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Carbon and nitrogen mineralization kinetics as affected by tillage systems in a calcareous loam soil

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ABSTRACT

Tillage systems may affect soil carbon (C) and nitrogen (N) kinetics. However, the effects of tillage on C and N kinetics have not yet been studied for the major calcareous soils (Calcixerepts) from Iran. The aim of this study was to assess the effect of four tillage systems on soil C and N mineralization kinetics in a semi-arid loam soil after six years of two conventional tillage (CT) systems (moldboard plow, MP and disk plow, DP) and two reduced tillage (RT) systems (chisel plow, CP and rotary plow, RP) under similar plant residue inputs and cover crops in Shahrekord, Central Iran. We tested the hypothesis that soil C and N mineralization kinetic parameters are higher in RT than CT systems because of differential soil disturbance and mixing. Tillage systems were established in 2005 and, an experiment was arranged in a randomized complete block design with each tillage system replicated three times and sampled over three years (2008, 2009 and 2011). Soil samples (0–20 cm) were incubated (at 25 °C for 11 weeks) to measure the cumulative C and N mineralization throughout the incubation and to estimate the potentially mineralizable C (Co) and N (No), and the rate constants for labile C (k_C) and N (k_N) using the first-order kinetic single model. Soil C, N and particulate organic matter (POM) remained unaffected by tillage systems and thus these properties are not a sensitive indicator of changes in soil C and N contents. The cumulative C and N mineralization; and Co indicated the effect of tillage systems over the period of study. RT systems had lower soil cumulative C mineralization (20%), Co (17%) and k_C (10%) than CT systems. The cumulative N mineralization was also lower (23%) in RT (20.7-34.3 mg kg^{-1}) than CT (28.1-42.2 mg kg^{-1}), while No tended to increase only in RP (231 mg kg^{-1}) when compared with other tillage systems (151–177 mg kg^{-1}). The k_N was generally lower (33%) in RT (0.017 week^{-1}) than CT (0.024 week^{-1}). The initial potential rates of C (Co × k_C) or N (No × k_N) mineralization tended to be lower in RT and were found to be more suitable indicators to differentiate tillage effects. Differences in C and N mineralization among tillage systems were much larger in 2011 than 2008. The data rejected our hypothesis with regard to higher C and N mineralization kinetic parameters in RT systems with less soil disturbance. In conclusion, when crop residue is maintained, RT systems can protect the labile C pools and decrease the incorporation of crop residues into the soil matrix with a lower supply of mineralizable organic C and N for microbes under the studied environmental settings. Our findings indicate that soil C and N kinetic parameters might be a more sensitive indicator of tillage effects on C and N turnover than the whole soil organic matter (SOM) and POM fraction, with a potential consequence for the soil CO_2 emissions and N transformation rates.

1. Introduction

Soil fertility and crop productivity in arid and semi-arid areas are low, owing to inadequate soil organic matter (SOM) and plant-available nutrients, poor soil structure and low water availability (Raiesi, 2006; Moreno et al., 2006; Zarea, 2011). In addition to low net primary production and high SOM decomposition rates (Zarea, 2011), intensive tillage and cropping practices, when combined with removal of crop residues also decrease SOM concentration and aggregate stability and consequently the soil quality and fertility in semi-arid agroecosystems (Moreno et al., 2006; Madejón et al., 2007). Hence, identification of key and sensitive soil properties as early warnings is essential for monitoring soil degradation by intensive tillage and possible ecological restoration of soils in these regions of the world.

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Although the concentration of bulk SOM is an important indicator of soil quality for assessing tillage effects on soil fertility and productivity, the biologically active carbon (C) and nitrogen (N) fractions such as potentially mineralizable C and N as well as the cycling of N and C in soils are more sensitive to tillage and cropping practices than the whole SOM (Carter and Rennie, 1982; Simard et al., 1994; Balota et al., 2004). Mineralization of soil C and N is an indicator of microbial activity, and C and N cycling in the soil (Gregorich et al., 1997; Filip, 2002). Soil C and N mineralization is closely related to the size and composition of the microbial community, litter quality and quantity as well as other parameters including soil moisture, temperature, substrate placement and mixing (Beare et al., 1992; Gregorich et al., 1994; Gregorich et al., 1997), which are strongly affected by tillage systems (Franzluebbers and Arshad, 1997; Mikha et al., 2006; Sharifi et al., 2008; Laudicina et al., 2011; Guo et al., 2015).

Tillage systems modified C and N mineralization turnover in both short-term (Simard et al., 1994) and long-term (Carter and Rennie, 1982; Alvarez et al., 1995; Balota et al., 2004) experiments, as a consequence of their effect on the quantity and quality of organic residues, SOM concentration and availability, soil microbial biomass and activity, soil aggregation and environmental conditions. For example, excessive tillage can stimulate soil microbial activity and respiration (CO_2 release) mainly due to greater aeration and exposure of SOM to decomposing microorganisms (Kristensen et al., 2003; Bini et al., 2014), with an important consequence for both C and N cycling in the soil. However, different effects of tillage systems on SOM mineralization, and more generally on soil microbial activity, were observed in previous studies; with decreased (Laudicina et al., 2011; Bini et al., 2014), increased (Balota et al., 2004; Sharifi et al., 2008; Mikha et al., 2006; Wang et al., 2011) or no clear effect (Simard et al., 1994; Wright et al., 2005; Kristensen et al., 2003; Sharifi et al., 2008; Mijangos and Garbisu, 2010; Bini et al., 2014) on soil microbial respiration and N release rates in different conservation tillage (*i.e.*, minimum, reduced and no-tillage) systems.

The mathematical description of C and N mineralization kinetics is an interesting procedure to characterize SOM pools, predict the ability of soils to supply potentially mineralizable N and, more generally, estimate SOM balance (Campbell et al., 1991; Dou et al., 1996; Wang et al., 2003). Furthermore, potentially mineralizable organic C (Co) and N (No) are the labile components of SOM with a key role in short-term C and N turnover (Campbell et al., 1991; Saviozzi et al., 1993). However, the use of C and N mineralization kinetics as a tool to underscore and measure the effects of different tillage and management systems on soil C and N release is limited (Campbell et al., 1991; Saviozzi et al., 1993; Franzluebbers and Arshad, 1997; Liebig et al., 2004). Doran (1987) and Liebig et al. (2004) reported that the concentration of No in the top 7.5 cm layer was greater in conservation tillage than conventional tillage (CT) systems. Higher potentially mineralizable N and microbial biomass in conservation tillage was reported by other researchers (Carter and Rennie, 1982; Franzluebbers and Arshad, 1997) because of crop residue accumulation on the soil surface. In some studies, the positive effect of conservation tillage systems on C and N mineralization as well as their kinetic parameters was restricted only to the topsoil layer (Carter and Rennie, 1982; Doran, 1987; Alvarez et al., 1995; Liebig et al., 2004; Wright et al., 2005). In contrast, soil No was not affected by tillage systems in the 0–16 or 0–20 cm layers under temperate and humid climates in northern Spain (Mijangos and Garbisu, 2010).

Despite the inconsistent effect of tillage systems on SOM dynamics and turnover, there is still a great gap in our knowledge about changes in C and N cycling as well as the concentration of active SOM pools in conservation tillage systems. This is largely due to differences in climate, management history, soil type or the type, depth and frequency of tillage operations. In addition, there are no available data on the effect of tillage intensity and systems on C and N mineralization kinetics for the predominant calcareous soils (Calcixerepts) with low C concentration under semi-arid conditions in Central Iran. The main aim of this study was to quantify changes in soil C and N mineralization kinetic parameters (*i.e.,* potentially mineralizable C and N as active fractions of soil organic C and N) in reduced tillage (RT) systems by chisel and rotary plows compared with CT systems by moldboard and disk plows under similar plant residue inputs and cover crops, using a first-order kinetic model, in a Calcixerepts soil from Central Iran. It is hypothesized that soil C and N mineralization kinetic parameters (*i.e.,* potentially mineralizable C and N, and mineralization rate constants) are higher in RT than CT systems due to differential soil disturbance and mixing of soil and residue.

2. Materials and methods

2.1. Site and experiment description

The experiment was established in 2005 at the Agricultural Research Station of Shahrekord University, Iran. Further information on the study location and a detailed description of the experimental set-up and treatments were provided by Kabiri (2014). The soil type is a Haplic Calcisols (FAO) or mesic Typic Calcixerepts (Soil Survey Staff, 2010) with a loamy texture (sand 290, silt 450 and clay 260 $g\,kg^{-1}$) (Kabiri, 2014). Three composite soil samples were collected randomly from the 0–20 cm depth to quantify the initial soil properties before tillage operations. The concentration of SOM was low (5.84 g organic C kg^{-1} and 0.49 g total N kg^{-1}) and the experimental site had not been cultivated for 5 years before the start of the experiment. Other soil characteristics were: pH 7.95, electrical conductivity 0.40 $dS\,m^{-1}$, $CaCO_3$ 350 $g\,kg^{-1}$, available phosphorus 12.2 $g\,kg^{-1}$ and available potassium 207 $g\,kg^{-1}$ (Kabiri et al., 2015). The experiment was organized in a randomized complete block design with four tillage systems and three sampling years (2008, 2009 and 2011). The tillage systems consisted of (1) moldboard plowing (MP, 18 cm tillage depth); (2) disk plowing (DP, 17 cm tillage depth); (3) chisel plowing (CP, 14 cm tillage depth) and (4) rotary plowing (RP, 10 cm tillage depth). Both MP and DP are inversion tillage systems and thus are considered as conventional tillage (CT), while CP and RP can be described as non-inversion systems and thus are considered as RT. Each tillage system was replicated three times (three blocks) using 4 m × 50 m plots. Clover (*Trifolium pratense* L.) and winter barely (*Hordeum vulgare* L.) were sown and rotated on an annual basis. The barley top residues (*ca.* 25–35%) were left and added to the soil surface after harvest in all the tillage systems. The clover residues were not harvested and fully added as green manure to the soil surface during tillage operations. Other agricultural management and practices were similar to those practiced by local farmers (Table 1).

2.2. Soil sampling and preparation

Composite soil samples were obtained in September–October 2008, 2009 and 2011 before tillage operations, using a flat-bladed stainless steel shovel. In each replicated plot, three individual soil samples (2 kg) at the 0–20 cm depth were collected and homogenized to make a composite sample (ca. 1 kg) for each replicate. Field-moist soil samples were crushed and sieved through a 2-mm screen to remove large plant material and stone fragments, and split into portions for analysis of C and N mineralization. Soil samples were kept in perforated plastic bags at 4 °C. Before measuring net C and N mineralization, field-moist samples were moistened to 70% water holding capacity (WHC) and pre-incubated in the dark

Table 1
Effect of tillage systems and sampling years on soil properties in the surface layer (0–20 cm) in a semi-arid loam soil (Calcixerepts) from Iran (Kabiri, 2014; Kabiri et al., 2015).

Soil attribute	Tillage system				Sampling year			
	Moldboard	Disk	Rotary	Chisel	2005*	2008	2009	2011
C ($g\,kg^{-1}$)	6.97a	6.93a	7.00a	7.18a	5.84	6.03c	7.37b	7.67a
N ($g\,kg^{-1}$)	0.75a	0.70a	0.65a	0.72a	0.49	0.53c	0.72b	0.88a
C/N	9.30a	9.90a	10.8a	9.96a	11.9	11.4a	10.3ab	8.02b
MBC ($mg\,kg^{-1}$)	109c	112c	133b	154a	83.0	101c	132b	148a
MBN ($mg\,kg^{-1}$)	12.7c	12.9c	13.7b	14.7a	8.50	10.1c	14.5a	15.9a
MBC/MBN	8.66c	8.65c	9.80b	10.5a	9.76	10.0a	9.05b	9.26b
MWD (mm)	0.504b	0.505b	0.510a	0.512a	0.498	0.504b	0.509a	0.511a

C, organic carbon; N, total nitrogen; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; MWD, mean weight diameter.
Mean values (n = 9 for tillage system and n = 12 for sampling year) followed by different letters are significantly different among tillage systems and sampling years at P < 0.05 as determined by Tukey's test.
* the year (2005) before the tillage treatments.

at room temperature for 3 days. This pre-incubation was needed as samples were collected from a dry area during late summer and early fall when the soil microbial communities were naturally exposed to high air temperatures (>28 °C) for several weeks before sampling. Under natural environmental conditions, surface soils of arid and semi-arid ecosystems can have water contents equal to or lower than the air-dried conditions (<3–5%) due to high temperatures in summer and early fall. Pre-incubating was thus required to minimize any possible effects of sampling time, soil temperature and water content of the field soils during sampling time (Broos et al., 2007) and to reduce the concentration of labile organic matter and to activate soil microbial communities.

2.3. Soil particulate organic matter

The particulate organic matter (POM) was measured according to the method described in Cambardella and Elliot (1992). Air-dried subsamples (25 g) were dispersed in 100 mL sodium hexametaphosphate ($5\,g\,L^{-1}$) and shaken for 16 h. The dispersed soil samples were passed through a 53 mm sieve to isolate the POM fraction. The floatable organic materials were collected, rinsed using distilled water and finally dried at 60 °C and weighed. Organic C in POM was determined using the wet oxidation method of Walkley and Black (Nelson and Sommers, 1982).

2.4. Soil C and N mineralization

Carbon mineralization or microbial CO_2-C production was measured in a laboratory incubation experiment for 11 weeks. Soil samples were placed into a 1 L plastic jar along with a scintillation vial containing 10 mL of 0.5 M NaOH to absorb the evolved CO_2. Jars were air-tightened and incubated in the dark under controlled conditions (70% WHC and 25 ± 1 °C). Alkali traps were replaced at weekly intervals. Carbon mineralization was determined as total CO_2 evolved by titrating alkali to a phenolphthalein endpoint with 0.25 M HCl (Alef and Nannipieri, 1995) and expressed as mg C kg^{-1} soil. Nitrogen mineralization was determined according to the method described by Raiesi (2012). Soil subsamples were incubated for 11 weeks at 25 ± 1 °C with optimal water content (70% WHC), extracted for 30 min with 50 mL of 0.5 M K_2SO_4 before (t = 0) and after incubation at weekly intervals, and the inorganic N (NH_4^+ and $NO_3\bullet$) concentrations were determined in the extracts colorimetrically (Alef and Nannipieri, 1995). Cumulative net C (Cm) or N (Nm) mineralization was calculated as the sum of mineralized C or N throughout the incubation. Total C (TCM) or N (TNM) mineralized is then the total concentration of cumulative net C or N mineralized throughout the incubation (*i.e.*, 77 days). Results were calculated on a 105 °C oven-dry weight basis.

2.5. C and N mineralization kinetics and labile pool

For C and N mineralization data, a single exponential model was used to determine the potentially mineralizable C and N or the concentration of labile C (Co) and N pool (No); and C and N mineralization rate (k) constants (Campbell et al., 1991; Dou et al., 1996; Wang et al., 2003):

$$\mathbf{X_m = X_o - X_o exp^{(-kt)}}$$

where, X_m is the cumulative concentration of net C or N mineralized after time t and it is expressed as mg kg^{-1} (dependent variable); t is the time from the start of incubation and it is expressed in weeks (independent variable); X_o is defined as the potentially mineralizable organic C or N pools at t = 0, and they are expressed as mg kg^{-1}; k is the rate constant or the potential turnover rate of soil labile C and N pools, and it is expressed in $week^{-1}$. Potential turnover time (week) was then calculated as the inverse of k value. Furthermore, the initial potential rate of C or N mineralization ($X_o \times k$, mg kg^{-1} $week^{-1}$) was calculated to indentify whether and how tillage systems affect soil organic C and N quality or availability (Campbell et al., 1991; Saviozzi et al., 1993).

2.6. Calculations and statistical analysis

Differences in C and N mineralization kinetic parameters among tillage systems and sampling years were analyzed using a mixed model and two-way analysis of variance (ANOVA) procedure. Before conducting ANOVA procedure, soil data were tested for normal distribution and variance homogeneity. To test the main effects and interactions of tillage system and sampling year, we used ANOVA procedure designed for experiments combined across multiple years with tillage system a fixed factor and sampling year as a random factor, using the sum-to-zero constraint for the expected mean squares (McIntosh, 1983). Means were separated by post-hoc Tukey HSD test when the ANOVA indicated treatment effects at $P \leq 0.05$. All statistical analyses were carried out using the Minitab 16 statistical software.

3. Results

3.1. Particulate organic matter

The concentration of soil POM (particle size: 2000–53 μm) ranged from $2.43 \pm 0.29\,g\,kg^{-1}$ in RT to $2.55 \pm 0.24\,g\,kg^{-1}$ in CT, and was not affected by tillage treatment (P > 0.05, Fig. 1A) while this variable tended to increase over the experiment (P < 0.01, Fig. 1B). POM concentration was significantly greater in 2008 (1.66 $\pm 0.10\,g\,kg^{-1}$) than both 2009 and 2011 ($2.91 \pm 0.15\,g\,kg^{-1}$) but without significant difference between these two sampling years.

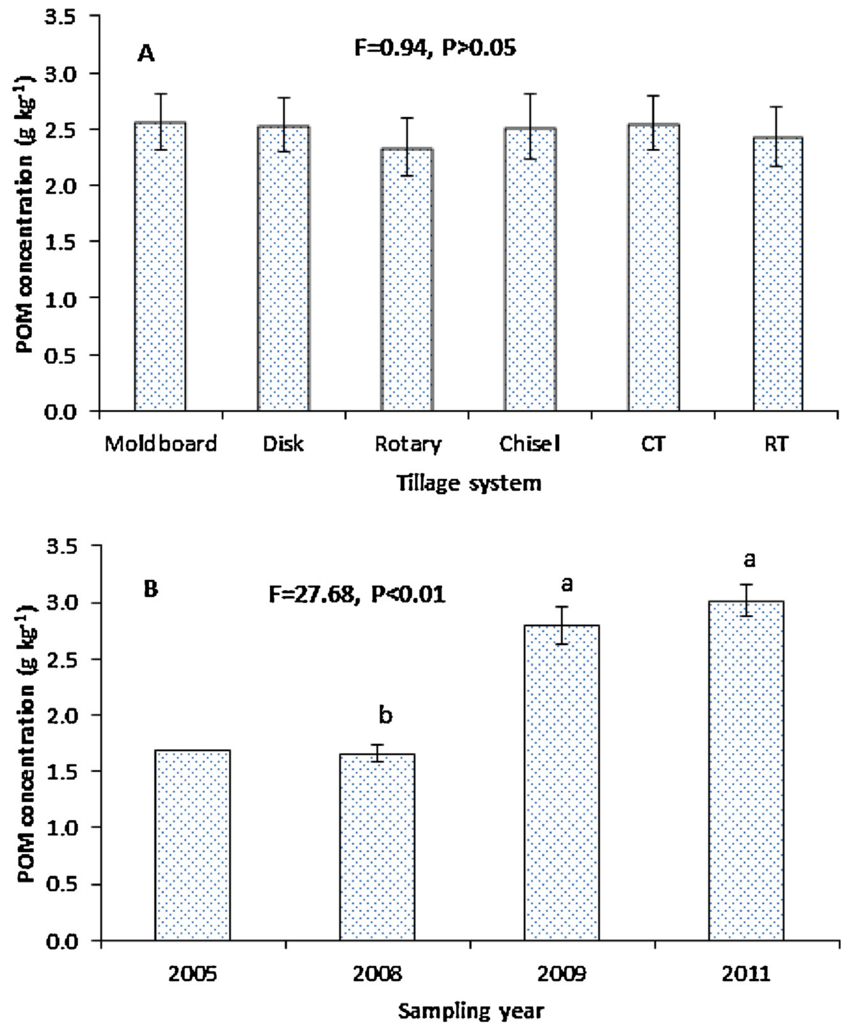

Fig. 1. The concentration of soil particulate organic matter (POM) in the surface layer (0–20 cm) in different tillage systems (A) and sampling years (B) in a semi-arid loam soil from Iran. Means (n = 9 for tillage system and n = 12 for sampling year) that do not share a letter are significantly different (P<0.05) according to Tukey's test. Bars represent standard errors of the mean (SEM).
CT, conventional tillage; RT, reduced tillage, 2005 is the year before the tillage treatments

3.2. C mineralization kinetics

The cumulative C mineralization (Cm) patterns of the incubated soils from tillage systems are presented in Fig. 2. The Cm was highest during the first 4 weeks of incubation for both tillage systems (Fig. 2), but the rates of increase in soil Cm tended to decrease subsequently. About 59–66% of the soil C was mineralized during the first 4 weeks of incubation when compared with that after 11 weeks. The Cm in RT soils (108–716 mg kg^{-1}) was generally lower than that in CT soils (142–911 mg kg^{-1}) throughout the incubation. These differences were more evident in 2009–2011 than 2008. The main and interactive effects of tillage regime and sampling year on the total C mineralized (TCM), the potentially mineralizable C (Co), and the initial potential rate of C mineralization (Co × k_C) were statistically significant (P < 0.001, Table 2).

At the end of the 77-day incubation, TCM was lower in RT (624–722 mg kg^{-1} or 1900–2240 kg ha^{-1}) than in CT (832–846 mg kg^{-1} or 2650–2700 kg ha^{-1}) soils when averaged across tillage years (Table 3). The TCM were lower in RP (14.6%) and CP (26.2%) than in both CT systems. Soils in RT had 16% lower TCM than those in CT in 2008, while the reduction of TCM was much higher (21%) in 2009–2011. After 11 weeks of the laboratory soil incubation, 8.7–12.1% of the initial soil organic C was mineral-

Table 2
Analysis of variance (ANOV) results (*F* values) showing the influence of tillage system with fixed effect and sampling year with random effect as independent variables on soil C and N kinetic parameters.

Soil variable	Year	Tillage	Year × Tillage
df	2	3	6
TCM	268.55 (40)***	37.18 (59)***	20.71(3.2) ***
Co	292.83 (45)***	28.92 (50)**	8.60 (3.5)***
k_C	84.36***	115.42***	0.61 ns
Co × k_C	222.31***	83.74***	16.91***
Co/TCM	82.56***	244.49***	0.17 ns
$1/k_C$	71.80***	538.43***	0.12 ns
TNM	360.75***	35.11***	22.92***
No	2.03 ns	66.52***	0.30 ns
k_N	10.80*	12.95**	1.46 ns
No × k_N	150.37***	24.21**	13.56***
No/TNM	37.55***	65.59***	0.53 ns
$1/k_N$	39.30***	54.30***	0.68 ns
TCM/TNM	20.93**	12.99**	2.02 ns
Co/No	11.03*	11.80**	1.21 ns

***, P < 0.001; **, P < 0.01; *, P < 0.05; ns, not significant.
TCM, total C mineralized; Co, potentially mineralizable organic C; k_C, rate constant for labile C; TNM, total N mineralized; No, potentially mineralizable organic N; k_N, rate constant for labile N.

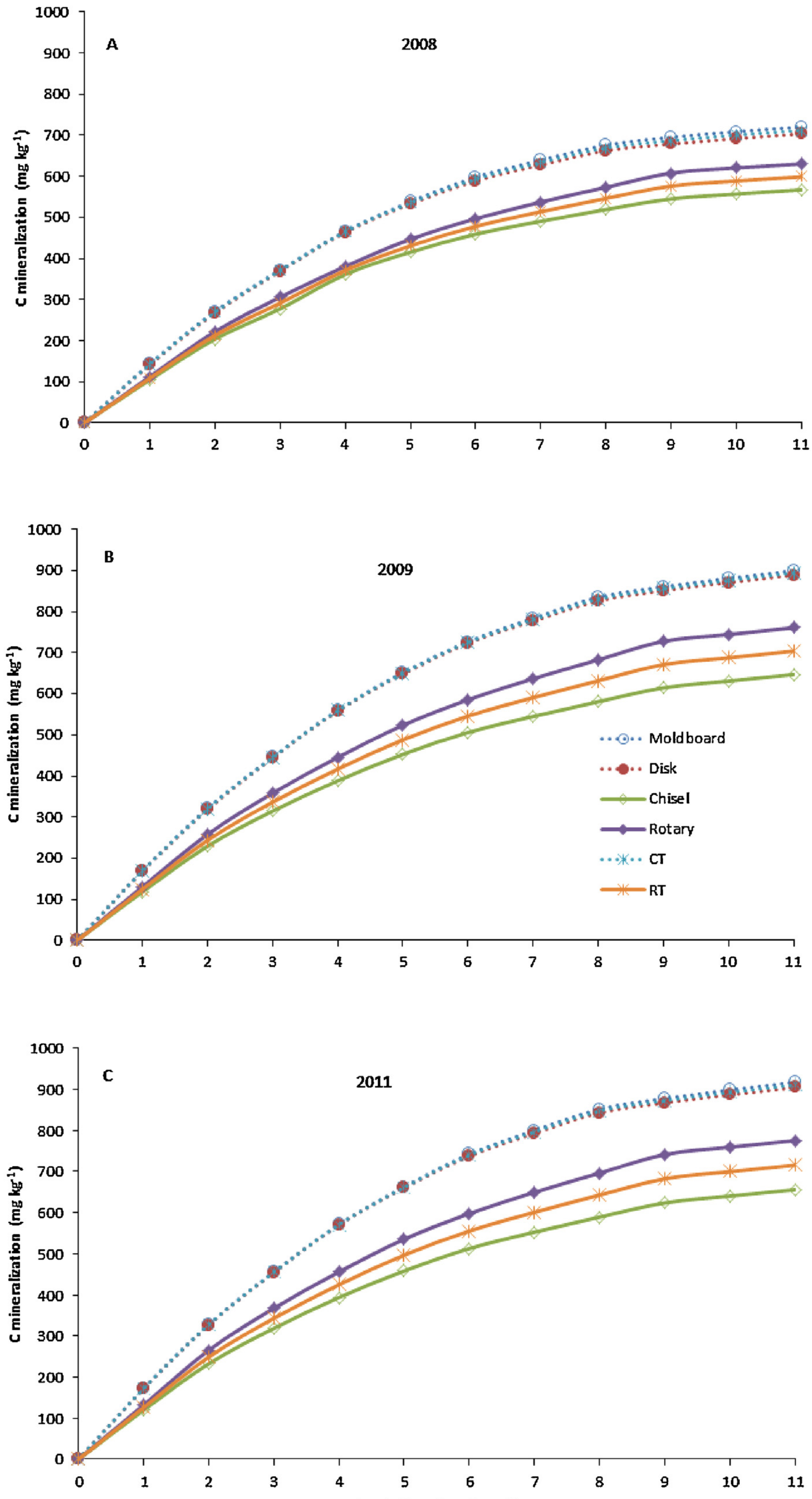

Fig. 2. The cumulative C mineralization in surface (0–20 cm) loam soils (Calcixerepts) sampled from different tillage systems over the experimental period (2008–2011) during 11 weeks of laboratory incubation at 25 °C. Each point represents mean (n = 3). CT, conventional tillage; RT, reduced tillage.

Table 3
Effect of tillage systems and sampling years on soil C and N kinetic parameters in the surface layer (0–20 cm) in a semi-arid loam soil (Calcixerepts) from Iran.

Year/tillage	TCM ($mg\,kg^{-1}$)	Co ($mg\,kg^{-1}$)	$Co \times k_C$ ($mg\,kg^{-1}$ $week^{-1}$)	$1/k_C$ (week)	TNM ($mg\,kg^{-1}$)	$No \times k_N$ ($mg\,kg^{-1}$ $week^{-1}$)
2008						
Moldboard	720(4.26)a	813(5.20)a	173(1.09)a	22.8(0.20)bc	28.5(0.36)a	2.97(0.03)a
Disk	703(4.04)a	788(6.93)ab	173(0.98)a	22.1(0.28)c	28.1(0.42)a	2.93(0.05)a
Rotary	630(7.57)b	747(11.8)b	134(1.30)b	27.0(0.58)a	24.2(0.45)b	2.38(0.06)b
Chisel	567(4.60)c	653(4.70)c	128(1.86)b	24.8(0.18)b	20.7(0.25)c	2.13(0.03)b
CT	712	801	173	22	28	3
RT	599	700	131	26	22	2
Change (%)	−16	−13	−24	15	−21	−24
2009						
Moldboard	900 (5.93)a	1040(12.9)a	202(2.03)a	25.0(0.42)b	39.2(0.31)a	4.39(0.05)a
Disk	889(2.09)a	1023(1.15)a	201(0.92)a	24.7(0.09)b	38.0(0.34)a	4.26(0.11)a
Rotary	761(14.3)b	923(25.3)b	153(0.31)b	29.2(0.76)a	32.0(0.25)b	3.30(0.03)b
Chisel	647(2.64)c	757(9.47)c	137(0.42)c	26.7(0.41)b	26.9(0.39)c	2.85(0.04)c
CT	894	1032	202	25	39	4
RT	704	840	145	28	29	3
Change (%)	−21	−19	−28	13	−24	−29
2011						
Moldboard	917(6.62)a	1061(7.62)a	206(2.16)a	25.0(0.36)ab	42.2(0.29)a	4.78(0.12)a
Disk	905(6.42)a	1040(11.3)a	206(1.36)a	24.4(0.41)b	40.7(0.83)a	4.59(0.18)a
Rotary	775(14.1)b	935(18.2)b	157(2.63)b	28.8(0.16)a	34.3(0.23)b	3.54(0.04)b
Chisel	656(8.56)c	769(14.3)c	139(1.32)c	26.9(0.53)a	27.6(0.46)c	2.93(0.07)c
CT	911	1050	206	25	41	5
RT	716	852	148	28	31	3
Change (%)	−21	−19	−28	13	−25	−31

Means (n = 3) ± SE followed by the same letter are not significantly different ($P > 0.05$) among tillage systems within each sampling year as determined by Tukey's test.
TCM, total C mineralized; Co, potentially mineralizable organic C; k_C, rate constant for labile C; TNM, total N mineralized; No, potentially mineralizable organic N; k_N, rate constant for labile N.
CT, conventional tillage; RT, reduced tillage.

ized and converted to CO_2 in all tillage systems (data not shown). On a C basis (C mineralization quotient or TCM/C), the cumulative C mineralized in soils in CT (on average 12%) was 14–27% greater than that in soils in RT (8.7-10.3%) systems.

Carbon mineralization (Cm) data were fitted using a single exponential model (Tables 3 and 4). The best fit for the C mineralization was described using the single-exponential model, as indicated by the high regression coefficients ($R^2 \geq 0.998$) and low standard error of estimate (SEE ≤ 11.7) (data not shown). The concentration of Co ranged from 726 to 971 $mg\,kg^{-1}$ soil among tillage systems and represented 10–14% (an average of 12.5%) of the soil organic C concentration. The Co generally followed a trend similar to TCM (Table 3). When averaged across tillage years, RT soils (726–868 $mg\,kg^{-1}$ or 2200–2700 $kg\,ha^{-1}$) had lower (17%) Co than CT soils (950–971 $mg\,kg^{-1}$ or 3020–3100 $kg\,ha^{-1}$) and these decreases were greater in 2008–2009 (19%) than 2008 (13%). However, Co did not differ between MP and DP systems while they were greater in RP than CP in all sampling years (Table 3). Soils in CT systems had a higher (12–27%) active fraction of organic C (Co/C ratio) when compared with those in RT systems (data not shown). The Co was always greater than the TCM in all soil samples after 11 weeks of incubation as indicated by Co/TCM ratios larger than 1 (Table 4), reflecting some of the C fraction was still available for further microbial mineralization. The largest Co/TCM ratio was observed in RP and the lowest in MP and DP treatments. The average rate constant (k_C) or decay rates for the labile C ranged from 0.20 $week^{-1}$ in CT soils to 0.18 $week^{-1}$ in RT soils (Table 3), which were statistically different between tillage systems and sampling years without an interaction between the two factors (Table 2). Similarly, the k_C was 10% lower in RT than CT soils, and they were higher (8%) in CP than RP systems without a difference between MP and DP systems (Table 4). The estimated k correspond to the potential turnover times ($1/k_C$) ranging from 5.0 weeks in both CT soils to 5.4 weeks in CP and 5.8 weeks in RP soils. The initial potential rate of C mineralization ($Co \times k_C$) varied considerably from 193 $mg\,kg^{-1}$ $week^{-1}$ in CT systems to 135–148 $mg\,kg^{-1}$ $week^{-1}$ in RT systems when averaged across tillage years (Table 4). RT soils indicated a significant decrease (20–48%) of the $Co \times k_C$ when compared with CT soils and this decrease was much larger in 2009–2011 (28%) than in 2008 (24%). Results showed that the TCM, Co, $Co \times k_C$ and Co/TCM increased while k_C tended to decrease over the experimental period when averaged across tillage systems (Tables 3 and 4).

3.3. N mineralization kinetics

The patterns of cumulative soil N mineralization (Nm) for tillage systems are shown in Fig. 3. In contrast to C mineralization, the Nm was highest during the first 6 weeks of incubation for both tillage systems (Fig. 3), but the rates of increase declined shortly. Almost 57–66-% of the soil N was mineralized during the first 6 weeks of incubation compared with that at the end of incubation. As with soil Cm, the Nm values in RT (1.4–31 $mg\,kg^{-1}$) were generally lower than those in CT (1.7–41 $mg\,kg^{-1}$) throughout the incubation and the decreases in Nm in RT were more striking (24–26%) during the later years of tillage operations (Fig. 3). There was a highly significant ($P < 0.001$) interaction effect of tillage system by sampling year on the total cumulative N mineralization or total N mineralized (TNM) over 77 days of soil incubation (Table 2). Table 3 presents mean TNM for each tillage system over the period of study. In agreement with faster soil C mineralization, TNM in RT soils were significantly ($P < 0.001$) lower in 2008 (21%) and 2009–2011 (24–25%) when compared with CT soils. TNM was significantly greater in RP (30.2 $mg\,kg^{-1}$ or 94 $kg\,ha^{-1}$) than CP (25.1 $mg\,kg^{-1}$ or 76 $kg\,ha^{-1}$) systems but without a significant difference between MP (36.6 $mg\,kg^{-1}$ or 117 $kg\,ha^{-1}$) and DP (35.6 $mg\,kg^{-1}$ or 133 $kg\,ha^{-1}$) systems. Averaged across sampling years, 5.1-5.3% of the initial N present (TNM/N) in CT soils was mineralized, whereas in RT soils 3.6-4.7% of the initial N was mineralized after 11 weeks (data not shown). There was a significantly lower TNM/N ratio in RT than CT systems.

As with C mineralization data, the cumulative soil N mineralization (Nm) data were fitted using a single exponential model

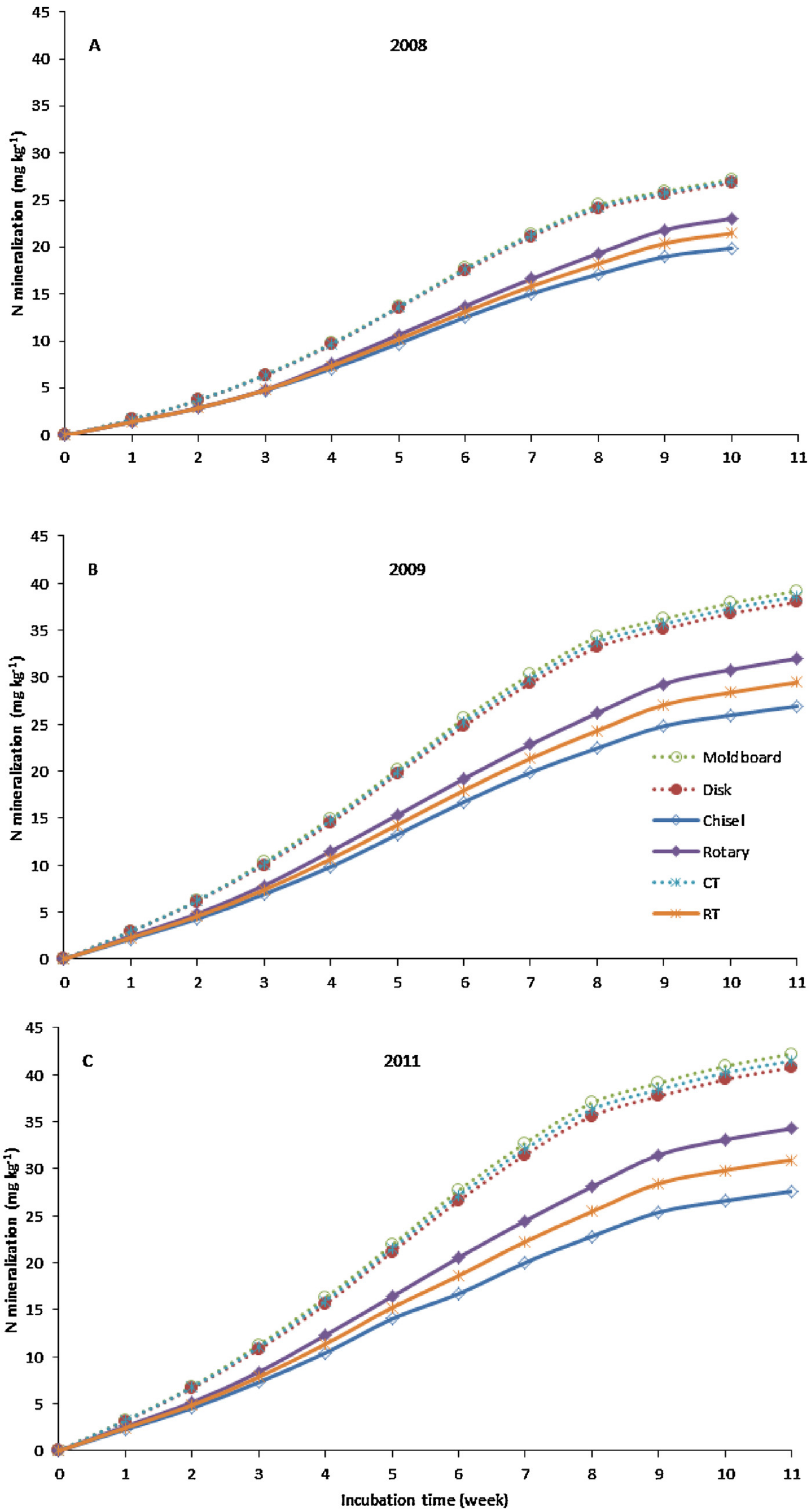

Fig. 3. The cumulative N mineralization in surface (0–20 cm) loam soils (Calcixerepts) sampled from different tillage systems over the experimental period (2008–2011) during 11 weeks of laboratory incubation at 25 °C. Each point represents mean (n = 3). CT, conventional tillage; RT, reduced tillage.

Table 4
Effect of tillage systems and sampling years on soil C and N kinetic parameters in the surface layer (0–20 cm) in a semi-arid loam soil (Calcixerepts) from Iran.

Tillage/year	k_C ($week^{-1}$)	Co/TCM	No ($mg\,kg^{-1}$)	k_N ($week^{-1}$)	No/TNM	$1/k_N$ (week)	TCM/TNM	Co/No
Moldboard	0.200 (0.0032) a	1.15 (0.0052) bc	177 (8.89)b	0.024 (0.003)a	5.02 (0.48)c	225 (24.8)c	23.3 (053)b	5.7 (0.46)a
Disk	0.205 (0.0031) a	1.14 (0.0053) c	174 (9.32) b	0.024 (0.003)a	5.08 (0.48)c	228 (24.7)c	23.6 (045)b	5.6 (0.49)a
Rotary	0.172 (0.0027) c	1.20 (0.0059) a	231 (7.98) a	0.014(0.001)b	7.86 (0.59)a	378 (32.1)a	24.2 (0.59)ab	3.8 (0.22)b
Chisel	0.186 (0.0028) b	1.16 (0.0049) b	151 (1.75) b	0.018 (0.001)b	6.12 (0.34)b	284 (17.6)b	25.1 (0.62)a	4.8 (0.15)a
CT	0.202	1.14	175	0.024	5.05	227	23.4	5.6
RT	0.180	1.18	191	0.016	6.98	331	24.6	4.3
2008	0.202 (0.0047) a	1.15 (0.0077) b	194 (9.95)a	0.014(0.001)b	7.73 (0.43)a	369(23.9)a	26.0 (0.36)a	3.9(0.15)b
2009	0.185 (0.0038) b	1.17 (0.0081) a	173 (10.1)a	0.022(0.002)a	5.21(0.36)b	235(18.7)b	23.6(0.20)b	5.5(0.43)a
2011	0.185 (0.0037) b	1.17 (0.0070) a	181 (11.9)a	0.023(0.002)a	5.13(0.39)b	231(20.5) b	22.6 (0.30)c	5.6(0.35)a

Means (n = 9 for tillage system and n = 12 for sampling year) ± SE followed by the same letter are not significantly different (P > 0.05) among tillage systems or sampling years as determined by Tukey's test.
TCM, total C mineralized; Co, potentially mineralizable organic C; k_C, rate constant for labile C; TNM, total N mineralized; No, potentially mineralizable organic N; k_N, rate constant for labile N.
CT, conventional tillage; RT, reduced tillage.

(Table 4). This model provided satisfactory fittings of the N mineralization data, as indicated by the high regression coefficients (R^2=0.990-0.994) and low standard error of estimate (SEE=1.03-1.89) (data not shown). The potentially mineralizable N (No) ranged from a minimum of 151 $mg\,kg^{-1}$ (457 $kg\,ha^{-1}$) in CP to a maximum of 231 $mg\,kg^{-1}$ (718 $kg\,ha^{-1}$) in RP systems, and was affected only by tillage system (Table 2). Although no clear trend was seen across the different tillage systems, RP soils showed greater No compared with other tillage systems (Table 4). For all tillage systems, the active fraction of organic N (No/N) ranged from 22 to 36% of total soil N, and this ratio was significantly higher in RP (36%) than other plowing systems (22–28%). As indicated by No/TNM ratios > 5 (Table 4), the cumulative mineral N released was always lower than the No in all the tillage systems, indicating some of the labile N fraction was still accessible for more microbial mineralization. The rate constant (k_N) for the labile N varied from an average of 0.024 $week^{-1}$ in both CT soils to an average of 0.016 $week^{-1}$ in both RT soils. The k_N were statistically affected by both tillage system and sampling year (Table 2) and tended to be lower in RT than CT soils with a significant difference between MP and DP or between RP and CP systems (Table 4). The estimated k corresponds to slow turnover times ($1/k_N$) of the labile N fraction, fluctuating from 46.7 weeks in CT soils to 58.5 weeks in CP and 78.0 weeks in RP soils. When averaged across tillage years, the initial potential rate of N mineralization ($No \times k_N$) varied from about 4 $mg\,kg^{-1}$ $week^{-1}$ in CT to about 2.8 $mg\,kg^{-1}$ $week^{-1}$ in RT, which was decreased by 23–34% in RT (Table 4). The decrease of $No \times k_N$ in RT systems was greater in 2009 (29%) and 2011 (31%) than 2008 (24%) sampling years (Table 3). Overall, the TNM, k_N and $No \times k_N$ were all greater in 2011 than 2008, while No/TNM showed a reverse trend (Tables 3 and 4). However, the effect of sampling year on No was not statistically significant (Table 2).

There was a statistically significant effect of tillage ($P < 0.05$) and sampling year ($P < 0.001$) on both TCM/TNM and Co/No ratios (Table 2). The highest and lowest TCM/TNM ratios were recorded in CP and MP soils, respectively, whilst the lowest Co/No was observed in RP and the highest in other tillage systems (Table 4). Furthermore, TCM/TNM ratios tended to decrease over the sampling years, whereas Co/No ratios indicated a reverse trend.

4. Discussion

4.1. Tillage effects on C and N mineralization

The objective of this research was to quantify the response of soil C and N mineralization and kinetics parameters to RT systems when compared with CT systems; and to test the hypothesis that soil C and N mineralization kinetic parameters would be higher in RT than CT systems. Results indicate that RT systems decreased net soil C and N mineralization when compared with CT, reflecting a reduced microbial activity and a lower turnover rate of organic matter with reduced intensity of tillage (*i.e.*, less soil disturbance and inversion) using both CP and RP systems. In other similar experiments performed under different climatic conditions, lower C and N mineralization and CO_2 emissions have also been found when soil management shifted from CT to conservation tillage (Mishra et al., 2010; Laudicina et al., 2011; Bini et al., 2014). Decreased soil C mineralization with RT is in line with the observed decrease of cumulative respiration (during 10 days of soil incubation) after 9 years of intensive tillage and with similar C inputs under Mediterranean conditions (Laudicina et al., 2011). Our results were further similar to those of Franzluebbers et al. (1995) who reported that C mineralization was lower in conservation tillage for the 0–20 cm depth than in CT soil. The concentration of soil mineralizable N at the 10–16 cm depth was greater in CT than conservation systems such as no-till after 2 years when organic input rate was identical for both tillage systems (Mijangos and Garbisu, 2010).

This study may indicate the supply of the readily mineralizable organic C and N (*i.e.*, substrate supply) for microbes would be the primary limiting factor for their activity throughout the incubation in RT soils; while C and N mineralization increases due to the high substrate availability in CT soils. Our previous finding (Kabiri et al., 2015) showed no significant changes in the concentrations of SOM (organic C and total N) and C/N ratios among the tillage systems, indicating that there were no differences in the quality and quantity of the bulk SOM. Furthermore, the concentration of soil POM, averaged 2.50 $g\,kg^{-1}$ or 20% of the total amount of SOM; was not affected by tillage treatments (Fig. 1). This result suggests that the POM fraction was not sensitive to the six years of tillage practices and soil disturbance in this study and that POM quantity is not an important determinant for C and N cycling under the studied settings. The lack of tillage impact on soil POM is primarily due to similar crop residue input rates and cover crop for all the tillage systems as this fraction of SOM consists mainly of fine root fragments and other organic debris at different phases of microbial decomposition (Cambardella and Elliot, 1992). Our finding is in contrast with previous studies that reported soil POM can serve as a sensitive indicator of changes in SOM because of its responsiveness to tillage (Mrabet et al., 2001; Liebig et al., 2004).

Reduced C and N mineralization observed in RT systems probably occurred as a combination of (1) lower availability and accessibility of labile substrate due to the physical protection of SOM following the formation of stable macroaggregates (Six et al., 2002a,b; Laudicina et al., 2011), (2) less incorporation and mixing of surface residues into a greater soil depth (Alvarez et al., 1995; Bini et al., 2014) and (3) changes in the microbial community composition (Beare et al., 1992; van Groenigen et al., 2010; Willekens et al., 2014).

The reduced microbial activity in RT can presumably be explained by the physical protection of SOM due to the formation of macroaggregates, which can lower SOM availability for microbial utilization and consequently C and N mineralization (Mishra et al., 2010; Laudicina et al., 2011). This is supported by tillage effects on soil aggregation and aggregate stability as measured by the mean weight diameter (MWD) index (Table 1). RT systems increased the MWD of the soil aggregates compared with CT systems (Kabiri et al., 2015; Table 1). An increase of soil MWD in RT systems is associated with an increase in the macroaggregate fraction and/or decreased microaggregates during tillage operations (Kabiri et al., 2015). SOM associated with macroaggregates is known to be more labile and easily decomposable than that associated with microaggregates (Mikha and Rice, 2004; Wright and Hons, 2005; Kahlon et al., 2013). There is evidence that microbial activity in RT is lower because of more SOM protection within and between macroaggregates or less SOM accessibility (Laudicina et al., 2011). Both soil aggregate stability and macroaggregate-protected SOM were found to increase with conservation tillage systems in the surface layer (Mikha and Rice, 2004; Kabiri et al., 2015). Lower C mineralization quotient (C mineralization per unit of organic C) in soils in RT than CT, again suggests decreased labile C availability or a slower labile C turnover in soils with minimal disturbance in RT systems. Apparently, RT soils with greater aggregation protected SOM against biochemical reactions and therefore a smaller concentration of labile SOM was potentially mineralizable.

Tillage systems may also affect the composition and biomass of soil microbial community (van Groenigen et al., 2010; Zhang et al., 2012; Willekens et al., 2014; Guo et al., 2015) with the subsequent change in C respiration and assimilation (Beare et al., 1992; Six et al., 2006). The concentrations of microbial biomass C and N, and microbial C/N ratios (MBC/MBN) were substantially greater in RT than CT soils (Table 1). A high MBC/MBN ratio indicates that the microbial biomass contains a higher proportion of fungi whereas a low ratio suggests that bacteria predominate in the microbial population (Horwath, 2007). It had been reported that CT favors more bacterial growth (low microbial C/N ratio) with lower C use efficiency and transformation of organic C into their biomass while conservation tillage systems (RT and no-till) favors more fungal growth (high microbial C/N ratio) with higher C use efficiency and less C loss (van Groenigen et al., 2010; Zhang et al., 2012; Willekens et al., 2014). Bacterial biomass was promoted by increasing tillage disturbance, while fungal biomass showed a negative response (Cookson et al., 2008). Furthermore, when plant residues are not incorporated completely into the soil by conservation tillage systems and not buried, fungal growth is dominated over bacterial growth as compared with full incorporation and burial and mixing of crop residues in CT (Beare et al., 1992). Thus, the predominance of fungal activity in RT may contribute to the formation of more humified SOM (Piovanelli et al., 2006) and total microbial biomass (Willekens et al., 2014; Guo et al., 2015) and less C respiration and cycling. However, further details of tillage system effects on the soil microbial community composition are required to understand the effect of RT on SOM decomposition and mineralization.

The ratio of mineralized C to mineralized N (TCM/TNM) characterizes a quality of substrate use (Burke et al., 1989) and is an index of N immobilization by soil microorganisms (Wood et al., 1990). High ratios indicate high immobilization rates relative to the concentration of C mineralized or N limitation for the soil microbial community (Burke et al., 1989; Wood et al., 1990). This ratio was greater in RT than CT soils, suggesting a stronger N than C limitation for microorganisms or more N immobilization in RT soils. This would mean a minor soil disturbance or greater tillage depth is needed for an increase of N cycling rate in these soils with poor structure and low SOM concentration.

Soil C mineralization increased over the sampling years. The increased soil C mineralization and microbial activity was most likely due to the annual addition of plant residues and consequently C availability (Table 1) for microbial oxidation during the experiment. This demonstrates that the annual addition of plant residues may enhance C mineralization in both conventionally and minimally tilled soils. Similarly, addition of crop residues to arid soils with low SOM content stimulated microbial respiration and C turnover (Raiesi, 2006).

4.2. Tillage effects on kinetic parameters

The parameters Co and No are measures of the active or labile organic C and N fractions, respectively, and have been widely considered as an estimate of soil C or N mineralization potential or index of soil N availability (Saviozzi et al., 1993; Wang et al., 2003; Curtin and Campbell, 2008). These parameters are usually used to determine the effects of agricultural practices and tillage systems on soil C sequestration, short-term nutrient turnover or fertility (Carter and Rennie, 1982; Saviozzi et al., 1993; Simard et al., 1994; Doyle et al., 2004). The concentration of No characterizes the highly labile and readily mineralizable fraction of total N in the soil (Campbell et al., 1991; Curtin and Campbell, 2008), and in fact represents a measure of N availability to plants (Campbell and Souster, 1982; Gregorich et al., 1994). The Co (653–1061 mg kg^{-1}) estimated with the first-order kinetic single model were in the range of Co reported by Raiesi (2004; 2006) for calcareous arable soils (400–1600 mg kg^{-1}) from Central Iran and by Carter and Rennie (1982) for soils in zero-tillage and CT systems (540–2160 mg kg^{-1}) from Canada. Likewise, estimates of No (151–231 mg kg^{-1}) were similar or close to previous estimates of No reported for semi-arid (Khorsandi and Nourbakhsh, 2008) and other (Carter and Rennie, 1982; Simard et al., 1994; Wang et al., 2003; Mikha et al., 2006) ecosystems. Estimated Co and No were observed to be greater than the measured total cumulative C and N mineralization, demonstrating the strength of the single model, since Co or No is theoretically the upper limit of C or N mineralization potential, and therefore it should be higher than the observed cumulative C or N mineralization at the last day of incubation (Dou et al., 1996). This indicates that some of the soil organic C fraction and a major fraction of organic N could still be accessible for more mineralization and assimilation. The k_C of 0.17–0.20 $week^{-1}$ is comparable to those reported by Raiesi (2004, 2006) for cultivated calcareous soils (0–30 cm) incubated at 25 °C for 40–60 days (0.10–0.43 $week^{-1}$) but higher than those reported by Liorente and Turrión (2010) for a cropland calcareous soil (0–20 cm) incubated at 28 °C for 98 days (0.10–0.43 $week^{-1}$). The estimated k_N (0.014–0.024 $week^{-1}$) were similar to the range reported by Mikha et al. (2006) for a silt loam soil at Kansas (0.018–0.039 $week^{-1}$), but were lower than what has been postulated for soils under different cultural and management practices (>0.097 $week^{-1}$) by Campbell et al. (1991) and soils in different tillage systems (0.070–0.15 $week^{-1}$) by Simard et al. (1994). Generally, differences in C and N kinetic parameters among the experiments can be attributed to differences in soil properties and environmental conditions, and more importantly the length and temperature of incubation, which are often varied among the studies (Dou et al., 1996; Wang et al., 2003).

The Co × k_C and No × k_N were found to be more suitable indicators to establish a direct link between SOM turnover and quality than individual parameters used separately (Campbell et al., 1991; Saviozzi et al., 1993), and for assessing the effects of agricultural management and practices on soil N dynamics (Campbell et al., 1991). Both parameters reflected changes in the soil C and N mineralization dynamics resulting from tillage operations more clearly than bulk C, N, POM or even No, and tended to be lower in RT. Similarly, the estimated No $\times$ k_N was found more sensitive to agricultural practices than TN, No and k_N (Campbell et al., 1991). Thus, RT systems had SOM concentrations similar to CT systems but a slow SOM mineralization and turnover, probably because of lower C and N availability. It is therefore suggested that when residue quality (*i.e.*, chemical composition) and quantity (*i.e.*, input rate) are similar, both Co $\times$ k_C and No $\times$ k_N parameters can also reflect changes in the availability of the labile C and N pools following different tillage systems.

5. Conclusions

Our results provided evidence that soil C and N cycling can be slowed down in RT systems after six years in Calcixerepts, rejecting the hypothesis that medium-term RT systems would result in higher microbial activity and higher Co and No concentrations than CT. However, these tillage effects on C and N dynamics did not change organic C and total N concentrations. Soil POM pool did not provide an early indication of changes in total soil C and N and their turnover under tillage systems. Differences in soil C and N mineralization kinetics in this study could be caused by differences in soil physical disruption and mixing due to tillage systems, and differences in the placement of plant roots and residues. Potentially active soil organic C and N are very sensitive to tillage systems in the study area, and are released under CT operations. We found that the differences in C and N kinetics among sampling years were as large as the differences among tillage systems.

Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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