Pedobiologia - Journal of Soil Ecology 93–94 (2022) 150819

Contents lists available at ScienceDirect

Pedobiologia - Journal of Soil Ecology

journal homepage: www.elsevier.com/locate/pedobi

Crop residues in corn-wheat rotation in a semi-arid region increase CO_2 efflux under conventional tillage but not in a no-tillage system

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ARTICLE INFO

Keywords:
Agricultural management
Greenhouses gases
Soil CO_2 efflux
Conventional tillage
No-till

ABSTRACT

Appropriate management of crop residue plays a key role in mitigating greenhouse gas emissions. However, it has been inadequately implemented in general agricultural management practices. In a field investigation using static chambers, we evaluated the effects of crop residue at three different rates - 100 % (R_{100}), 50 % (R_{50}), and residue removal (R_0) - on carbon dioxide (CO_2) efflux. The field study was conducted in corn-wheat rotation under conventional (CT) and no-tillage (NT) systems in a semi-arid region. The main results showed that CO_2 efflux was positively correlated with higher soil temperature (0.43–0.79) and microbial biomass carbon (0.66–0.89). The crop residue treatments affected these traits. A strong positive relationship between CO_2 efflux and the crop residue ($R^2 = 0.96$, CT and $R^2 = 0.9$ for NT) was observed. In the CT system, significant increases were detected among residue rates on cumulative CO_2 efflux, where R_{100} and R_{50} resulted in 36 % and 25 % higher cumulative CO_2 efflux, respectively, than R_0. In contrast, there was no significant difference in cumulative CO_2 efflux among the crop residue retention (R_{100} and R_{50}) and removal (R_0) treatments under the NT system. Our study revealed that crop residue retention led to increased CO_2 efflux under the CT system in semi-arid conditions during the first year of application, while under the NT system, CO_2 efflux was not impacted by crop residue. Our results indicate that there is considerable potential for improving soil management practices in the context of soil degradation, climate change, increasing crop productivity, and carbon (C) sequestration.

1. Introduction

The continuous increase in the concentration of greenhouse gases (GHGs) produced by human activities has become a major concern due to their direct impact on global warming and climate change (Oertel et al., 2016). The concentration of CO_2 in the atmosphere increased from 278 ppm in 1750 to 390.5 ppm in 2011 (Ciais et al., 2013), and then up to 418 ppm in 2021 (Tanhua et al., 2021). CO_2 emission is the primary mechanism of soil C loss and contributes to the elevated CO_2 concentration in the atmosphere (Parkin and Kaspar, 2003). Most of the CO_2 emitted from the soil is due to the decomposition of plant residue and roots, due to microbial metabolism and respiration (Sainju et al., 2008; Campbell et al., 2014).

It was estimated that 75–120 Pg C per year is emitted from soil to the atmosphere (Hibbard et al., 2005). Therefore, maintenance and build-up of soil C are essential in improving soil functions and offsetting atmospheric CO_2 concentration (Smit, 2004; Delgado-Baquerizo et al., 2017), which is a key challenge for humankind (Lal, 2004; Scharlemann et al., 2014; Rodrigo-Comino et al., 2020a). Crop residue management affects CO_2 emissions, primarily via altering C and nitrogen (N) cycling

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https://doi.org/10.1016/j.pedobi.2022.150819
Received 16 December 2021; Received in revised form 31 May 2022; Accepted 10 June 2022

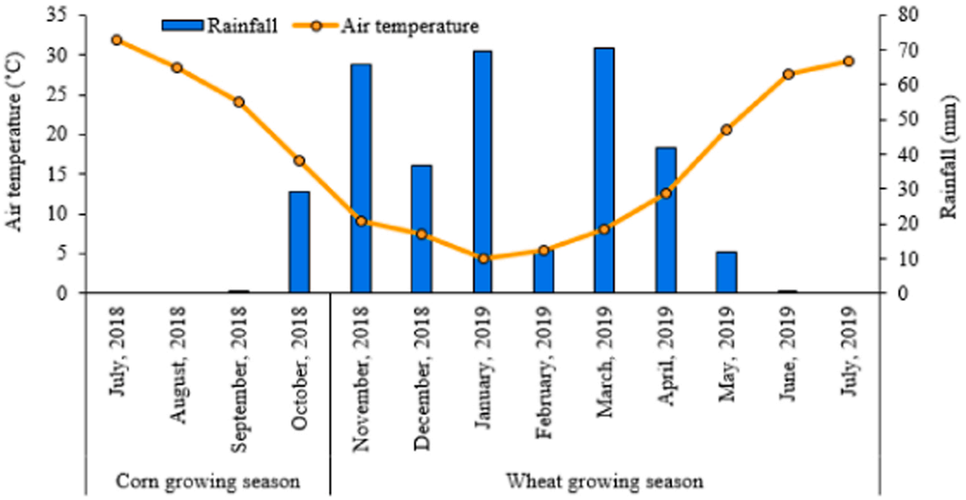

Fig. 1. Monthly precipitation and mean air temperature during the period of the experiment.

(Guzman et al., 2015; Nawaz et al., 2017). However, multiple factors regulate CO_2 emissions from the soil. Changes in soil temperature and moisture levels (Dong et al., 2017), organic matter (OM) inputs from decomposing residues- and their effect on faunal and microbial activities, all influence soil respiration (Toosi et al., 2012).

Due to the complexity of factors governing soil respiration following the addition of crop residues and their interactions, contrasting observations have been reported in the literature, i.e., increases (Badía et al., 2013; Sugasti and Pinzón, 2020) or decreases in soil CO_2 emissions following the application of crop residue in soil (Bai et al., 2017). Most cropping lands in Iran are semi-arid regions (i.e., high pH and $CaCO_3$, low OM, and suppressed biological status) where corn-wheat rotation is a common grain production cropping system. Despite its value as a source of OM, much of the postharvest crop residue is grazed or collected as a feed source. Residue removal and excessive tillage are the main cause of soil OM depletion in grain crops in the region (Mirzaei et al., 2021). Efforts have been made at the national level to encourage farmers to return crop residues to the soil. The effect of residue retention on CO_2 emission from the soil, typical of semi-arid conditions, has not been adequately studied.

Previous studies have shown that frequent drying-wetting cycles in arid and semi-arid conditions could lead to substantial C losses in soil from newly added OM (Borken and Matzner, 2009). We hypothesized that: i) the addition of crop residue to the soil results in higher CO_2 efflux compared to residue removal, independent of the tillage effect; ii) the cumulative CO_2 efflux would increase with an increasing amount of crop residue to the soil.

To test the above-mentioned hypotheses, we monitored CO_2 efflux in a field study, using crop residue at three rates – 100 % (R_{100}), 50 % (R_{50}), and residue removal (R_0) in corn-wheat rotation under conventional (CT) and no-tillage (NT) systems. As key regulators of soil respiration, microbial biomass and soil moisture and temperature were also monitored during the experiment to link their possible association with the soil CO_2 efflux.

2. Materials and methods

2.1. Site characteristics and experimental design

The study was conducted in 2018 at the Agriculture Research Station of the College of Agriculture and Natural Resources, University of Tehran, Karaj, Iran (35°48′32" N, 50°58′06" E, 1308 m a.s.l.). This area has semi-arid climate conditions with a mean annual temperature of 13.7 °C and precipitation of 245 mm (Fig. 1). Two fields under contrasting tillage management, conventional tillage (CT) and no-tillage (NT), were selected. Both systems were under a wheat (*Triticum aestivum* L.) - corn (*Zea mays* L.) rotation for at least fifteen years before the study. Each field of 11 × 16 m was divided into nine 3 × 4 m sub-plots. The experimental design was a randomized complete block with three replicates per treatment. Table 1 summarizes the main physical and chemical soil properties. Ten soil samples were collected randomly using an auger sampler (8 cm diameter) from 0 to 10 cm and 10–20 cm depths in each field. Subsequently, soil samples were uniformly mixed to one composite sample per soil depth. Soil samples were air-dried, sieved (2 mm), and stored until analyzes were carried out. Soil texture was determined by the hydrometric method (Gee and Bauder, 1986). Soil organic carbon (SOC) using the Walkley and Black method (Walkley and Black, 1934), pH, and electrical conductivity (EC) were measured in saturated soil extracts (Richardes, 1954). Available phosphorus was determined using the $NaHCO_3$ method (Olsen and Sommers, 1982). The ammonium acetate method was used for determining available potassium (Knudsen et al., 1982). Total nitrogen (TN) was measured using the Kjeldahl method described by Bremner and Mulvaney (1982). Micronutrients were measured in DTPA extracts (Lindsay and Norvell, 1978) using atomic absorption spectrophotometry.

Table 1
Soil properties of 0–10 and 10–20 cm soil depths in the fields in 2019.

Soil properties	Conventional tillage (CT)		No-tillage (NT)	
	0–10 cm	10–20 cm	0–10 cm	10–20 cm
pH	*7.8 ± 0.1	7.7 ± 0.1	7.8 ± 0.0	7.6 ± 0.1
EC (ds m^{-1})	0.9 ± 0.0	0.7 ± 0.2	1 ± 0.0	0.7 ± 0.2
OC (mg/g)	0.9 ± 0.1	0.8 ± 0.2	1.2 ± 0.0	1.01 ± 0.1
TN (mg/g)	0.09 ± 0.01	0.07 ± 0.01	0.1 ± 0.0	0.08 ± 0.0
Avail K (mg kg^{-1})	167 ± 4	134 ± 3	279 ± 5.2	237.4 ± 6.0
Avail P (mg kg^{-1})	9 ± 0.2	9.5 ± 0.6	15 ± 1.5	15.3 ± 0.7
Bulk density (g cm^{-3})	1.52	1.56	1.32	1.38
Total Porosity (%)	54 ± 2	52 ± 1.1	48 ± 1.9	45 ± 1
Sand (%)	57 ± 1	53 ± 1	28 ± 0.3	27 ± 0.7
Silt (%)	25 ± 1	28 ± 1	42 ± 0.2	42 ± 0.6
Clay (%)	18 ± 1	19 ± 2	30 ± 0.4	31 ± 0.7
Soil texture	Sandy Loam	Sandy Loam	Clay Loam	Clay Loam

EC: electrical conductivity, OC: organic carbon, TN: total nitrogen, Avail K: available potassium, Avail P: available phosphorus.

* Values are Mean ± Standard Deviation (n = 3).

2.2. Treatment applications

The wheat residue was applied following wheat harvest (Jul 2018) in both NT and CT fields. The three levels of residue were 3.5 t ha^{-1}

Table 2
Elemental composition of wheat and corn residue.

Plant residue	N	P	K	C	C/N
	%				–
Wheat	*0.84 ± 0.12	0.09 ± 0.01	1.75 ± 0.07	55.4 ± 1.80	66 ± 2.56
Corn	0.92 ± 0.06	0.25 ± 0.02	1.08 ± 0.01	53.65 ± 1.30	58 ± 1.63

[*] Values are Mean ± standard deviation (n = 3).

(100 %, R_{100}), 1.75 t ha^{-1} (50 %, R_{50}), and no residue (residue was completely removed, R_0). The selection of residue levels was based on crop yield, which was almost similar in both CT and NT systems. The plant residue was weighed according to the treatment and was then homogeneously and manually distributed over the surface of each plot. In the CT field, all the three residue levels were tilled and incorporated into the soil, while in the NT they were just left on the soil surface. For the residue removal treatment (R_0), under both CT and NT systems, the whole residue from the previous crop was removed from the plot, and the soil surface was left uncovered. After this, silage corn was planted by using a row crop planted at a dose of 35 kg ha^{-1} with a distance of 15 cm within the row and 75 cm between the rows. In the NT field, seed placement was made using a planter with a single coulter to eliminate residue and loosen the soil before the standard planter unit. In the CT field, before seeding, the soil was plowed to a depth of 35 cm with a moldboard plow, disked, and leveled. Both NT and CT received equal basal NPK fertilizers equal to 50 kg ha^{-1} Urea, 70 kg ha^{-1} Potassium sulfate, and 150 kg ha^{-1} Superphosphate. Additional N was top-dressed at eight leaves (80 kg Urea ha^{-1}) and ten leaves (270 kg Urea ha^{-1}) stages. Plots were irrigated after cultivation and 7–10 days intervals thereafter using the sprinkler irrigation method. After harvesting the corn (Oct 2018), three levels of residue were applied equally to 1.8 (100 %, R_{100}), 0.9 ton ha^{-1} (50 %, R_{50}), and no residue (0 %, R_0). Winter wheat was planted in Nov 2018, at a dose of 208 kg ha^{-1} seed with a row distance of 13 cm by a mechanical drilling machine. Basal fertilization included the equivalents of 50 kg ha^{-1} urea, 200 kg ha^{-1} superphosphate, and 150 kg ha^{-1} potassium sulfate. Additional N fertilizer was supplied during late tillering (110 kg Urea ha^{-1}), stem elongation (110 kg Urea ha^{-1}), and spiking (50 kg Urea ha^{-1}).

2.3. *Plant residue analyses*

A sub-sample of wheat and corn residues was dried and finely ground for chemical analyses (Table 2). Organic carbon (OC) was measured by wet oxidation (Walkley and Black, 1934), and the Kjeldahl method was used for determining total nitrogen (TN) content. For measurement of total phosphorus (P) and potassium (K), the samples were combusted at 500 °C, and P and K were determined using spectrophotometric and flame photometric methods, respectively.

2.4. *Soil CO_2 efflux*

Gas sampling was started in late July and early August 2018 in the

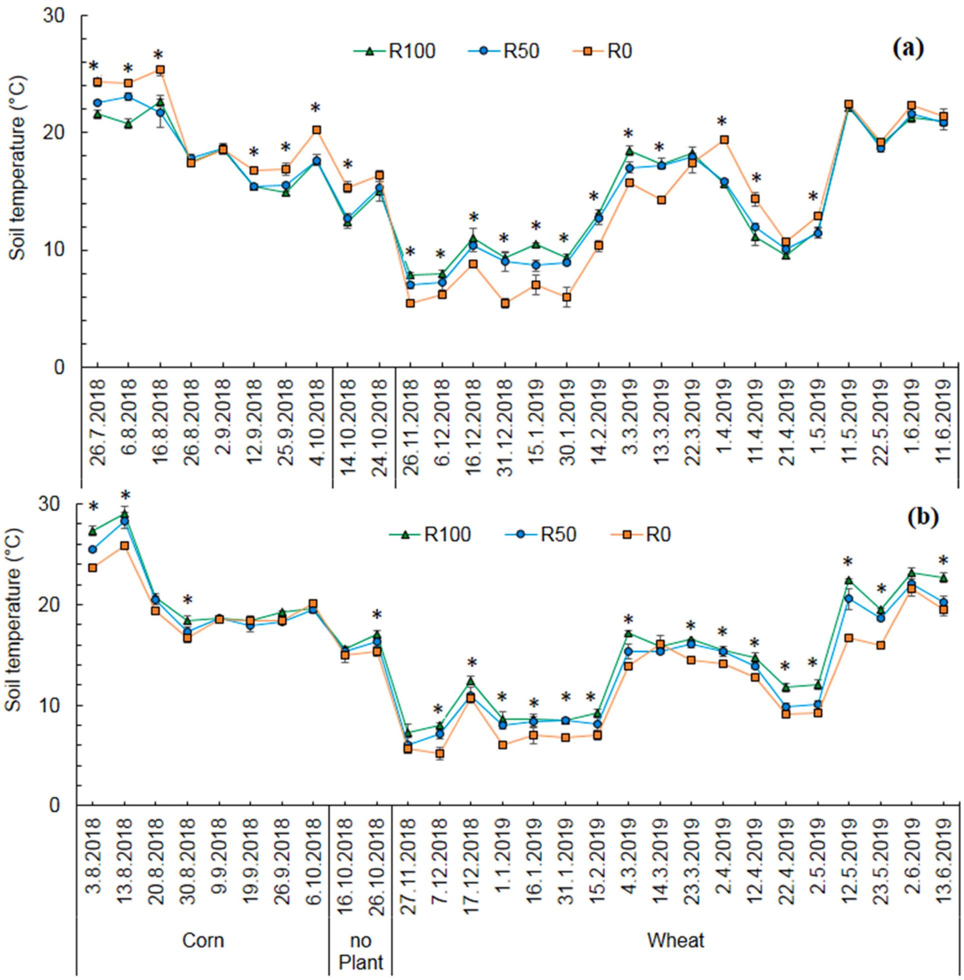

Fig. 2. The effect of residue levels on soil temperature at the gas sampling events under the no-tillage (NT) (a) and conventional tillage (CT) (b) systems. Bars represent standard error (n = 3). An asterisk (*) shows a significant difference between residue levels within a day at $P < 0.05$.

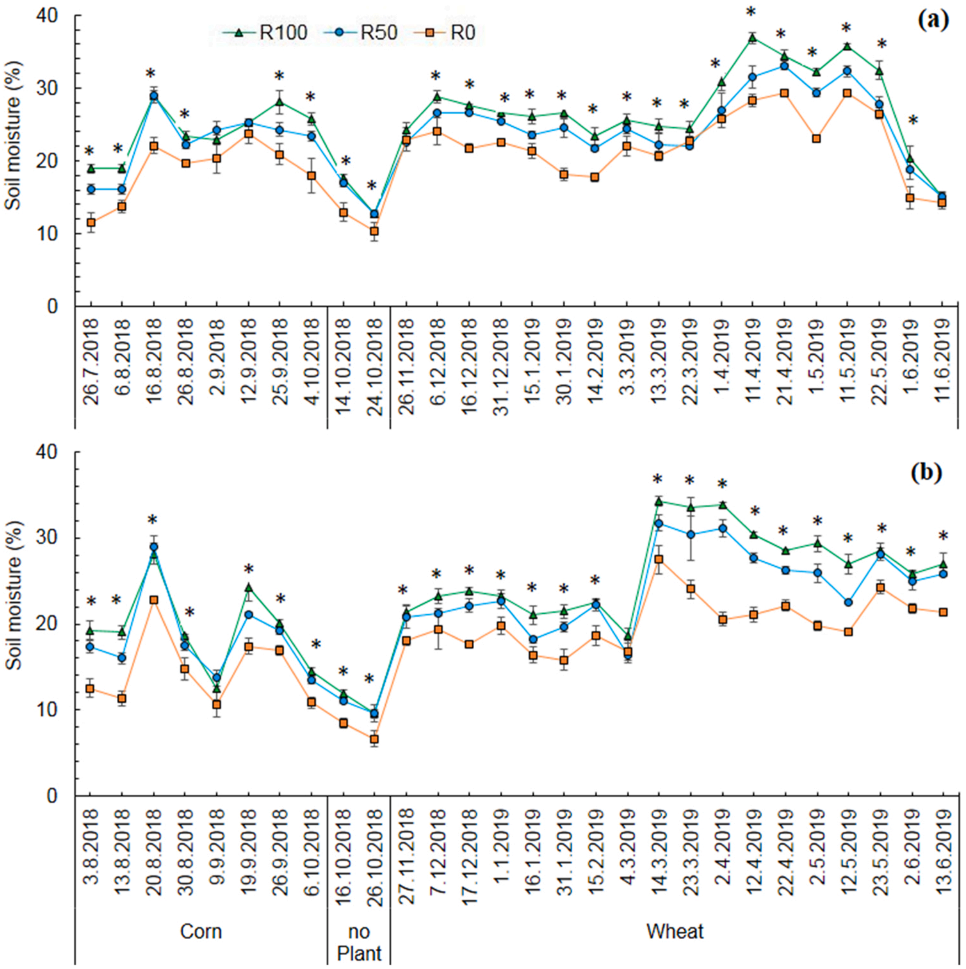

Fig. 3. The effect of residue levels on soil moisture at the gas sampling events under the no-tillage (NT) (a) and conventional tillage (CT) (b) systems. Bars represent standard error (n = 3). An asterisk (*) shows a significant difference between residue levels within a day at $P < 0.05$.

corn cropping system under the NT and CT systems respectively and ended in early June 2019 in the wheat cropping system under both systems. Gas sampling was performed at 7–10 d intervals generally, and every two weeks in winter (December–February), based on the GRACEnet Chamber-based Trace Gas Flux Measurement protocol (Parkin and Venterea, 2010). The static closed chamber method was used to measure the amount of CO_2 efflux from the soil. The method has been widely used for the measurement of soil gas efflux, including carbon dioxide, methane, and nitrous oxide (Oertel et al., 2012). Polyvinyl chloride (PVC) chambers (15 cm diameter, 12.5 cm height) with ports for gas sampling were gradually hammered into the soil surface to depths of 5 cm during the whole monitoring period. Chambers were only removed during cultivation events. To enable chamber operation, the crops were mowed when their height exceeded the chamber's height. Gas samples were collected at least 24 h after chamber installation to avoid disturbance effects. Gas sampling was performed from 9 to 10 am at 0, 30, and 60 min time points by inserting a needle attached to a 20 mL syringe in the sampling port and transferring in 12 mL pre-vacuumed vials sealed with butyl rubber septa (Labco Exetainer, UK). The concentration of CO_2 in the vials was measured using gas chromatography (Teif Gostar Faraz, TG 2552, Iran), equipped with a thermal conductivity detector (TCD).

The CO_2 efflux was calculated as the changes in linear concentration gradient over time and from the ratio between chamber volume and soil surface area (Liebig et al., 2010). The CO_2 efflux was converted to its carbon equivalent (CO_2-C) by multiplying it by the ratio of the molecular weight of carbon to that of carbon dioxide (12/44). Cumulative amounts of CO_2 efflux were calculated using linearly interpolating data points and integrating the underlying area (Sainju et al., 2012; Wegner et al., 2018).

2.5. *Ancillary measurements*

To evaluate the relationship between soil conditions and CO_2 efflux, soil temperature, and moisture contents, as well as microbial biomass C, were determined at each gas sampling event. Soil temperature was measured with a thermometer at 10 cm depth next to the collars. Three soil samples (0–10 cm) were taken with a core sampler (100 cm^3 volume) from each plot that was then mixed into one composite sample. The soil moisture content of the samples was determined using oven-drying at 105 °C multiplied by soil bulk density. Soil bulk density was measured using stainless steel cylinders (100 cm^3 volume). Microbial biomass carbon (MBC) was determined by the chloroform fumigation extraction method (Jenkinson et al., 2004).

2.6. *Statistical analyses*

The data were analyzed using the Analysis of Repeated Measures procedure in general linear models (GLM) of SAS software version 9.4 (SAS Institute, Cary, NC, USA). Residue rate, tillage type, and sampling time were the fixed effects. Soil parameters (moisture, temperature, MBC) and CO_2 efflux were the repeated measure variables. Means for each residue rate, tillage type, and sampling time were compared by the Duncan method at the 0.05 probability level. Pearson linear correlation

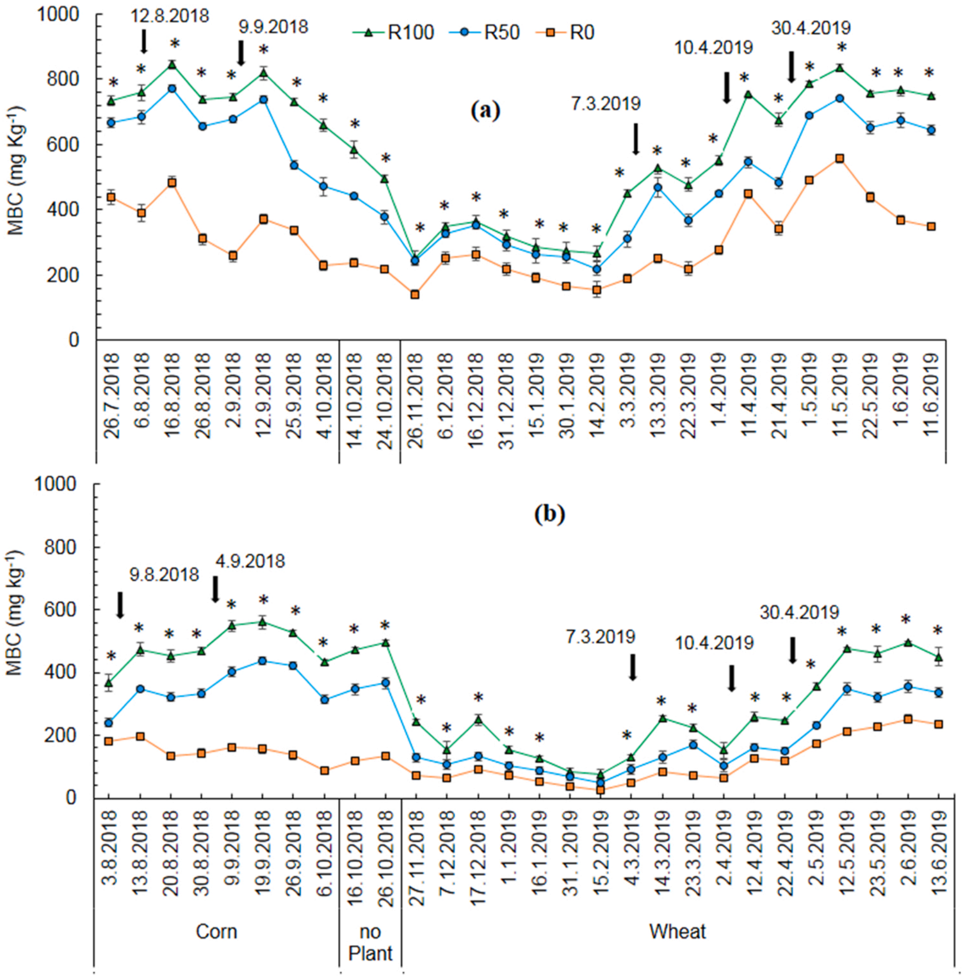

Fig. 4. The effect of residue levels on soil microbial biomass carbon (MBC) in no-tillage (NT) (a) and conventional tillage (CT) (b) systems at the gas sampling events. Bars represent standard error (n = 3). The bold black arrows indicate fertilization events. An asterisk (*) shows a significant difference between residue levels within a day at $P < 0.05$.

analysis was used to determine the relationships between soil parameters (moisture, temperature, MBC) and CO_2 efflux.

3. Results and discussion

3.1. Soil temperature and soil moisture

In the NT system, during the corn season (Jul–Oct), and also in the fallow period between corn and wheat seasons (14/10/2018 and 24/10/2018), soil temperature was higher in plots receiving residue at lower rates, where a significant increase ($P < 0.05$) in soil temperature was observed in the R_0 compared to R_{50} and R_{100} treatments (Fig. 2a). On the other hand, in most cases, no significant differences were observed between R_{100} and R_{50}. From the beginning of the wheat-growing season in autumn (26/11/2018) until the end of winter (22/3/2019), the opposite trend was noticed, where high residue rate led to increased soil temperature, and R_{100} and R_{50} resulted in a significant increase ($P < 0.05$) in soil temperature compared to R_0. Here, in most cases, the differences between R_{100} and R_{50} were not significant. In addition, from the beginning of spring until the end of the experimental period, the soil temperature in R_0 treatment increased compared to R_{100} and R_{50} treatments. The results of this study are consistent with previous findings (Guzman et al., 2015). The increasing soil temperature in R_0 in summer and R_{100} and R_{50} in autumn and winter under the NT system can be attributed to the insulating effect of plant residue. The presence of plant residue on the soil surface in the NT system protects the soil against severe thermal fluctuations and modulates surface radiation energy and thermal changes between soil and atmosphere (Horton et al., 1996). In the summer, plant residue on the soil surface prevents the absorption of more radiation, thus preventing the soil surface from warming. In autumn and winter, plant residue on the soil surface prevents heat exchange and, thus causes the soil to warm up compared to bare soil.

During crop rotation under the CT system, soil temperature increased with increasing residue rate at all sampling times, and, in most cases, these increases in R_{100} and R_{50} treatments were significant ($P < 0.05$) compared to R_0. Still, in some cases, no significant difference was observed between R_{100} and R_{50} treatments (Fig. 2b). Results obtained in the CT system are congruent with Zhang et al. (2018) in their study in China. In the CT system, crop residue is incorporated into the soil instead of remaining on the soil surface, leaving a small amount of plant residue on the soil surface, which reduces the effect of crop residues and causes the soil to absorb more heat, and leads to increases in soil temperature (Dendooven et al., 2012).

In almost all sampling times, R_{100} and R_{50} treatments caused a significant increase ($P < 0.05$) in moisture compared to R_0 under both CT and NT systems (Fig. 3a,b). However, in several cases, no significant differences were observed between R_{100} and R_{50}. Increased soil moisture in R_{100} and R_{50} treatments compared to R_0 under both CT and NT systems could be explained by the fact that crop residue reduces moisture evaporation and increases water-holding capacity and soil water content. Previous studies have also suggested that crop residue increases

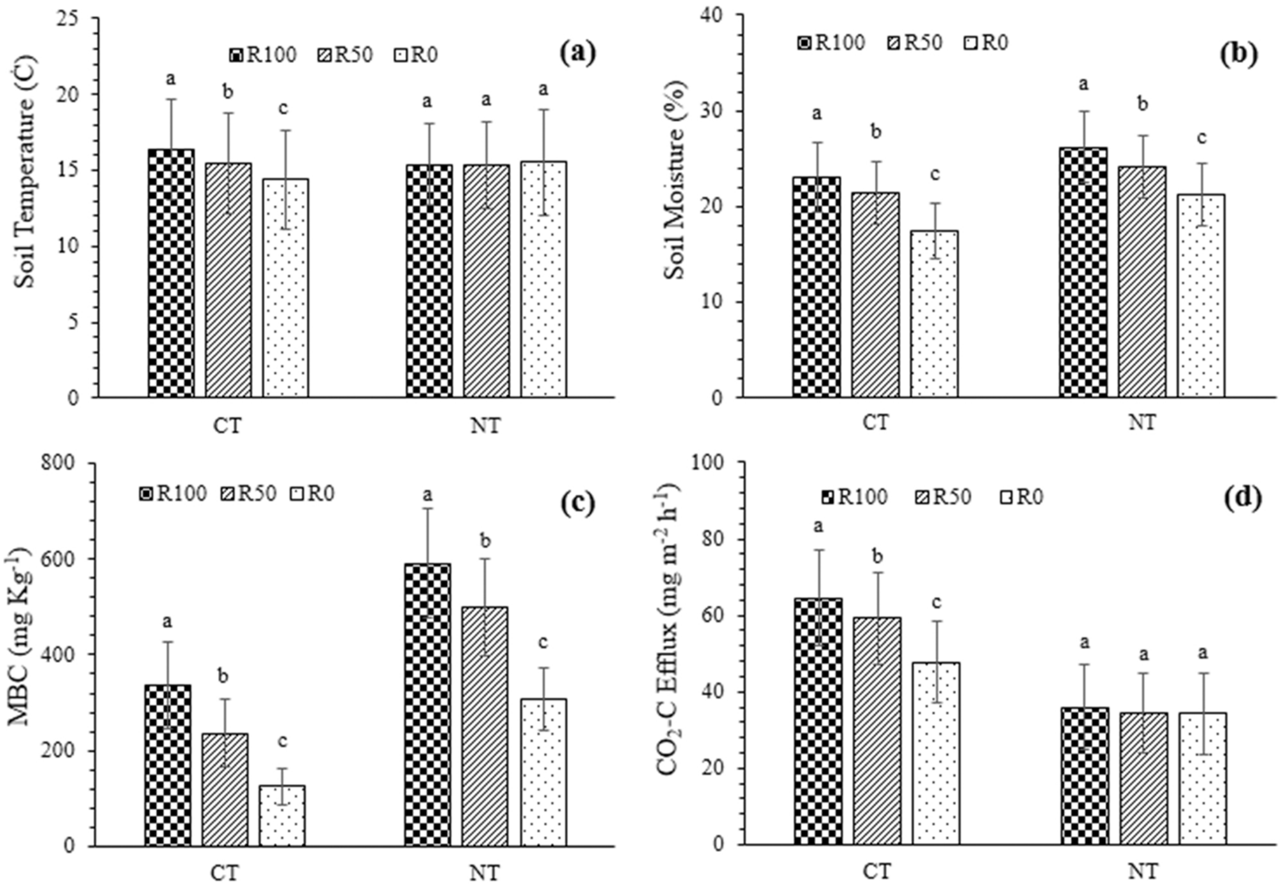

Fig. 5. The effect of crop residue rates on annual mean soil temperature (a) moisture (b), microbial biomass carbon (MBC) (c), and CO_2-C efflux (d) during corn-wheat rotation under conventional tillage (CT) and no-tillage (NT) systems. Means with the same letter are not significantly different. Bars represent standard error (n = 3).

soil water content (Sainju et al., 2012; Chalise et al., 2019) as well as other types of cover crops or mulches (Rodrigo-Comino et al., 2020b).

3.2. Soil microbial biomass carbon

There were significant differences for microbial biomass carbon (MBC) across all treatments of residue rates during the rotation cycle under both tillage systems (Fig. 4a,b). MBC was the highest in summer during the corn season; and declined during the cold season and again increased with rising soil temperature. In both CT and NT systems, MBC was positively correlated with the level of crop residue, i.e., the annual means of 335, 236, and 125 (mg kg^{-1}) in R_{100}, R_{50}, and R_0 under CT, and 590, 500, and 300 (mg kg^{-1}) for R_{100}, R_{50}, and R_0 under NT (Fig. 5c). The addition of N resulted in microbial growth, as measured by MBC, in both CT and NT, consistent with the literature (Stewart et al., 2018; Mgelwa et al., 2019). The soil microbial biomass pool is one of the biological properties that strongly regulates the dynamics of nutrients and C in soil (Toosi et al., 2012). It has also been shown that microbial biomass responds more rapidly to plant residue management compared to the total soil OM pool (Yang et al., 2012). Our findings are in line with previous studies, indicating that increasing the level of crop residues positively affects the MBC pool size (Chowdhury et al., 2015; Li et al., 2017). These could be due to the elevated MBC in soils covered by crop residue, namely enhanced soil moisture content, and also a supply of soluble C (and other nutrients) derived from the decomposing residue (Yang et al., 2012). The lower rate of MBC during the cold season could be attributed to the lower soil temperature during this period. A significant and positive correlation between soil temperature and MBC also confirms this (Table S1). Low soil temperature may limit soil microbial activity and their population. Temperature and moisture are the most important factors influencing soil microbial biomass (Babur and Dindaroglu, 2020).

3.3. CO_2 efflux

CO_2 efflux for all residue rates followed a similar pattern for all residue levels in both NT and CT (Fig. 6a,b). Higher soil CO_2 efflux during summer and spring is attributed to higher soil temperature (Fig. 2a,b), and as a result, enhanced biological (microbial, faunal, and root) activity. Seasonal fluctuations in soil temperature and their influence on CO_2 (and other GHGs) efflux from the soil are well documented (Schaufler et al., 2010).

The CO_2-C efflux rate decreased with increasing residue retention at all sampling dates during the corn season in summer (26/7/2018–4/10/2018) under the NT system, where soil respiration was significantly higher ($P < 0.05$) under R_0 than R_{100} and R_{50} treatments (Fig. 6a). A higher intensity of soil respiration in uncovered soil has also been reported previously (Guzman et al., 2015). A key reason for the significant increase in soil CO_2 efflux in R_0 compared to R_{100} and R_{50} treatments during the corn season under the NT system appears to be greater fluctuations in soil temperature (Fig. 2a,). A positive and significant correlation between soil temperature and CO_2 efflux also confirms this (Table 3). Soil temperature is the main factor influencing the emission of CO_2 from the soil (Dendooven et al., 2012). Yin et al. (2016) and Wegner et al. (2018) also reported a positive correlation between CO_2 emissions and soil temperature. In addition, another reason for the increasing CO_2 efflux in R_0 compared to R_{100} and R_{50} can be possibly attributed to the high C/N ratio (66) of wheat residues (Table 2) applied before the corn

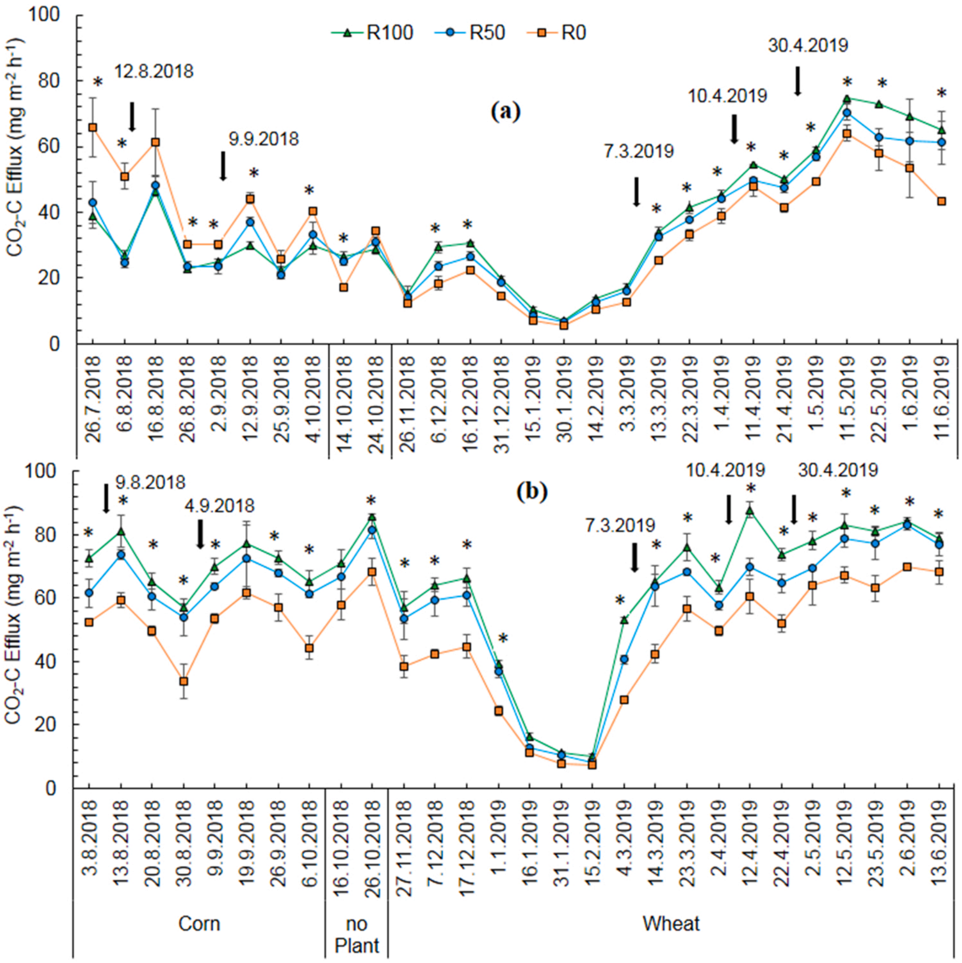

Fig. 6. Residue rate effect on daily soil CO_2-C efflux at the time of greenhouse gas measurement in corn-wheat rotation under no-tillage (NT) (a) and conventional tillage (CT) (b) systems. Bars represent standard error. The bold black arrows indicate fertilization events. An asterisk (*) shows a significant difference between residue levels within a day at $P < 0.05$.

growing season, which reduces the decomposition rate and release of CO_2. It has also been reported that the C/N ratio of an organic residue applied to the soil mostly determines the rate of its mineralization (Nguyen and Marschner, 2016).

When residue was added, there was no difference in soil respiration between R_{100} and R_{50}. In contrast, from the start of the wheat season until the end of the experiment, CO_2 efflux increased with an increasing residue retention rate at all sampling events compared to R_0. However, the differences among the residue treatments were not significant from early to late winter in 2019, which could be related to lower soil temperature and limited microbial activity and root respiration during this period. In the spring of 2019, significant increases ($P < 0.05$) were recorded for R_{100} and R_{50} compared to R_0 on several sampling dates, especially after urea fertilization events. A significant increase in CO_2 efflux after fertilization activities could be attributed to improved plant growth, photosynthesis, and respiration (Holou, 2010), stimulating and increasing the mineralization of crop residue (Dendooven et al., 2012; Sainju et al., 2012). In the CT system, the CO_2-C efflux rate increased with increasing residue rate, and these increases were significant ($P < 0.05$) at almost all sampling times in R_{100} and R_{50} treatments compared to R_0, but the significant differences ($P < 0.05$) between R_{100} and R_{50} treatments were only noticed in a few sampling dates, mainly after urea fertilization events in spring 2019, and for the most of the dates the differences were not significant (Fig. 6b).

The significant increase in CO_2 efflux in the R_{100} and R_{50} compared to the R_0, which was observed in both CT and NT during the spring, can be explained by a substantial input from decomposing residue that serves as a substrate for soil microbes (Toosi et al., 2017).

Several studies have reported that the incorporation of plant residue increases soil CO_2 emissions (Badía et al., 2013; Wang et al., 2019). Meanwhile, increased plant residue mineralization, soil organic carbon, microbial biomass carbon, and dissolved organic carbon accounted for increasing CO_2 emissions (Zhao et al., 2014; Ding et al., 2017; Yang et al., 2017). However, other studies reported reduced soil CO_2 emissions due to the retention of plant residue in the soil (Bai et al., 2017).

3.4. Cumulative CO_2 efflux

The annual cumulative efflux of CO_2-C did not differ significantly between residue rate treatments under the NT system. Still, the cumulative efflux of CO_2-C was higher ($p < 0.05$) in the CT system where R_{100} (4.65 Mg CO_2-C ha^{-1} y^{-1}) and R_{50} (4.26 Mg CO_2-C ha^{-1} y^{-1}) represented 36.5 % and 25 % greater cumulative CO_2-C efflux, respectively, than R_0 (3.4 Mg CO_2-C ha^{-1} y^{-1}) (Fig. 7). Similarly, Drury et al. (2021) reported that corn residue minimally affected CO_2 efflux in soils under the NT. Still, in the CT system, full retention of corn residue increased soil respiration up to 47 %. Contrasting results on the effect of residue in soil respiration (e.g., Wegner et al., 2018) are due to the complex interaction of different factors such as residue amount and quality, as well as soil and environmental conditions.

The strong positive relationship between cumulative CO_2 efflux and the crop residue ($R^2 = 0.96$ for CT and $R^2 = 0.9$ for NT) suggests the

Table 3
Correlations of CO_2 with selected soil properties for different rates of plant residues under conventional tillage (CT) and no-tillage (NT) systems.

Tillage system	Residue rate	Soil parameters	CO_2 emission	
			Pearson correlation (R)	P-value
CT	R100	Temperature	**0.61****	0.001
		Moisture	0.13	0.49
		Microbial biomass carbon	**0.68****	.000
	R50	Temperature	**0.49****	0.001
		Moisture	0.11	0.46
		Microbial biomass carbon	**0.69****	.000
	R0	Temperature	**0.60****	0.001
		Moisture	0.00	0.99
		Microbial biomass carbon	**0.78****	.000
NT	R100	Temperature	**0.46***	0.01
		Moisture	0.17	0.36
		Microbial biomass carbon	**0.66****	.000
	R50	Temperature	**0.43****	0.004
		Moisture	0.12	0.44
		Microbial biomass carbon	**0.70****	.000
	R0	Temperature	**0.79****	.000
		Moisture	0.06	0.73
		Microbial biomass carbon	**0.89****	.000

**. Correlation is significant at the 0.01 level.
*. Correlation is significant at the 0.05 level.

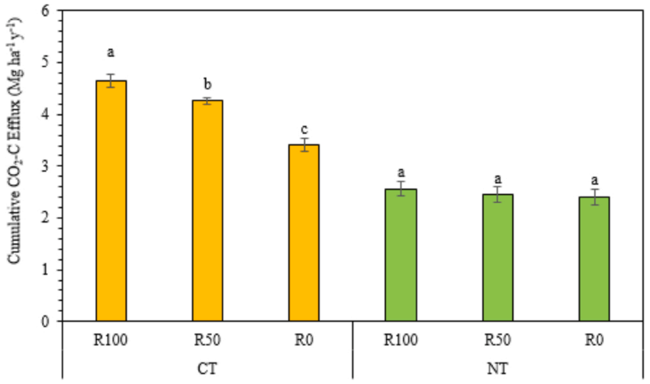

Fig. 7. Residue rate effect on annual cumulative CO_2-C (Mg ha^{-1} y^{-1}) efflux under no-tillage (NT) and conventional tillage (CT) systems. Means with different letters in each tillage system indicate significant differences ($P < 0.05$). Bars represent standard error ($n = 3$).

contribution of the plant residue to soil respiration (Fig. 8).

In the CT system, when calculated, an additional 1.25 Mg C ha^{-1} was respired from the R_{100} than from the no residue soil, equivalent to 43 % of the total (2.9 Mg C ha^{-1}) of the added residue (Table 4). For the R_{50}, this was equivalent to 59 % of the added residue (1.44 Mg C ha^{-1}). Under the NT system, these values were 5.5 %, and about 3 % of total C added from crop residue in R_{100} and R_{50}, respectively, compared to that respired from the no residue treatment. This indicates that under both CT and NT systems, there was C accumulation in the soil following the addition of crop residue. However, it has been well documented that in the long term, the vast majority of the added C from residue will respire to the atmosphere and only a small fraction of residual C will be incorporated into soil OM (Kuzyakov, 2006; Campos et al., 2011).

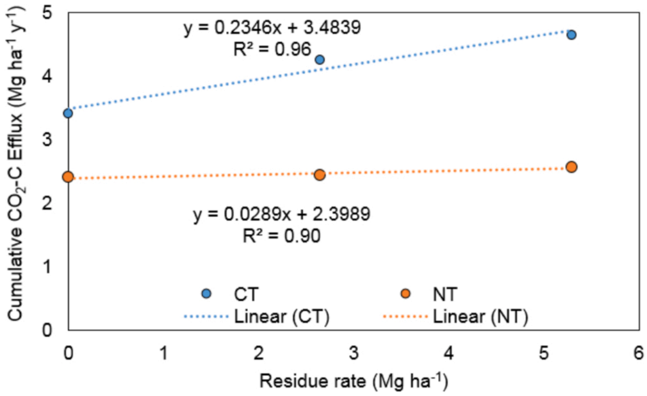

Fig. 8. Linear regression between residue rates and cumulative CO_2-C efflux per soil management system. CT: conventional tillage; NT: no-tillage. The points on each CT and NT line represent the annual cumulative CO_2-C efflux for different rates of residue (corn and wheat) during the whole corn-wheat rotation cycle.

Table 4
Crop residue carbon application rates (dry weight basis) in corn-wheat rotation under each conventional tillage (CT) and no-tillage (NT) system.

Crop residue rate (%)	Wheat residue (Mg C ha^{-1})	Corn residue (Mg C ha^{-1})	Total (Mg C ha^{-1})
100	[*]1.93	0.96	2.90
50	0.96	0.48	1.44
0	0	0	0

[*] Crop residue carbon application rates (dry weight basis) were based on crop yield and almost similar under both CT and NT systems.

Table 5
The effect of tillage on mean soil CO_2 emissions, soil temperature, soil moisture, microbial biomass carbon, and cumulative CO_2 emissions.

Tillage system	Mean CO_2 emissions (mg m^{-2} h^{-1})	Temperature (°C)	Moisture (%)	Microbial biomass carbon (mg kg^{-1})	Cumulative CO_2 emissions (Mg ha^{-1} y^{-1})
CT	[a]57.15 ± 12.36a	15.41 ± 3.30a	20.62 ± 3.52b	232.05 ± 85.80b	4.10 ± 0.55a
NT	34.86 ± 10.71b	15.40 ± 3.01a	23.89 ± 1.82a	465.96 ± 117.93a	2.47 ± 0.10b

Means with the same letter in each column are not significantly different.
[a] Mean ± standard deviation, n = 3.

3.5. The effect of tillage and interaction effects of residue rate and tillage system on soil properties (temperature, moisture, MBC), and CO_2 efflux

The effect of tillage and the interaction effects of residue rate and tillage system on soil temperature was not significant (Table 5 and Fig. 9a). More significant increases ($P < 0.05$) in mean and cumulative CO_2 efflux were observed in the CT system than in the NT system (Table 5). Soil moisture and microbial biomass carbon were significantly higher in the NT system compared to the CT system.

In addition, significant ($P < 0.05$) interaction effects of residue rate and tillage system were observed for soil moisture, soil microbial biomass carbon, and mean and cumulative CO_2 efflux (Fig. 9b–e). NT_{100} resulted in the highest values of soil moisture (26 %) and microbial biomass carbon (591 mg kg^{-1}) among the treatments, while the lowest value of soil moisture (17.5 %)) and microbial biomass carbon (124.5 mg kg^{-1}) were obtained from CT_0 (Fig. 9b,c). The highest values of mean CO_2 efflux (64.5 mg m^{-2} h^{-1}) and cumulative CO_2 efflux (4.65 Mg ha^{-1} y^{-1}) were observed in CT_{100} (Fig. 9d,e), whereas the

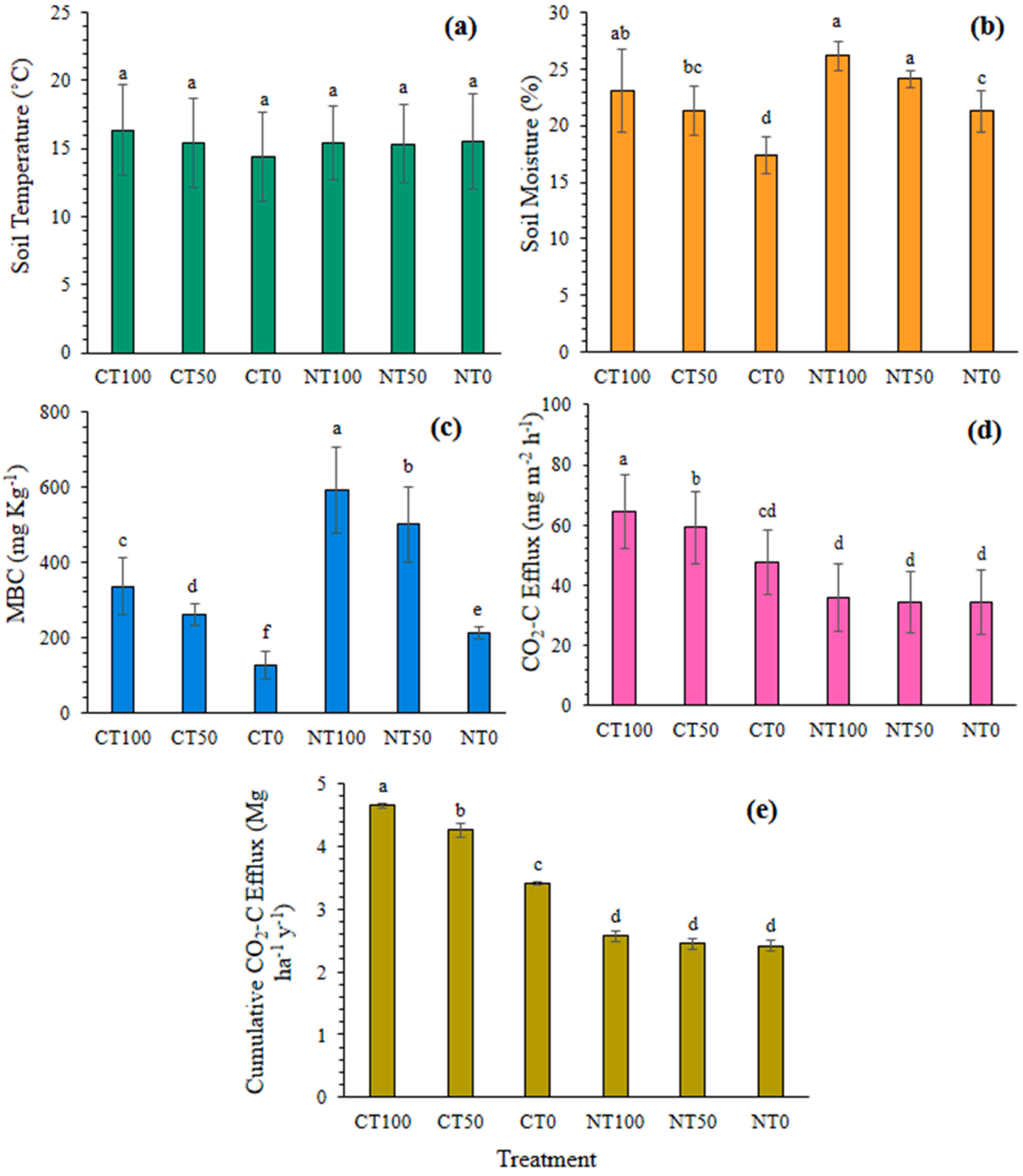

Fig. 9. The interaction effect of residue rate and tillage system on annual mean soil temperature (a), moisture (b), microbial biomass carbon (MBC) (c), CO_2-C efflux (d), and cumulative CO_2-C efflux (e). Means with the same letter are not significantly different. Bars represent standard error (n = 3).

lowest values of mean CO_2 emissions (34 mg m^{-2} h^{-1}) and cumulative CO2 efflux (2.4 Mg ha^{-1} y^{-1}) were found in NT_0 (Fig. 9d,e). Furthermore, no significant differences were found for cumulative CO_2 efflux among NT_{100}, NT_{50}, and NT_0 (Fig. 9e). In the NT system, during the corn cropping season CO_2 efflux was higher in the R_0 compared to R_{100} and R_{50}, while during the wheat season, a reverse trend was observed in which the rate of CO_2 efflux increased in R_{100} and R_{50} compared to R_0 (Fig. 6a). By considering the whole corn-wheat rotation, it is possible that these two different trends neutralized the effect of each other and led to no significant differences among the residue treatments. Also, under conservation tillage systems including the NT system, crop residue is not incorporated into the soil and they are not sufficiently fragmented and decomposed, which consequently reduces the real potential of crop residue management on CO_2 efflux. In agreement with our findings, Drury et al. (2021) reported no significant effect of different crop residue removal rates on CO_2 emissions under the NT system. Also, Teixeira et al. (2013) found no large differences in CO_2 emissions from plots with or without crop residues under rotary tillage.

There are several reasons for higher CO_2 efflux in the CT system than in the NT system. Tillage intensifies the oxidation of soil organic carbon and leads to the release of large amounts of carbon dioxide (La Scala Jr et al., 2006). Also, the incorporation of crop residue into the soil under conventional tillage practices accelerates the decomposition of crop residues (Lal, 2010). Furthermore, tillage operations break down soil aggregates and cause faster decomposition of soil OM (Mitchell et al., 2019). Reduction of tillage intensity using modern conservation tillage methods, including the no-tillage method, has positive effects on reducing soil organic matter mineralization and reducing CO_2 efflux (Snyder et al., 2009). Higher soil moisture and microbial biomass carbon in the NT system with full retention of crop residue (NT_{100}) could be related to the fact that NT accompanied by higher residue retention increases organic inputs into the soil and reduces soil disturbance, which consequently favors greater microbial biomass carbon and enzyme activities (Choudhary et al., 2018). Additionally, greater infiltration, reduced evaporation, and soil protection from rainfall impact can account for the highest soil moisture content under NT_{100} (Šarauskis et al., 2009).

4. Conclusions

In this study, the effect of crop residue at three rates - 100 %, 50 %, and no residue (0 %) - on soil CO_2 efflux under conventional and no-tillage systems was investigated. The results showed that soil CO_2 efflux was responsive to the application of residue mainly by alterations of soil temperature and microbial biomass carbon. Higher cumulative CO_2 efflux coincided with the addition of a higher crop residue rate under the CT system when R_{100} and R_{50} significantly increased the cumulative CO_2 efflux compared to R_0. Under the NT system, residue treatments had minimal impact on cumulative CO_2 efflux, and no significant differences were observed among residue treatments. Also, CO_2 efflux was significantly higher under the CT system compared to the NT system. Among the treatments, conventional tillage with the full incorporation of crop residue (CT_{100}) led to the highest amount of CO_2 efflux, while the lowest amount of CO_2 efflux was observed in no-tillage without residue (NT_0), but no significant differences were found between NT_{100}, NT_{50}, and NT_0.

In conclusion, the findings of this study show that in this region or similar semi-arid environments, the agricultural conservation practice of no-tillage with full retention of crop residue (100 %) is a potential tool for mitigating CO_2 emissions and, consequently, global warming. This research can contribute to soil conservation on a practical level, offering valuable information which can improve agricultural management, and hence the efficiency of food production. The achievement of these positive effects depends, however, on the incorporation of the results in strategies of territorial planning.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

We introduced “Funding for open access charge: Universidad de Granada / CBUA”. The authors greatly acknowledge Iran National Science Foundation (INSF) for financing this study.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.pedobi.2022.150819.

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