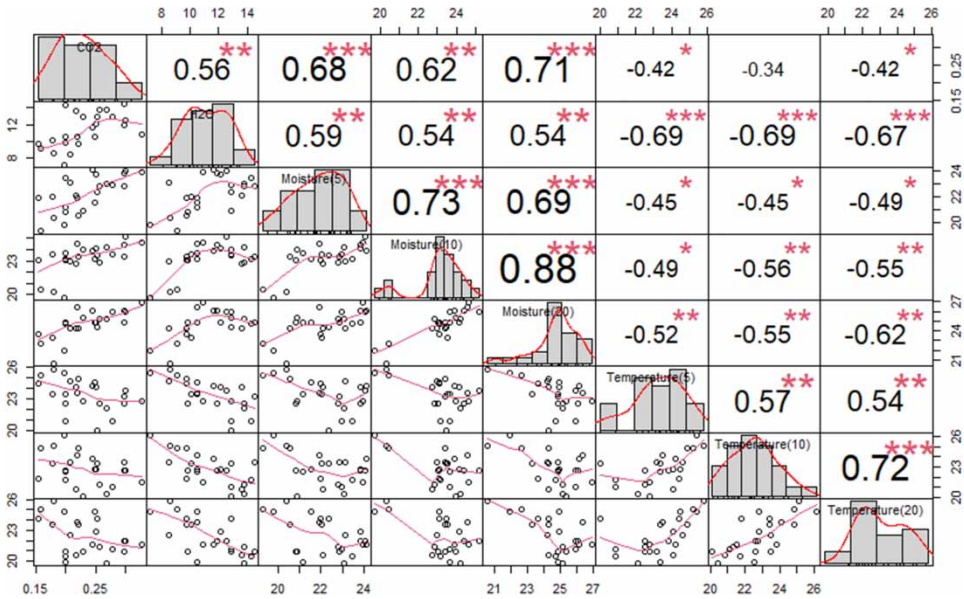

Figure 3 | Correlation matrix in conventional tillage. ***, **, and *: Significant at the level of 0.001, 0.01, and 0.05, respectively.

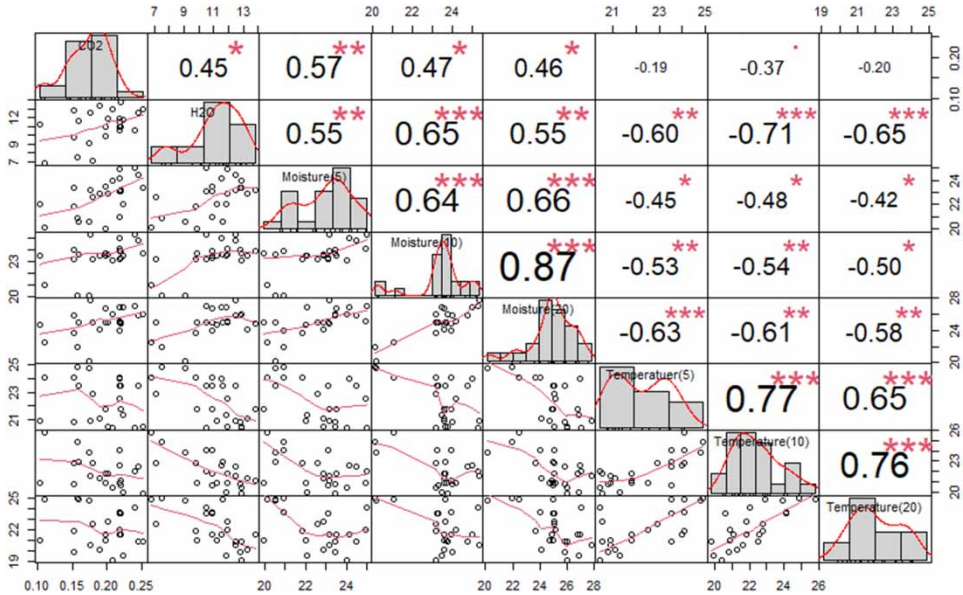

Figure 4 | Correlation matrix in direct sowing. ***, **, and *: Significant at the level of 0.001, 0.01, and 0.05, respectively.

can be evaluated in relation to the fact that using the shading effect of the residues on the soil surface in direct sowing reduces the soil temperature. Shen *et al.* (2018) stated that the soil temperature was lower between 0 and 1.5 °C due to the covering effect of residues on the soil surface in direct sowing compared to intensive tillage treatments. In addition, tillage practices significantly can influence the thermal conductivity of the soil by changing soil properties such as the bulk density and aggregation (Van Wie *et al.* 2013). Similarly, Salem *et al.* (2015) reported that the soil temperature was lower under direct sowing conditions.

It has been determined that the negative linear relationships of CO_2 emission with soil temperature values at two soil depths (5 and 20 cm) were significant ($p<0.05$) in the conventional tillage practice (Figure 2). Similarly, Buragiene *et al.* (2019) reported a negative correlation between soil temperature and CO_2 emissions from soil. However, in direct sowing practice, the correlations were not significant (Figure 3). In conditions where the effect of soil temperature on CO_2 emission is evaluated independently of moisture, increases in CO_2 emissions can be observed with the positive effect on soil biological activity of the increase in soil temperature. Therefore, many previous studies reported that soil temperature is positively

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correlated with CO_2 emission (Sainju *et al.* 2008; Rey *et al.* 2011; Nosalewicz *et al.* 2013; Chen *et al.* 2018; Du *et al.* 2019; Zhao *et al.* 2020). In this study, although soil temperatures increased with water deficit (Table 1), soil moisture contents also were reduced significantly. Therefore, it was concluded that soil moisture had dominant effect on CO_2 emission compared to the soil temperature. It is indicated that a general result, the moisture balance of the soil and the processes of keeping it moist greatly affect the oxidation of organic carbon in the soil (Morugan-Coronado *et al.* 2011; Shi & Marschner 2014). Considering mentioned approaches above, it also could be said that lowering soil temperatures in the direct sowing practice, compared to the conventional tillage, made the effect of temperature insignificant on CO_2 release with better soil moisture conditions.

CONCLUSIONS

The harvesting time findings in silage maize cultivated conditions revealed that full irrigation with wastewater increased CO_2 emissions, and while the CO_2 emission, H_2O emissions, and soil moisture contents in deficit irrigation conditions with wastewater were lower, soil temperatures were higher. In addition, direct sowing practice significantly contributed to the reduction of CO_2 emissions when compared to conventional tillage by providing carbon savings. It was found that direct sowing practice resulted in lowering soil temperatures than the conventional tillage. While the significant positive linear relationships were determined between CO_2 emissions with H_2O emissions and the soil moisture contents measured in different soil depths (5, 10, and 20 cm), soil temperatures negatively correlated to the CO_2 emissions.

Climate change threatens populations and countries through damages to ecosystems, increases in hazardous weather events, declines in productivity, and causes greater costs to maintain current infrastructure. As a conclusion of this study, since full irrigation with wastewater and conventional tillage significantly increase CO_2 emissions from soil, it was clearly seen that deficit irrigations with wastewater in direct sowing practice reduce CO_2 emissions from soil at a considerable level. However, there is a need to increase the practicality of short-term findings with the results of long-term wastewater applications that will provide more organic carbon recovery in different geographic locations.

FUNDING

This study was financially supported by the Scientific and Technological Research Council of Turkey (TUBITAK Project No: 119O528).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICTS OF INTEREST

The authors declare there is no conflict.

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First received 27 May 2022; accepted in revised form 24 June 2022. Available online 5 July 2022

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