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RESEARCH ARTICLE

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Soil carbon dioxide emissions from maize (*Zea mays* L.) fields as influenced by tillage management and climate*

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Abstract

Emissions of CO_2 from the soil are the second-largest component of the global carbon cycle, which has altered the climate and led to climate change. The main aim of this research was to evaluate the direct impact of climate and soil management systems on soil carbon emissions. Thus, CO_2 emissions were measured from maize fields located in two different climate regions (continental and semi-arid). The experimental design involved two different soil management systems (conventional tillage [CT], non-tillage [NT]) from two different sites (Debrecen [Hungary], Karaj [Iran]). The results showed that total CO_2 emission from the cultivated system (CT) was higher than that from the non-cultivated (NT) one, regardless of the climate region. However, CO_2 emissions from agricultural soil in a humid region are significantly different ($p < .05$) from semi-arid regions, which clearly emphasizes the role of climate conditions in the CO_2 emission processes. However, the general linear model reveals that all studied variables (soil management systems, date of measurement, soil temperature, soil water content) had a significant ($p < .05$) effect on soil carbon emission, where the explained variance was 0.866. The findings of this research stress the importance of NT in CO_2 mitigations on the farm scale. However, the output could help to draw up mitigation strategies to minimize the total greenhouse gas emissions from agricultural soil in both countries.

KEYWORDS

agricultural system, carbon cycle, climate impacts, food security, global warming, sustainable development goals (SDG)

Résumé

Les émissions de CO_2 par le sol est le deuxième principal composant du cycle du carbone global. Cela souline l'impact de ces émissions sur le climat actuel et leur rôle dans les changements climatiques. L'objectif principal de cette

* **L'impact du climat et de la gestion du travail du sol sur les émissions de dioxyde de carbone (CO_2) dans les cultures de maïs (*Zea mays L.*)**

étude était d'évaluer l'effet du climat sur les émissions de CO_2 par le sol. Nous avons mesuré les émissions de CO_2 par le sol des champs de maïs dans deux régions soumis aux climats différents (continental et semi-aride). Le design expérimental a impliqué deux différentes méthodes de gestion des sols (labour conventionnel (CT: *conventional tillage*), sans labour (NT: *non-tillage*)) dans deux sites différents (Debrecen (Hongrie) et Karaj (Iran)). Les résultats de cette étude ont montré que les émissions totales de CO_2 étaient plus élevées par les sols labourés (CT) que par les sols non-labourés (NT) et que cet effet était indépendant du climat de la région. Cependant, il y a eu une différence significative dans les émissions de CO_2 par le sol entre la région humide et semi-arides ($p < 0.05$), ce qui met en évidence l'effet des conditions climatiques sur les émissions de CO_2 par le sol. L'analyse du Modèle Linéaire Généralisé (*Generaliesd Linear Model* (GLM)) a montré que toutes les variables étudiées (système de gestion des sols, température du sol, humidité du sol et la date de mesure des émissions) avaient un effet significatif sur les émissions de CO_2 par le sol ($p < 0.05$), et que ces variables ont expliqué 86,6% de la variance dans les émissions de CO_2. Les résultats de la présente étude soulignent le rôle du travail du sol dans l'augmentation des émissions de CO_2 à l'échelle des fermes. Ces résultats sont également d'une grande importance pour la mise en place d'une stratégie de gestion des sols visant à diminuer les émissions de GES (*Greenhouse gases*) dans les champs cultivés.

MOTS CLÉS

Cycle du carbone, les effets du climat, systèmes de cultures, réchauffement climatique, sécurité alimentaire, développement durable, objectifs de développement durable (ODD)

1 | INTRODUCTION

The major challenges that the world faces today include food insecurity, water scarcity, land degradation, energy shortages, increasing greenhouse gas (GHG) emission, and climate change (Alsafadi et al., 2020; Mohammed et al., 2020a, 2020b). The GHG are active gases that trap solar radiation reflection from the earth and increase global warming (Tessum, Hill, & Marshall, 2014). The main GHG are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Oertel et al., 2016).

In recent years, anthropogenic activities have contributed to more than 55% of total GHG emissions (Xi-Liu & Qing-Xian, 2018; Mohammed et al., 2021). More than 22% of total GHG emissions have originated from the agricultural sector (Platis et al., 2019), where different activities as well as the degradation of agricultural lands have increased GHG emissions (Gozubuyuk, Sahin, & Celik, 2020). Thus, determining and measuring CO_2 emissions from agricultural land has received major attention from scientists and policymakers all around the world (Li et al., 2016).

Globally, carbon dioxide (CO_2) is one of the greenhouse gases, and its concentration has increased by 35%, from 280 ppm in 1750 to 377 ppm in 2004, and is currently increasing by 0.47% per year (Follett et al., 2005; Lal et al., 2007). According to 2010 global emissions estimates, approximately 76% of global CO_2 is emitted as a result of the use of fossil fuels, industrial processes, deforestation, and other land uses (IPCC, 2013). Due to their impact on carbon dynamics, agricultural activities make a significant contribution to CO_2 emissions (Nawaz et al., 2017).

Agricultural soils play a significant role in CO_2 emissions, with large amounts of CO_2 being released as a result of microbial decomposition, burning of plant residue after harvest, and respiration of soil microorganisms and plant roots (Smith et al., 2008; Nawaz et al., 2017). Furthermore, CO_2emissions are affected by soil properties, including organic matter, temperature, moisture, soil type, and agricultural management operations (Smith et al., 2008).

Tillage operations are among the major agronomic activities which accounted for the release of large amounts of CO_2 (Abdalla et al., 2013). Some studies have reported lower soil CO_2 emissions under conservation tillage compared to conventional tillage (CT) (Almaraz et al., 2009), while higher CO_2 emissions have also been reported from untilled soil compared with soil under CT in some climatic conditions (Hendrix, Han, & Groffman, 1988; Plaza-Bonilla et al., 2014). Tillage has a significant effect on carbon emissions from the soil and is one of the major agronomic activities involved in the loss of soil organic carbon (Abdalla et al., 2013). Comparative studies on the effects of tillage practices under different climates on CO_2emissions are still rare. For instance, La Scala, Bolonhezi, & Pereira (2006) stated that tillage intensifies the oxidation of soil organic carbon and leads to the release of large amounts of CO_2. It is estimated that tillage operations on US farmland release an average of 36 t of carbon per hectare (Lal, 1997). The use of conservation tillage methods in Europe has significantly reduced CO_2 emissions (Holland, 2004). It is estimated that by converting CT systems to no-tillage (NT), 100% of carbon emissions from all fossil fuels in Europe can be offset (Smith et al., 1998). Most field studies have reported different results regarding the effects of tillage on CO_2emissions. For example, the results of previous studies indicate that soil CO_2 emissions under conservation tillage compared to CT may decrease (Almaraz et al., 2009; Fuentes et al., 2012; Rutkowska et al., 2018), increase (Hendrix, Han, & Groffman, 1988; Oorts et al., 2007), or remain similar (Fortin, Rochette, & Pattey, 1996; Aslam, Choudhary, & Saggar, 2000). Bista et al. (2017) in a 2-year study on the effect of a tillage system on GHG emissions in the wheat-fallow system reported that the NT system reduced CO_2 emissions by 35% compared to CT. Nawaz et al. (2017) reported that the use of a NT system reduced CO_2 emissions as a result of improving soil properties.

Changes in climatic factors such as temperature and precipitation can affect CO_2 emission by altering plant and microbial activity, soil organic matter mineralization, and thermal and hydrologic regimes (Schollert et al., 2017; Ray et al., 2020). Increasing soil microbial respiration and plant root respiration explain higher soil CO_2 emissions in response to increased soil temperature, soil moisture, and rainfall, according to previous studies (Ren et al., 2017; Ray et al., 2020). Because of the variability in CO_2 emissions resulting from climatic conditions, uncertainty still remains about the mitigation potential of tillage management on CO_2 emissions in different climatic conditions. A better understanding of how different tillage practices alter soil CO_2 emissions under different climatic conditions is required. Thus, the main aim of this research was (1) to track changes in soil CO_2 emission rates from maize (*Zea mays* L.) fields under contrasting tillage (CT and NT) systems in two different climate regions including continental (Debrecen in Hungary) and semi-arid (Karaj in Iran) and (2) to evaluate the impact of soil moisture and soil temperature on CO_2 emissions.

2 | MATERIAL AND METHODS

2.1 | Site description and experimental design

To fulfil the research goals, two different locations with different climate classification were chosen. The first location was an agricultural field at the University of Tehran, Karaj (Iran) (50°58′ E, 35°48′ N), representing a semi-arid climate, while the second location was the Látókép research station at the University of Debrecen (Hungary) (47°33′ E, 21°26′ N), representing a continental climate.

The climate characteristics of the studied locations are shown in Figure 1. The average temperature in Látókép was 11°C and the rainfall 600 mm (Figure 1F), while in Karaj the mean air temperature and rainfall were 13.7°C and 245.5 mm, respectively (Figure 1G).

In accordance with the study goals, in each location two fields under different maize cultivation managements were selected (Figure 1). The first management approach was CT, while the second was NT. In the following step, 10 random soil samples (0–20 cm) from each location were collected and analysed, as shown in Table 1.

The experiments followed the randomized complete block design with three replications in each climatic region. The total number of plots was 12 (2 climate regions × 2 treatments × 3 replicates; Figure 2). The tillage characteristics and land preparation are presented in Table 2.

2.2 | Measurement of CO_2 emissions

Scientifically, 13.8% of the total GHG emissions originate from the agricultural sector, where different land use managements and different climates can significantly affect the GHG, in particularly CO_2 emissions. Thus, in this section the CO_2 emissions from two different climate zones with same land use (maize) and land management were investigated for one crop cycle. Gas sampling was performed at 7–10-day intervals at each subplot based on the GHG sampling protocol of GRACEnet Chamber-based Trace Gas Flux Measurement (Parkin & Venterea, 2010; Tenesaca & Al-Kaisi, 2015). In this sense,

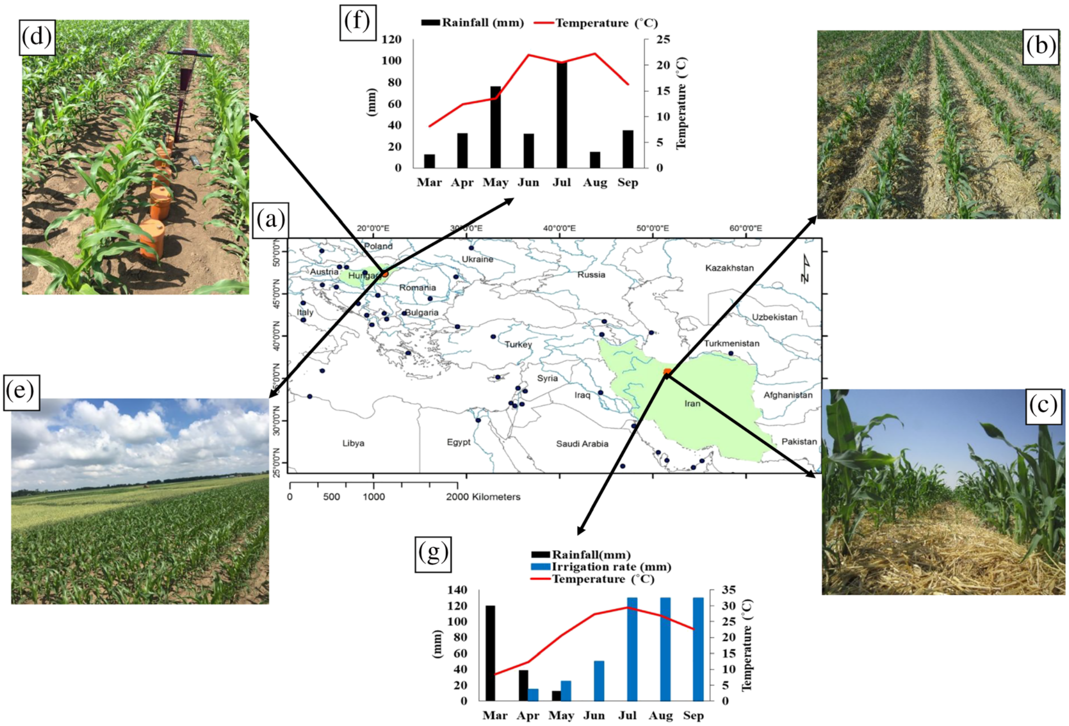

FIGURE 1 View of the experimental sites. A) Geographical map of the studied locations, B) conventional tillage (CT2) (Karaj), C) no-tillage (NT2) (Karaj), D) CT1 (Debrecen), E) NT1 (Debrecen), F) climate in Debrecen, G) climate in Karaj [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Soil properties of 0–20 cm soil depth in the fields of the studied areas

Soil properties	Debrecen (Hungary)	Karaj (Iran)
Sand (%)	11	25
Silt (%)	65	57
Clay (%)	24	18
Texture	Silt loam	Silt loam
pH_{KCl}	6.46	7.73
EC (ds m^{-1})	0.4	0.74
OM%	2.3	1.2
$CaCO_3$%	0	1.5
Soil depth (cm)	80	80
Phosphorus mg kg^{-1} (P_2O_5)	133	34
Potassium mg kg^{-1} (K_2O)	240	300
Classification	Calcareous chernozem/ Mollisol-Calciustoll	Xeric Haplocalcids

Abbreviations: EC, electrical conductivity; OM, organic matter.

the well-known static closed chamber method was used to measure CO_2 emissions (Oertel et al., 2012).

In the semi-arid region experiment (i.e., Karaj), the polyvinyl chloride chambers (15 × 12.5 cm) with ports for gas sampling were placed on the soil surface to a depth of 5 cm. In each subplot, two chambers (one within the plant row and one in between plant rows) were installed in three replications of each treatment, giving a total of 12 chambers for each location (2 tillage systems × 3 replicate× 2 chambers = 12 chambers). The average of two chambers was considered to be the soil surface emission for the entire subplot. Gas samples

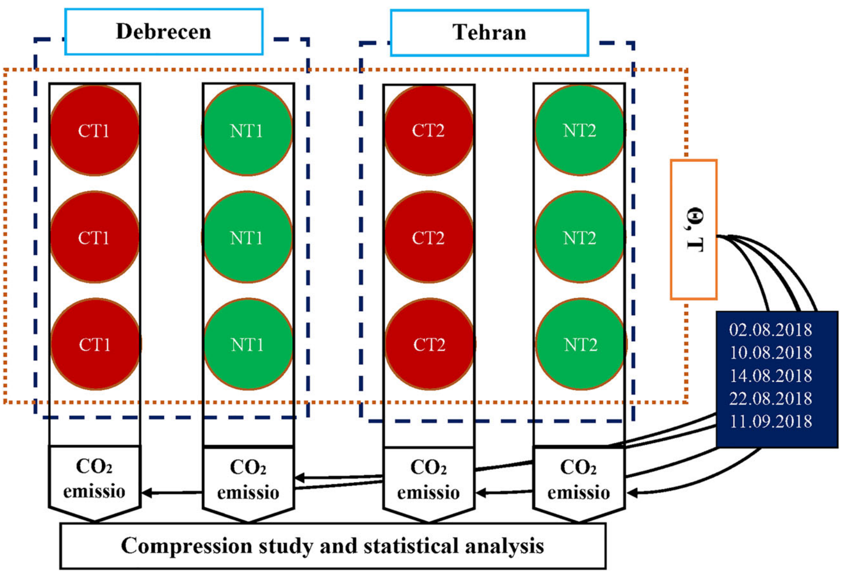

FIGURE 2 Flowchart of the experimental design. CT1, conventional tillage plots in Debrecen; CT2, conventional tillage plots in Karaj; NT1, non-tillage plots in Debrecen; NT2, non-tillage plots in Karaj [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Tillage practices and land preparation for the experimental sites in Debrecen and Karaj

Conventional tillage schedule	No-tillage schedule	Conventional tillage schedule	No-tillage schedule
Debrecen		**Karaj**	
Moldboard ploughing	NONE	Moldboard ploughing	NONE
Stem crushing (stubble)	NONE	Stem crushing (stubble)	NONE
N = 120 kg/ha	N = 120 kg/ha	N = 185 kg/ha	N = 185 kg/ha
P = 60 kg/ha	P = 60 kg/ha	P = 30 kg/ha	P = 30 kg/ha
K = 90 kg/ha	K = 90 kg/ha	K = 30 kg/ha	K = 30 kg/ha
Disc tillage	NONE	Disc tillage	NONE
Moldboard ploughing (Autumn)	NONE	Moldboard ploughing (Autumn)	NONE
Secondary tillage (Spring)	NONE	NONE	NONE
Seedbed preparation	Seedbed preparation	Seedbed preparation	Seedbed preparation
Sowing (April 22 +/− 4 days)	Sowing (April 22 +/− 4 days)	Sowing (July 7 +/− 2 days)	Sowing (July 7 +/− 2 days)
Weed control	Weed control	Weed control	Weed control
Inter-row cultivator	Inter-row cultivator	Inter-row cultivator	Inter-row cultivator
Harvesting (October 10 +/− 5 days)	Harvesting (October 10 +/− 5 days)	Harvesting (October 7 +/− 3 days)	Harvesting (October 7 +/− 3 days)

Abbreviations: EC, electrical conductivity; OM, organic matter.

were collected during the day from 9 to 10 a.m. at 0-, 30-, and 60-min intervals after 24 hr of chamber installation to avoid disturbance effects. The sampling approach included inserting a needle attached to a 20-mL syringe in the sampling port and then transferring the gas sample in 12-mL evacuated glass vials sealed with butyl rubber septa. The gas vials were analysed for CO_2 concentration using a gas chromatograph equipped with a thermal conductivity detector (Teif Gostar Faraz, TG, 2552, Iran).

In the continental experiment (i.e., Debrecen), the digital meter Testo 535 (TESTO; 0560 5350) was used for capturing and recording CO_2 emission. This devise measures CO_2 concentration via infrared absorption with 1 ppm of CO_2 measuring resolution (Törő et al., 2019). Five chambers (118 × 250 mm) were placed in each subplot, then CO_2 emission was measured and recorded, giving a total of 25 chambers for each location (2 tillage systems × 3 replicate× 5 chambers = 30 chambers). At the end of each monitoring day, the average of five chambers from each subplot was calculated and recorded as a representative value (Törő et al., 2019).

2.3 | Auxiliary measurements

In parallel with soil CO_2 emission measurements, soil temperature and soil water content were also recorded. In the semi-arid region experiment (i.e., Karaj), soil temperature was measured with a thermometer at approximately 10 cm soil depth. The volumetric soil moisture content was determined using oven-drying at 105°C multiplied by soil bulk density. In Debrecen, soil temperature was measured by the digital thermometer TFA LT101 (TFA Dostmann GmbH & Co. KG; 10 cm soil depth), while soil moisture was recorded by using TDR 300 (Spectrum Technologies, Inc.).

2.4 | Statistical analysis

Fisher's least significant difference (LSD) was applied to compare the mean of the first group with other groups and vice versa. Scientifically, the LSD approach is applied in analyses of variance (ANOVA), when it gives a significant result, which reveals that at least one variable differs significantly from the others. However, this variable is still anonymous; thus, we applied the LSD test (Williams & Abdi, 2010).

We applied a robust ANOVA based on a trim proportion of 0.2 to reveal whether the combined variable of site and treatments (i.e., cultivated and non-cultivated experiments in Debrecen and Karaj) had a significant effect on the CO_2 emissions of the soils. This version of ANOVA was able to handle the deviations from non-normality of the CO_2 values. Our null hypothesis (H_0) was that CO_2 measurements had the same trimmed means in all experimental groups. We performed a robust type of post hoc test (Lincoln function) implemented in the WRS2 package of R (R Core Team, 2021; Mair & Wilcox, 2020).

For advanced statistical analysis between studied plots, we applied the general linear model (GLM) to assess the factors affecting CO_2 emissions as a dependent variable in the soil. We involved both the factors (sites, dates of measurements, treatment types) and the covariates (soil temperature, soil moisture). In the model, we determined whether the involved variables had significant effects. Regarding the factors, we had the H_0 that there were no significant differences in group means in sites, dates, and treatments. We applied log-transformation to the CO_2 values to ensure the assumption of normal distribution of the residuals, which was checked with the Shapiro–Wilk test. Homogeneity of variance was checked with the Levene test. We determined the main effects of the factors and also the statistical interactions. Besides the significance, effect sizes (ω^2p) were also determined to quantify the contribution to the explained variance of a given variable or interaction in a standardized and comparable form. The effects of $\omega^2 p > 0.04$ can be considered large (Field, Miles, & Field, 2012).

3 | RESULTS

3.1 | A comparative analysis on a daily scale of CO_2 emissions

Figure 3 depicts the differences in CO_2 emissions among treatments on a daily scale. According to the results obtained, we can separate the observed data into three groups. The first group contains results from 02/08/2018 and 10/08/2018, the second one contains data between 14/08/2018 and 11/09/2018, while the third group represents data from 13/09/2018. The results indicate that CO_2 emissions from CT2 plots in the semi-arid region are significantly different ($p < .05$) from all plots in the continental region (i.e., CT1, NT1). In a similar vein, CO_2 emissions from NT1 plots in the continental region are significantly different ($p < .05$) from all plots in the semi-arid region (i.e., CT2, NT2). In most of the cases our results indicate the absence of significant differences from the following pairs: CT2-NT2, and CT1-NT1, and NT2-CT1 (Figure 3).

As this study attempted to measure soil temperature and soil moisture, the results showed that the average soil temperature was 22.7 ± 2.5°C in the continental region and 20 ± 2.8°C in the semi-arid region. In most of the cases, the results showed a significant difference ($p < .05$) in soil temperature between Debrecen and Karaj (regardless of the soil treatment type) (Figure 4).

Soil water content was varied among soil treatments. In this sense, the average soil moisture ranged between 18.75% ± 4.3% in CT1 and 23.58% ± 2.7% in NT1, while it ranged between 15.6% ± 3.5% in CT2 and 20.74% ± 5.2% in NT2. The direct impact of soil treatment (i.e., cultivation and non-cultivation) resulted in significant differences ($p < .05$) regarding the soil moisture regardless of the climate zone (Figure 5).

3.2 | A comparative analysis on total CO_2 emissions

Total CO_2 emissions from the cultivated system (CT) were significantly higher than those from the non-cultivated (NT) one, regardless of the climate region. The

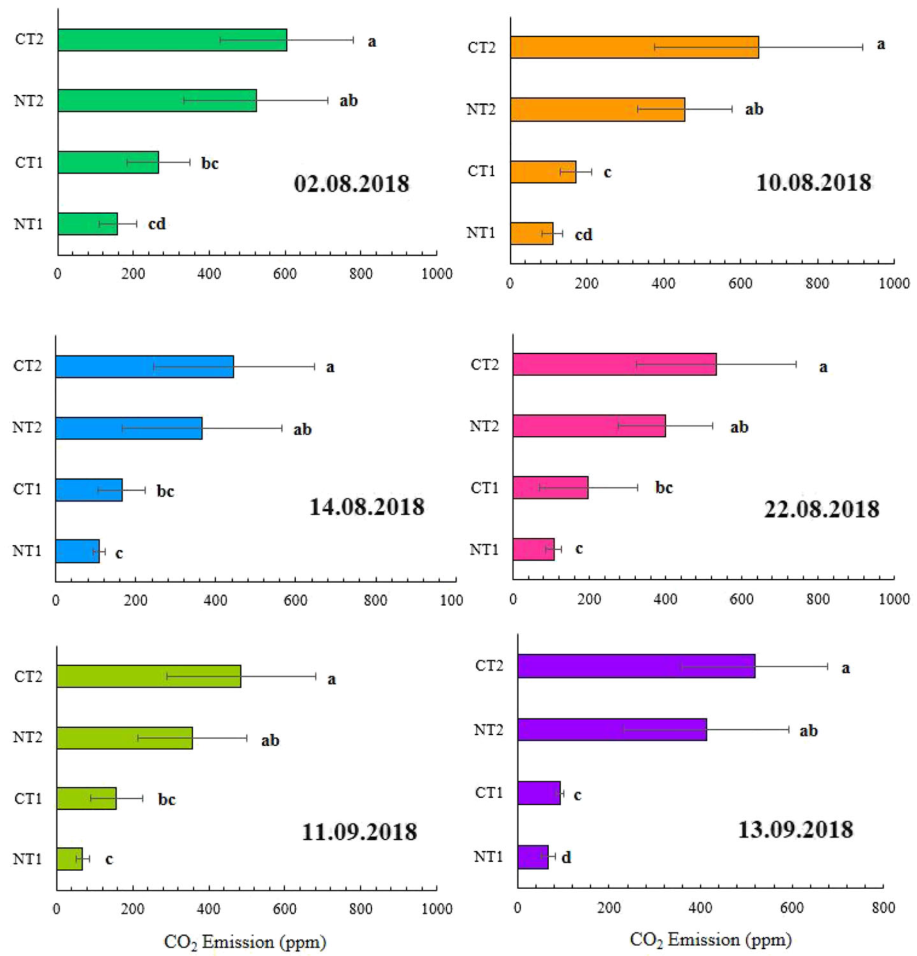

FIGURE 3 Soil CO_2 emissions (ppm) affected by tillage treatments in different climate regions during the monitoring period. Means with the same letter are not significantly different. Bars represent standard deviation (n = 3). CT1, conventional tillage field in Debrecen; CT2, conventional tillage field in Karaj; NT1, non-tillage field in Debrecen; NT2, non-tillage field in Karaj [Colour figure can be viewed at wileyonlinelibrary.com]

average CO_2 emissions from CT2 were 538.92 ± 180.93, while they were 174.72 ± 79.73 from CT1. However, the average CO_2 emissions from NT2 (418.93 ± 144.12) were higher than those from NT1 (102.83 ± 37.93) (Figure 6).

In this section, all the data collected from each system/treatment (i.e., CT1, NT1, CT2, NT2) were plotted against each other to test whether there is a significant difference among them or not. ANOVA of the combined variable of sites and treatments on the CO_2 emissions revealed a significant result; thus, we rejected the H_0 ($F = 45.9$; $p < .001$). According to the post hoc analysis, all possible groups differed from each other (Table 3). In this sense, Table 3 indicates that CO_2 emissions from the cultivated system are significantly different from those from the non-cultivated one in both climate regions (CT1-NT1: $p = .020$; CT1-NT2: $p = < .001$; CT2-NT1: $p = < .001$), except for one treatment: CT2-NT2 ($p = .076$). Nonetheless, regardless of the treatment type, emissions from agricultural soil in humid regions are significantly different from those in semi-arid regions (CT1-NT2: $p = < .001$; CT2-NT1: $p = < .001$, NT1-NT2: $p = < .001$) (Table 3).

3.3 | Analysis of the impacts of different ecological factors on total CO_2 emissions

We also highlighted the direct impact of different ecological factors (i.e., temperature, soil moisture, treatment type, date) on total CO_2 emission with the GLM technique. Accordingly, we found that all involved variables were significant ($p < .05$), and the explained variance, based on the adjusted R^2, was 0.866 (Table 4).

The effect sizes indicated that the treatment type (i.e., CT, NT) made the largest contribution to total CO_2 emissions ($\omega^2 p = 0.833$, $p = .006$), and the next important factor was the climate zone (continental [Debrecen] or semi-arid [Karaj]), which can also be referred to as the *Site* ($\omega^2 p = 0.333$, $p = < .001$) (Figure 6). Accordingly, a warmer climate and cultivation increased the level of CO_2 emissions. The date of measurement had also a significant ($p < .001$) and remarkable effect ($\omega^2 p = 0.280$), and the interaction of the cultivation type (i.e., treatment) with the date of measurement had a similar effect ($\omega^2 p = 0.281$, $p = < .001$), that is, the presence of cultivation had a significant effect with the plant phenotype. Also, the interaction between location, treatment,

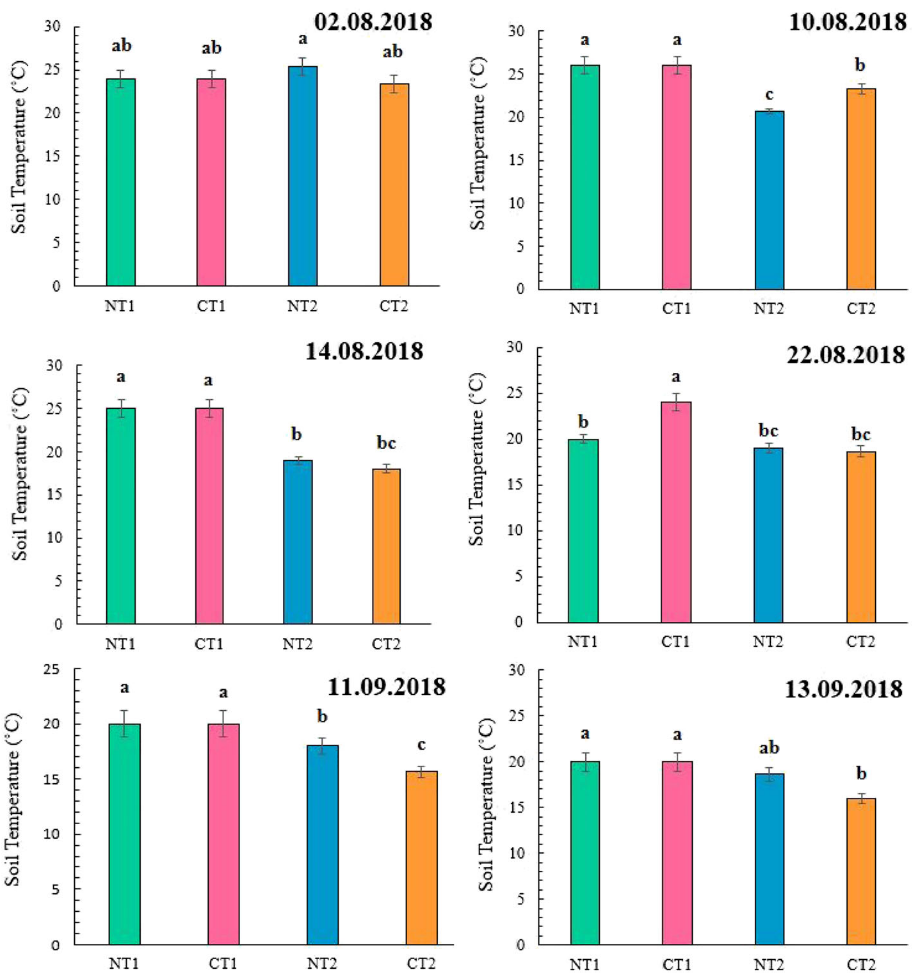

FIGURE 4 Soil temperature (°C) affected by tillage treatments in different climate regions during the monitoring period. Means with the same letter are not significantly different. Bars represent standard deviation (n = 3). CT1, conventional tillage field in Debrecen; CT2, conventional tillage field in Karaj; NT1, non-tillage field in Debrecen; NT2, non-tillage field in Karaj [Colour figure can be viewed at wileyonlinelibrary.com]

and date of measurement (i.e., Site × Treatment × Date) was significant ($\omega^2p = 0.201$, $p = .002$). All other interactions and covariates also had a large effect; however, their relevance was less than a tenth of those presented above (Table 4).

4 | DISCUSSION

CO_2 emissions were tracked in two different climate regions with almost the same conditions (except for the climate). The results reveal that CO_2 emissions from the CT system were higher than from the NT system. Also, CO_2 emissions were higher in the semi-arid region represented by Karaj (field of the Faculty of Agriculture) than in the continental region represented by Debrecen (Látókép field).

The outcomes of this study revealed that soil management systems (e.g., CT and NT) have a substantial impact on total soil carbon emissions. In this context, the cultivation process (Moldboard ploughing) separates soil aggregates into small particles, which directly accelerates soil aeration and microbial activity (de Oliveira Silva et al., 2019). Also, microaggregates enhance the biochemical process in the soil, leading to decomposition of soil organic matter and mineralization of organic carbon, and boost CO_2 emissions, which could explain our results (Table 3 and Figures 3 and 6). Furthermore, soil management activities (sowing, harvesting, fertilization, etc.) have a direct impact on biomass, soil moisture, and the nutrient cycle through the ecosystem, which undeviatingly affect soil carbon emissions (Barcza et al., 2009). Unlike the NT system, crop management in the CT system causes a sharp decrease in total biomass due to the harvesting and removing of plant residue, which indirectly changes the carbon pools and affects the carbon balance; consequently, the physiological response will be varied in comparison with NT. In this sense, La Scala, Bolonhezi, & Pereira (2006) reported that the CT system generates a higher amount of CO_2 emissions compared with other tested soil management systems (i.e., NT and reduced tillage). In corn and corn–soybean rotations (Midwestern USA), CO_2 emissions from the chisel plough method were significantly higher than from the

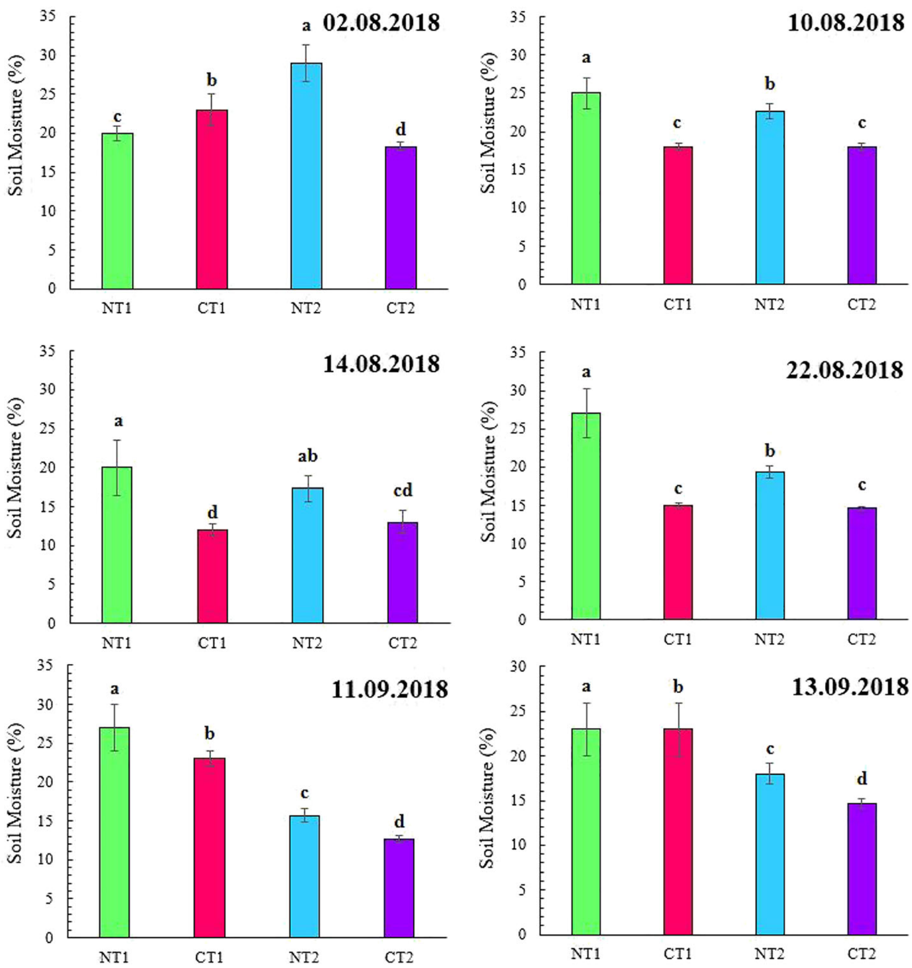

FIGURE 5 Soil moisture (%) affected by tillage treatments in different climate regions during the monitoring period. Means with the same letter are not significantly different. Bars represent standard deviation (n = 3). CT1, conventional tillage field in Debrecen; CT2, conventional tillage field in Karaj; NT1, non-tillage field in Debrecen; NT2, non-tillage field in Karaj [Colour figure can be viewed at wileyonlinelibrary.com]

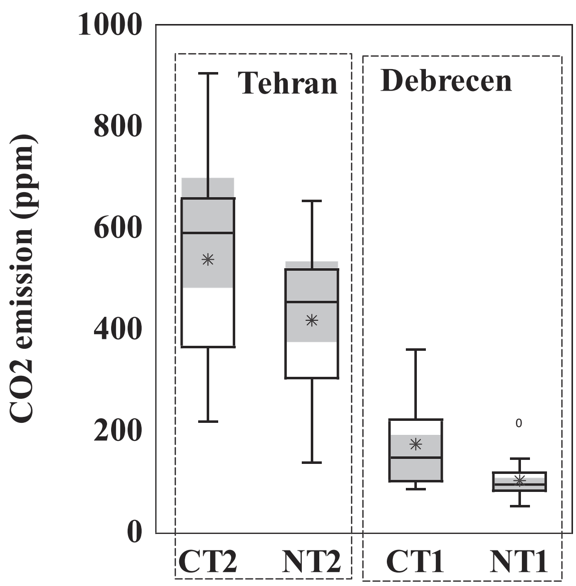

FIGURE 6 Boxplot of CO_2 emission from each treatment. Median (______), mean (*), near outlier (^{0}), median 95% CI (shaded). CT1, conventional tillage field in Debrecen; CT2, conventional tillage field in Karaj; NT1, non-tillage field in Debrecen; NT2, non-tillage field in Karaj

TABLE 3 Comparison of treatments based on robust post hoc test

Treatments	Psi-hat	*P* (<0.05)	95% CI Lower	95% CI Upper
CT1-CT2	−386.3	**< .001**	−545.48	−227
CT1-NT1	62.3	**0.020**	−1.09	126
CT1-NT2	−268.5	**< .001**	−399.76	−137
CT2-NT1	448.6	**< .001**	293.63	604
CT2-NT2	117.8	0.076	−64.07	300
NT1-NT2	−330.8	**< .001**	−456.05	−206

Note: Bold values indicate significance at $p < .05$.
Abbreviations: CT, conventional tillage; NT, non-tillage; psi-hat, test statistic.

Moldboard plough and NT; hence, CO_2 emissions are significantly affected by the tillage system (Omonode et al., 2007). An identical conclusion to this research was drawn by Silva-Olaya et al. (2013) in Brazil, reporting that CT plots were the highest emitters of CO_2 in

TABLE 4 CO_2 emission of soils based on soil properties, management, and the location using the general linear model

Parameters	SS	*df*	*F*	*p* value	ω^2p
Model	20.503	25	19.56	< .001	0.866
Site	5.884	1	72.47	< .001	0.300
Treatment	0.663	1	8.17	0.006	0.833
Date	2.046	5	5.04	< .001	0.280
Temperature	0.396	1	4.88	0.032	0.012
Soil moisture	3.390	1	41.75	< .001	0.038
Site × Treatment[a]	0.547	1	6.74	0.013	0.022
Site × Date[a]	1.305	5	3.21	0.014	0.048
Treatment × Date[a]	4.397	5	10.83	< .001	0.281
Site × Treatment × Date[a]	1.875	5	4.62	.002	0.201
Residuals	3.735	46			
Total	2167.159	72			

Abbreviations: *df*, degrees of freedom; *F*, *F* statistics; SS, sum of squares; ω^2p, effect size.
[a]The multiplication sign represents the interaction between factors.

TABLE 5 Some measured values for greenhouse gas emission (GHG) in Hungary and Iran

			GHG emission			
Country	**Year**	**Land use**	**CO_2**	**CH_4**	**N_2O**	**Reference**
Hungary	2006–2007	Grasslands	–	−0.04 to 0.05 kg CH_4 ha^{-1} $year^{-1}$	0.5 kg N ha^{-1} $year^{-1}$	Horváth et al. (2008)
Hungary	2002–2007	All Hungarian ecological systems (50% agriculture)	8.7 Mt per year	–	–	Barcza et al. (2009)
Hungary	2002	Tillage experiment	0.030–0.092 mg CO_2 m^{-2} s^{-1}	–	0.003–0.516 μg N_2O m^{-2} s^{-1}	Dencső et al. (2021)
Hungary	2010	Agricultural lands	379 mg kg^{-1}	–	10.4 μg kg^{-1}	Kong et al. (2013)
Iran	2021	Maize field	-	–	0.93–1.62 kg N_2O-N ha^{-1}	Borzouei et al. (2021)
Iran	2013	Forest	2–3.5 t C ha^{-1} $year^{-1}$	–	–	Moghiseh, Heidari, & Ghannadi (2013)

comparison with other soil management treatments, such as minimum tillage and reduced tillage.

Soil temperature is one of the key regulators of CO_2 emissions from the soil (Almaraz et al., 2009). Increased soil temperature can promote CO_2 emissions, mainly by accelerating the decomposition of plant residue and increasing root and microbial respiration (Campbell et al., 2014; Ding, Wang, & Zhang, 2017). Oertel et al. (2016) reported that increased soil temperatures result in higher soil respiration, which is in agreement with our results (Tables 3 and 4, Figures 4 and 6). Previous studies have also found a positive correlation between soil temperature and CO_2 emission rates (Raich, Potter, & Bhagawati, 2002; Lopes de Gerenyu, Rozanova, & Kudeyarov, 2005).

Soil moisture can also directly affect the emission of GHG. In this research, changes in soil moisture content driven by rainfall and irrigation altered soil CO_2 emissions. Soil moisture is crucial for providing substrate for soil microorganisms (Schindlbacher, Zechmeister-Boltenstern, & Butterbach-Bahl, 2004), and it can also influence gas diffusivity (Smith et al., 2003). Gas diffusivity varies inversely with water content, and it controls the movement of gases to and from the atmosphere (Smith et al., 2018). The higher soil moisture content in Debrecen compared to Karaj is probably one of the reasons which explain its lower soil CO_2 emissions. Drier soil conditions also restrict soil microbial activity and respiration (Smith et al., 2018). Rey et al. (2002) have also reported lower soil respiration during dry summers, which highlights the importance of soil moisture for the rate of soil respiration.

Many studies have dealt with GHG emissions from agricultural land in Hungary and Iran separately (Table 5). Regardless of land use, GHG emissions from the Iranian agroecosystem are obviously higher than from the Hungarian one. All in all, determining the direct impact of climate, soil and crop management on the soil carbon balance (sink, emissions) is a difficult task that necessitates a long period of observation before any conclusions can be drawn. Nonetheless, the primary aim of this scientific work was to provide a summary of CO_2 emissions in two separate climate regions, and its findings may serve as a starting point for future studies in this field.

5 | CONCLUSION

In this research, CO_2 emissions were measured in two different agroecological regions; the first was a continental region represented by a field in Debrecen, Hungary. The second was the Karaj field, representing a semi-arid region in Iran. This research showed that CO_2 emissions were higher in semi-arid plots compared with continental ones. However, the highest emissions were observed in the tillage system compared with the NT system (regardless of the climate region). Considering the positive impacts of NT systems on soil carbon mitigation, the findings of this study could help scientists and decision-makers to draw up mitigation strategies to minimize the total GHG emission from the agricultural sector in both countries. However, further studies and longer-term experiments in agricultural systems are required to determine the full potential of different soil management practices on GHG emissions under different climatic conditions.

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CONFLICT OF INTEREST

None.

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