Title: Effect of crop residue addition on soil organic carbon priming influenced by temperature and soil properties

Authors

Sangeeta Lenka[1]*, Pankaj Trivedi[2,3], Brajesh Singh[2,4], Bhupinder Pal Singh[5], Elise Pendall[2], Adrian Bass[2,6], Narendra Kumar Lenka[1]

Complete postal address(es) or affiliations

[1]Indian Institute of Soil Science, Nabibagh, Bhopal 462038, India

[2] Hawkesbury Institute for the Environment, Western Sydney University, Penrith, NSW 2570

[3]Bioagricultural Sciences and Pest Management, Colorado State University, Fort Collins, Colorado USA 80523

[4]Global Centre for Land-Based Innovation, Western Sydney University, Penrith, NSW 2570

[5]NSW Department of Primary Industries, Elizabeth Macarthur Agricultural Institute, Menangle, NSW 2568, Australia

[6]School of Geographic and Earth Sciences, University of Glasgow, University Avenue, Glasgow G12 8QQ.

***Corresponding author:** Sangeeta Lenka, ICAR-Indian Institute of Soil Science, Nabibagh, Bhopal 462038, India Email: sangeeta.lenka@icar.gov.in; sangeeta_2@rediffmail.com

Telephone: +91 755 2730946 fax: +91 755 2733310

Abstract

Priming of soil organic carbon (SOC) is a crucial factor in ecosystem carbon balance. Despite its increasing importance in the changing global climate, the extent of influence of temperature and soil properties on the priming effect remains unclear. Here, soil priming was investigated using ^{13}C labeled wheat residues in two cultivated subtropical soils of Australia (Vertisol and Luvisol) at four incubation temperatures (13, 23, 33 and 43°C). The priming effect was computed from respired CO_2 and associated $\delta^{13}C$, which were measured periodically over the 52-day incubation period. Wheat residue addition resulted in greater priming effect in the Luvisol (1.17 to 2.37% of SOC) than the Vertisol (0.02 to 1.56 % of SOC). The priming of SOC was the highest at 23°C in the Luvisol, and at 43°C in the Vertsiol, which indicates a variable positive priming effect of temperature in different soil types. Wheat residue addition significantly increased the temperature sensitivity (Q_{10}) of SOC mineralization in the Vertisol at temperature ranges below 33°C (i.e., 13-23 and 23-33°C) and had no significant effect in the Luvisol. A negative correlation was observed between temperature and the Q_{10} values. Across soils, the Q_{10} of residue C was lower than SOC suggesting that soil C is more vulnerable to climatic warming. This work demonstrates that the magnitude of SOC priming by wheat residue and Q_{10} of SOC mineralization varied significantly with soil type (Luvsiol > Vertisol) and incubation conditions (temperature and time). Given the current trend towards increasing atmospheric temperatures, future studies should evaluate temperature effects on the priming of different pools of SOC induced by crop residue in different agro-ecosystems.

Key words: SOC priming, Q_{10},^{13}C, Wheat residue, SOC mineralization, Temperature

1. Introduction

Understanding the potential impact of crop residue on soil organic carbon (SOC) storage is a key focus to understand the magnitude of current and future global changes in temperature (Fang et al., 2017; Lal, 2004; Thiessen et al., 2013). This is because crop residue is a significant source of external carbon (C) input, while concurrently impacting native SOC mineralization (Fang et al., 2018). Moreover, crop residue retention and application to soil is an integral component of sustainable and conservation agriculture worldwide (Campbell et al., 2001; Corsi et al., 2012; Lal and Kimble, 1997; Lenka et al., 2015)) with numerous benefits to soil properties, functioning and processes (Chen et al., 2014; Fang et al., 2018; Sarker et al., 2018; Singh et al., 2014). Directly, residues are the sources of energy and nutrients to the soil microbiome which may consequently affect SOC and residue C mineralization (Shahbaz et al., 2017a). Therefore, crop residue addition can either increase or decrease the mineralization of native SOC, termed the priming effect (Kuzyakov et al., 2000; Shahbaz et al., 2017b; Zhang et al., 2013). The priming effect of crop residue is hypothesized to be a function of abiotic factors including temperature and soil type (Blagodatskaya and Kuzyakov, 2011). While increasing the temperature can increase the mineralization of SOC in residue treated soil, the effect depends on the soil condition and properties (Fang et al., 2018).

Multiple studies have elucidated the effect of residue C on SOC mineralization rate using crop residues derived from various species (Guenet et al., 2010a; Liu et al., 2015; Mazzilli et al., 2014; Nottingham et al., 2009; Shahbaz et al., 2017b; Wang et al., 2015; Zhang et al., 2013) . However, SOC priming by crop residue as a function of temperature in different soils is still poorly understood. Crop residue input has been observed to result in both positive and negative priming effects. For example, negative priming could be the result of preferential residue C utilization over

SOC by the microbes that results in less SOC mineralization (Guenet et al., 2010a; Liu et al., 2015; Wang et al., 2015). Nevertheless, crop residue input generally results in positive priming of native SOC mineralization (Fang et al., 2018; Sarker et al., 2018; Shahbaz et al., 2017a; Wang et al., 2015; Zhang et al., 2013). The possible mechanisms for positive SOC priming suggested by previous studies include co-metabolism (Guenet et al., 2010b), preferential substrate utilization (Gontikaki et al., 2013), soil nutrient mining (Fang et al, 2018), shifts in microbial community structure that enhance native SOC mineralization (Fang et al., 2015), stimulation of microbial biomass and activity (Liang et al., 2017; Thiessen et al., 2013; Xiao et al., 2015), microbial necromass as a soil primer (Shahbaz et al., 2017b), and changes in production of extracellular enzymes (Blagodatskaya and Kuzyakov, 2008; Rousk et al., 2015).

The extent and direction of SOC priming have been shown to be controlled by temperature (Thiessen et al., 2013; Zhang et al., 2013; Fang et al., 2015). Generally, temperature changes the rates of enzyme reactions through influencing activation energy (Davidson and Janssens, 2006). Concurrently, temperature can directly affect microbial soil respiration (Curiel Yuste et al., 2007) or change microbial community structure (Biasi et al., 2005) through influencing microbial activity. Furthermore, temperature can affect microbial utilization of substrate C (Manzoni et al., 2012), and thus to influence SOC priming. Critical to improving our understanding is assessing the relationship of temperature on priming effects, an area where data is still scarce and consequently difficult to generalise (Zhang et al., 2013). For example, in a long-term incubation study, the addition of fresh plant materials increased the rate of SOC mineralization, with higher temperatures resulting in a similar effect (Thiessen et al., 2013). In another study, addition of ^{13}C-labeled glucose induced stronger priming at 25°C than at 15°C (Li et al., 2017). The potential effects of temperature on priming are likely to depend on substrate quality as well as soil type.

The extent and direction of priming by crop residue input have been shown to be influenced by variations in physical, chemical and/or biological properties of different soils, such as soil texture (Krull et al., 2001; Mtambanengwe et al., 2004; Razafimbelo et al., 2013; Xu et al., 2016), SOC content (Guenet et al., 2010b; Zhang et al., 2013), C:N ratio (Wang et al., 2016; Xu et al., 2016) and nutrient availability (Wang et al., 2016; Zhang et al., 2007). Mineralization of SOC and crop residue is generally slower in fine than in coarse textured soils (Hassink, 1992; Mtambanengwe et al., 2004; Sarker et al., 2018; Xu et al., 2016; Yadvinder-Singh et al., 2005), because clay can physically protect organic C in soil and may limit its microbial access (Hassink, 1992; Xu et al., 2016). Therefore, soil texture may attenuate the SOC and residue C mineralization in soils with high clay content. This concept contradicts the view of greater contribution of SOC content and C:N ratio on higher SOC priming (Wang et al., 2016; Zhang et al., 2013;). In fact, most previous studies have examined the priming effect of crop residues in one soil (Liu et al., 2015; Mazzilli et al., 2014; Shahbaz et al., 2017a; Thiessen et al., 2013; Wang et al., 2015; Zhang et al., 2013), thus making it difficult to compare the effect in different soils, particularly at different temperatures (Fang et al., 2018). Therefore, in this study, two contrasting cultivated soils (Vertisol and Luvisol) originating from subtropical (Vertisol) and semi-arid (Luvisol) regions were used to co-investigate the effect of crop residue in different soil types and at different temperatures on the priming of SOC.

Crop residue quality also influences temperature sensitivity (Q_{10}) of SOC mineralization (Dai et al., 2017; Karhu, 2010; Stewart et al., 2015). The temperature sensitivity of SOC mineralization is referred to as Q_{10} and is defined as the rate of change in soil respiration as measured by soil CO_2 emission with a 10°C increase in temperature (Karhu, 2010; Kirschbaum, 1995). Application of crop residues to the soil increased Q_{10} of SOC mineralization in some studies (Benbi and Khosa, 2014; Dai et al., 2017; Thiessen et al., 2013; Wetterstedt et al., 2010) and reduced it in others (Guixiang et al., 2016; Wang et al., 2016; Zhang et al., 2013), potentially reflecting preferential substrate C utilization during mineralization (Fierer et al., 2005; Hartley and Ineson, 2008; Leifeld and Fuhrer, 2005). Because quality and quantity of substrate C dictates the activation energy requirement of the decomposers and influences the Q_{10} of SOC mineralization (Davidson and Janssens, 2006; Thiessen et al., 2013). It is apparent that the interactions of residue C with incubation conditions like temperature and soil properties affect Q_{10} of SOC mineralization. Incubation of soils under controlled conditions using ^{13}C labeled substrate is the most widely used method for partitioning of the total respired CO_2 into C derived from crop residue and SOC (Thiessen et al., 2013). In this study, we hypothesized that (1) the higher temperature will accelerate positive priming of SOC by wheat residue, relative to lower temperatures, (2) the priming would be higher in a clay- and C-rich Vertisol compared to a clay- and C-poor Luvisol, and (3) the wheat residue application will increase the temperature sensitivity of SOC mineralization.

2. Materials and methods

To test whether crop residue addition in soil can affect priming on SOC at different temperatures and how these responses are modulated by soil types, we used a laboratory based soil incubation approach. In this study, we incorporated a ^{13}C labeled wheat residue with two contrasting soils (see below) from two separate long-term experiments in Australia (Sarker et al., 2018; Trivedi et al., 2017) at four temperatures (13, 23, 33 and 43°C). These temperatures were selected because aboveground mean annual maximum and minimum surface temperatures may reach above 30°C and below 15°C in sub-tropical and semi-arid regions during different crop growing seasons (Zimmermann et al., 2012). We partitioned different C sources in the CO_2 derived from the added wheat residue C and native SOC using a two-pool C isotopic model (Balesdent and Mariotti, 1996).

2.1. Study site and soil sample preparation

The soils used for the incubation study were from a Luvisol and a Vertisol of Australia. The Vertisol (clayey soil) was collected in November 2014 from a 46-year-old field trial conventional tillage, stubble retained and nitrogen fertilized (90 kg N ha^{-1} yr^{-1}) under a continuous wheat cropping system at the Hermitage Research Station (28°12'S, 152°06'E), Queensland (QLD). The native vegetation in this soil type before the cropping system trial was a predominately C_4 grass vegetation, while C_3 vegetation, mostly wheat crops, has contributed to SOC at this site, resulting in a mixed C_3–C_4 value of SOC, i.e. -19.05‰ (Table 1). A detailed description of the Hermitage trial site is given in Dalal et al. (2011). The Luvisol (sandy clay loam soil) was collected in April 2015 from a long-term conservation agriculture cropping system experiment established in 2007 at the Cunderdin College of Agriculture (117 °14'E, 31°38'S) in Western Australia. The site has predominately C_3 vegetation under a Mediterranean-type environment with a 20-year average rainfall of 300 mm. The Luvisol at the selected experimental plots received high C inputs (continuous cereals; no-tillage disc seeder) (Trivedi et al., 2017). A corer was used to randomly sample the soil (0-10 cm depth) from three replicated plots under a wheat rotation treatment. The three field replicates were taken as three replicated samples in the laboratory incubation experiment. Fresh soils were immediately transported to the laboratory. All visible roots and wheat residue materials were removed from the collected soil, and the samples were passed through a 2-mm sieve to remove larger wheat residue fragments and particles. Soils were stored at 4°C until further analysis. The concentration of C and N in the initial bulk soil and wheat residue was determined by an elemental analyzer (LECO TruMac CN-analyzer, Leco Corporation, USA). The $\delta^{13}C$ signatures of SOC and wheat residue were determined using a stable isotope ratio mass spectrometer (IRMS; Delta V, ThermoFinnigan). The physicochemical properties of the two soils and wheat residue are given in Table 1.

2.2.Production of ^{13}C-labeled wheat residue

The procedure for isotopically labelling wheat residue is outlined in Fang et al. (2016). Briefly, wheat was grown in a 2-hactare experimental plot located ~10 km east of Condobolin, New South Wales, Australia. At the heading growth stage (September 2015), a smaller micro-plot (1.8-m length × 2.0-m width; 8 wheat rows) was covered with a transparent chamber, constructed with 25 mm thick PVC tubing and 200 μm thick clear high density polyethylene sheet (Gro-tuff HDPE, 89% light transmission, Cheltenham, Victoria, Australia). The extra HDPE sheet was buried inside soil ditches (10-cm deep) and covered with moist soil to ensure good sealing of the chamber. The wheat plants inside the chamber were then pulse labelled with 10.0 l $^{13}CO_2$ (99.0 atom% ^{13}C, Cambridge Isotope Laboratories, Andover, MA, USA) (with ~ 300 to 3,000 μmol photons m^{-2} s^{-1} of maximum photosynthetic active radiation). The ^{13}C-labelled CO_2 was injected into the sealed chamber through a flow meter (S325-15-170-F/M CO_2, Influx Duff and Macintosh, Gascon

Systems, Sydney) at 300 to 500 cm^3 min^{-1}. The chamber air was circulated by two battery operated mini-fans. The chamber CO_2 concentration was monitored using a portable CO_2 probe (Vaisala GMP 343, Helsinki, Finland), which temporarily reached ~700-800 ppm and then decreased. Air temperature inside the chamber increased from 22.0 to 38.0°C within a few hours after the chamber closure and started to decrease after 4 pm. After injection of ^{13}C-labelled CO_2 at ~ 2 pm, the chambers were kept sealed for ~ 20 h to maximize uptake of overnight respired $^{13}CO_2$, and were opened after the night-accumulated CO_2 in the chamber decreased to < 200 ppm (~ 10 am). The wheat plants continued to grow in the field until they were harvested 50 days after pulse labelling. The plants were dried at 60°C. The wheat stem portion after removal of leaves was then separated from the whole plant and ground to <2 mm prior to incubation in the soils (Fang et al. 2016). Total C, total N, $\delta^{13}C$, and C:N ratio in the wheat stem are 46±0.071%, 0.54 ±0.001%, 583.58±15.054‰ and 85±0.099, respectively.

2.3. Incubation and sampling

The wheat residue (<2 mm) was thoroughly mixed with each of the two soils (<2 mm) and homogenized prior to incubation. Briefly, the treatment consisted of: (a) 20 g of each of two soils (dry weight basis) treated with 4.55 mg g^{-1} soil ^{13}C labelled ground wheat stem residue corresponding to 5 t/ha residue in 470 ml glass jars; and (b) 20 g soil (dry weight basis) without wheat stem residue (control). A blank glass jar without soil and residue was included for C isotopic mass correction and accounting for the atmospheric CO_2 concentration present in the headspace of the incubation jars. All treatments were replicated three times and incubated at four different temperatures, that is, 13, 23, 33 and 43°C. Soil moisture was adjusted to field capacity moisture content (-33 kPa pressure) at the start of the incubation and was maintained periodically throughout the experiment by weighing the jars and adding water to replace water lost to evaporation. After gas sampling, all bottles were opened for 20 min to refresh headspace oxygen and CO_2 and then resealed with the caps. Headspace gases were sampled at regular interval on fixed days (1, 3, 6, 9, 13, 17, 24, 31, 38, 45, and 52 days of incubation). The gas samples were drawn from the incubation jars using a syringe and immediately transferred to an evacuated gas vial. The unequal interval was designed to capture the asymptotic decrease commonly observed in incubation experiments (Townsend et al., 1997). Concentration of total headspace CO_2 was measured via gas chromatography (Agilent Technologies model 7890A). The C mineralization rate was calculated as the change in headspace CO_2 concentrations (µg C) per gram soil (dry wt. equivalent) per unit incubation time (day). Relative abundances of $^{13/12}CO_2$ were determined via Cavity Ring-down Spectrometry (CRDS) using a PICARRO G2201-*i* analyser with accuracy to ± 0.05% for CO_2 and 0.1‰ for ^{13}C-isotopic composition of CO_2.

2.4. Partitioning of CO_2-C from soil and wheat residue

The isotopic composition of control soil and residue treated soil was calculated using the chemical and isotopic mass balance equation (Mary et al., 1992) as given below:

Control soil

The respired CO_2 from the control soil jar without residue constitutes CO_2 originating from SOC mineralization and the blank atmospheric CO_2. The isotopic composition of the control soil δ_{cs} can be calculated as:

$$Q_{cs} = Q_{ts} - Q_{blank} \quad (1)$$

$$\delta_{cs} = \frac{Qts \times \delta ts - Qblank \times \delta blank}{Qcs} \quad (2)$$

where, Q_{cs} is the amount of CO_2-C derived from the soil and δ_{cs} is its isotopic composition; Q_{ts} is the total amount of CO_2-C in the soil and δ_{ts} is its isotopic composition; and Q_{blank} is the amount of CO_2-C in the blank jar, and δ_{blank} is its isotopic composition.

Residue treated soil

The respired CO_2 from the residue treated soil jar (Q_{rs}) constitutes CO_2 originating from mineralization of both SOC and residues and the blank atmospheric CO_2.

$$Q_{rs} = Q_{trs} - Q_{blank} \quad (3)$$

The isotopic composition of residue-treated soil (δ_{rs}) can be calculated as:

$$\delta_{rs} = \frac{Qtrs \times \delta trs - Qblank \times \delta blank}{Qrs} \quad (4)$$

where, Q_{rs} is the amount of CO_2-C derived from residue plus soil (after subtraction of the amount of CO_2-C in the blank jar) and δ_{rs} is its isotopic composition; and Q_{trs} is the total amount of CO_2-C from the soil plus residue, and δ_{trs} is its isotopic composition.

The proportion of residue derived CO_2-C (F_r) in the total CO_2-C evolved was determined using a two pool model as described by Balesdent and Mariotti (1996):

$$F_r = \frac{\delta rs - \delta cs}{\delta r - \delta cs} \quad (5)$$

$$F_s = 1 - F_r \quad (6)$$

$$Q_{res} = F_r \times Q_{rs} \quad (7)$$

$$Q_{soil\text{-}r} = F_s \times Q_{rs} \text{ or } Q_{rs} - Q_{res} \quad (8)$$

where, F_s is the proportion of soil derived CO_2-C, Q_{res} is C mineralized from residue in the soil, and $Q_{soil\text{-}r}$ is C mineralized from the soil treated with residue.

Priming effect

The priming of SOC induced by wheat residue (Q_{Pr}) was calculated as (Kuzyakov and Bol, 2006):

$$Q_{Pr} \text{ (Primed SOC by residue)} = Q_{soil\text{-}r} - Q_{cs} \quad (9)$$

where, $Q_{soil\text{-}r}$ is C mineralized from native soil after residue application and Q_{cs} is C mineralized from native soil without residue application.

2.5.Temperature sensitivity of mineralization rate (Q_{10})

The temperature sensitivity of soil respiration (denoted as Q_{10}) represents the difference in respiration over a 10°C interval measured during the incubation period for both temperatures. A time series of Q_{10} values for instantaneous mineralization rates of residue and soil C were determined by the following Q_{10} model (Kirschbaum, 1995):

$$Q_{10} = \frac{R_{tT2}}{R_{tT1}}^{\left(\frac{10}{T2-T1}\right)} \quad (10)$$

where, R_t is the C mineralization rate at incubation time t; and T_1 and T_2 are two different incubation temperatures.

2.6.Statistical analysis

All data were tested for normality and homogeneity of variance. Log-transformation was applied, if the transformation improved the normality and variance substantially. The data were statistically analyzed using SPSS software (version 21.0, SPSS Inc., Chicago, IL, USA); the significance level was set at P = 0.01. Repeated measures ANOVA was employed to determine the effects of sampling time, temperature and their interaction on observed properties viz., respiration rates, Q_{10} and cumulative respiration. Tukey's HSD multiple comparison method was used to compare the means. A two-way analysis of variance was performed for comparing the means of observed data among treatments. Pearson correlation was performed to test the relationship between priming and incubation temperature, temperature and Q_{10} of SOC mineralization.

3. Results

3.1. Soil and residue C mineralization

The SOC mineralization was significantly influenced by the interactive effects of residue, temperature, soil and time (Table S1). The cumulative SOC mineralization increased exponentially and levelled off as the incubation proceeded (Fig. S1). The cumulative native SOC and residue C mineralization (Fig. S1) increased in both soils as the incubation temperatures were increased. Wheat residue addition triggered the mineralization of native SOC to CO_2 in both soils, which was significantly greater at higher (43°C) than lower temperatures (13°C) (Fig. S1). However, residue addition at lower incubation temperatures (13 and 23°C) had no significant effect on mineralization of SOC in the Vertisol. The mineralization of residue C significantly ($p<0.01$) increased with incubation temperature (Fig. S1e and f) in each soil. The total residue C mineralization ranged from 754.1 to 1264.3 μg-CO_2-C g^{-1} soil in the Vertisol and 780.1 to 1274.2 μg-CO_2-C g^{-1} soil in the Luvisol. There was no difference in total residue C mineralization between the Vertsiol and the Luvisol.

The two soils differed in their C content therefore SOC mineralization was normalized by initial SOC content of the soils (Fig. 1a, b, c and d). For the control Vertisol, 1.3, 2.7, 3.6, 5.0 % of initial SOC was mineralized during the incubation at 13, 23, 33 and 43°C, respectively. The corresponding values for the Luvisol were 1.9, 4.9, 8.4 and 11.2 % (Fig. 1c and a). Residue addition caused a significant ($p<0.05$) increase in the total amount of mineralized CO_2-C from both soils, and the increase was higher for the Luvisol than the Vertisol. Similar to SOC, residue C mineralization was normalized by residue C (Fig. 1e and f). The soil had no significant effect on the proportion of cumulative residue C mineralization at all temperatures (Fig. 1e and f). The cumulative mineralization of residue C increased with increasing incubation temperatures till 43°C for the Luvisol, and remained constant after 33°C for the Vertisol.

3.2. Priming of SOC

Wheat residue addition significantly ($p<0.05$) primed mineralization of SOC in both soils at all incubation temperatures; however, the direction and magnitude of SOC priming changed over time (Fig. 2a and b). Though all soils experienced positive priming initially, negative priming was also observed (as reflected by a dip in the cumulative priming curve). Nevertheless, the net result was positive priming at all incubation temperatures. The shift from negative to positive priming occurred early at higher temperatures and later at lower temperatures. The magnitude of primed SOC during the incubation period was very low at 13°C (*cf*. 33 and 43°C), particularly for the Vertisol (Fig. 2). The total priming over the incubation period ranged from 112.9 to 229.6 μg C g^{-1} soil in the Luvisol, and from 4.1 to 316.6 μg C g^{-1} soil in the Vertisol. Like SOC mineralization, the cumulative primed soil CO_2-C was normalized by initial SOC and was expressed as percent of SOC primed which ranged from 0.02 to 2.4% across soils and temperatures (Fig. 2c). Wheat residue addition primed SOC mineralization, however the effect was different for the two soils. The normalized priming was greater for the Luvisol than the Vertisol, especially at the two lower temperatures (Fig. 2c). A significantly positive correlation ($p<0.01$) was observed between temperature and priming for the Vertisol, but no trend was observed for the Luvisol (Fig. 2c).

3.3. *Temperature sensitivity of SOC and wheat residue C mineralization (Q_{10})*

The main effects of temperature, soil type and the interaction effect of time, temperature and soil were significant on the Q_{10} of SOC mineralization in the control soils (Table S2). The average Q_{10} values of SOC mineralization ranged from 1.42 to 2.21 for the Luvisol and 1.41 to 1.75 for the Vertisol (Table 2). For the wheat residue treated soils, the Q_{10} of SOC mineralization was significantly influenced by temperature, soil, time of incubation and their interactive effect (Table S2). The average Q_{10} values of SOC mineralization in the residue treated soil ranged from 1.47 to 2.33 for the Luvisol and 1.44 to 2.41 for the Vertisol (Table 2). Residue application significantly increased the average Q_{10} values of SOC mineralization for the Vertisol at the 13-23 and 23-33°C ranges. However, the effect of residue was insignificant on the Q_{10} of SOC mineralization at 33-43°C for the Vertisol and for the Luvisol at all temperature ranges (Table S2). The Q_{10} values of SOC mineralization for the control and residue treated soil significantly decreased with increase in temperature from 13 to 43°C in both soils.

The Q_{10} of wheat residue C was significantly affected by the main and interactive effects of temperature, soil and incubation time (Table S2). The Q_{10} values of the wheat residue C mineralization were greater for the low temperature range (13-23°C) than the high temperature range (33-43°C). The average Q_{10} values ranged from 0.81 to 1.13 at 13-23°C and 1.53 to 1.66 at 33-43°C. The Q_{10} values of wheat residue C were significantly higher for the Luvisol than the Vertisol at 13-23 and 23-33°C. However, at 33-43°C, the Q_{10} values of wheat residue C mineralization was significantly greater for the Vertisol than the Luvisol. These results indicated that there was a negative correlation between temperature and Q_{10} of SOC mineralization and residue C mineralization.

The Q_{10} dynamics of SOC mineralization in the control Vertisol decreased from the first day of incubation to the 17^{th} day and increased afterwards until the end of incubation at the 13–23°C temperature range (Fig. 3). However, at 23–33 and 33–43°C, the Q_{10} values increased from the first day of incubation and decreased after the 13^{th} and 6^{th} day at 23–33 and 33–43°C, respectively**.** Similar variation of Q_{10} with incubation time was observed for the Luvisol. Temperature had significant effects on the Q_{10} values of SOC mineralization in the control and residue treated soils, and of residue-C mineralization at different time points of incubation. The Q_{10} variability of residue-C mineralization decreased with increasing incubation time.

4. Discussion

4.1. Soil organic C priming and mineralization

Our first hypothesis that wheat residue addition will accelerate positive priming of SOC at higher compared to lower temperatures was true for the Vertisol only. By contrast, for the Luvisol, the magnitude of positive priming decreased with increase in temperature above 23°C. It is known that the input of crop residues would likely to increase substrate availability, microbial growth and extracellular enzyme activities in both soils (Thiessen et al., 2013; Blagodatsky et al., 2010; Fang et al., 2018; Shahbaz et al., 2017b; Wutzler et al., 2008). However, the increased residue-induced positive priming from 13 to 43°C for the Vertsiol may be attributed to greater microbial growth and activity (Fang et al., 2018) and higher SOC content in the Vertisol than Luvisol (Table 1). This may have caused constant microbial accessibility and decomposability of relatively stable (resistant) SOC fractions induced by the residue input after the depletion of labile SOC in the Vertisol. A similar mechanism was also proposed by Kuzyakov (2010), who predicted that incubation temperature may mediate SOC priming, for example, increasing temperature can accelerate most enzyme activities, thus increasing SOC mineralization (Thiessen et al., 2013). Furthermore, low temperatures could retard soil microbial activity, as evident from the significantly lower cumulative CO_2-C mineralization at 13°C relative to the higher temperatures in both soils (Fig. S1). This suggests that due to the retarded microbial activity at low temperatures, soil microbes may not be able to decompose resistant SOC fractions, such as in the Vertisol, thus decreasing positive SOC priming (Kuzyakov, 2010; Thiessen et al., 2013). On the other hand, for the Luvisol, the decrease in positive priming with increasing temperature was possibly due to high cumulative SOC mineralization in both control (without residue) and residue treated Luvisol for the temperatures >23°C (Fig. S1). This indicates an equivalent accessibility and decomposability of stable SOC fractions in the Luvisol induced by the increasing temperatures with or without the input of residues. A similar observation of higher priming effect below 20°C than above 20°C was reported by Zhang et al. (2013) and Kuzyakov (2010). Another potential explanation could be a quick loss of labile C above 23°C during the first day of incubation (Fig. 1). The first 1 % of initial SOC is assumed to be labile C across all incubation temperatures (Conant et al., 2008). At temperature >23 °C, the loss of labile SOC during the initial phase of residue mineralization could have changed the soil microbial biomass stoichiometry (C:N), because residue retention is known to increase microbial N content *via* the residue induced microbial N immobilization (Wang et al., 2018). It seems that all these above mentioned soil microbial processes may have occurred rapidly in the Luvisol (*cf*. Vertisol). Thus, we assume that preferential microbial substrate utilization (Blagodatskaya and Kuzyakov, 2011; Shahbaz et al., 2017b; Thiessen et al., 2013) and changes in microbial community structure (Anderson et al., 2011) may have decreased SOC priming by the residues at temperature above 23°C in the Luvisol. The microbial enzyme activities may also shift to degrade relatively resistant C (Zimmermann et al., 2012). Such potential shifts in microbial communities and their enzymes to degrade the relatively resistant SOC may have contributed to the change in the magnitude of native SOC priming by wheat residue with increasing temperature.

In this study, we observed a switch from positive to negative priming and then again positive across incubation temperatures in both soils. The initial positive priming may be attributed to growth of r-strategists that respond quickly to newly available C sources (Kuzyakov et al., 2000; Kuzyakov, 2010; Fang et al., 2018), while mineralizing labile pools of residue C and SOC. The switch from positive to negative priming observed in some treatments during the intensive phase of residue mineralization could be ascribed to preferential utilization of easily available residue-derived C compared to native SOC (Blagodatsky et al., 2010; Thiessen et al., 2013; Shahbaz et al., 2017a). Further, in later stages, K-strategists may predominate, and are likely to co-metabolize resistant SOC fractions (Wu et al., 1993; Kuzyakov, 2010). The decline in microbial biomass after the initial phase of rapid residue mineralization results in accumulation of microbial necromass which would act as a soil primer to induce native SOC mineralization (Kallenbach et al., 2016; Rousk et al., 2015; Shahbaz et al., 2017b).

To study the effect of different soil properties on priming, our second hypothesis was that priming would be higher in the Vertisol compared to the Luvisol because the Vertsiol has higher SOC and clay content than the Luvisol. However, our results differed from our hypothesis because the priming was higher for the Luvisol than the Vertisol. According to Zhang et al. (2013), the difference in properties of the two soils, for example, the nature of organic-clay mineral complexation, texture, clay content and C:N ratio could be the probable reason for the different magnitude of SOC priming. Previous studies have suggested that higher stabilization of SOC through organo-mineral associations in a smectite clay-rich soil would limit the accessibility of SOC to microorganisms (von Lützow and Kögel-Knabner, 2009; Fang et al., 2014). This can be a more important mechanism for lowering the residue induced priming of SOC for the Vertisol than Luvisol. This corresponds to observations of Fang et al. (2015) where a biochar treated Inceptisol (sandy soil) had higher positive priming than a biochar treated Vertisol under similar temperatures. Therefore, our finding strongly indicates that the magnitude and direction of priming depends on incubation temperature and soil types.

4.2. Q_{10}

In this study, wheat residue addition significantly ($p<0.01$) increased the Q_{10} of SOC mineralization in the Vertisol, thus supporting our third hypothesis, although there was no difference in the Q_{10} between the control and residue treated Luvisol. This indicates that the Q_{10} of SOC mineralization in the residue treated soil was influenced by soil type, as reported previously (Dai et al., 2017; Wang et al., 2016). This different response may be attributed to differences in physico-chemical properties between the two soils, for example, C:N ratio, texture and pH (Table 1). The results from the Vertisol agree with observations of previous studies that suggested that the addition of a C substrate increased Q_{10} (Benbi and Khosa, 2014; Dai et al., 2017; Davidson and Janssens, 2006; Gershenson et al., 2009; Sandeep et al., 2016; von Lützow and Kögel-Knabner, 2009; Zhu and Cheng, 2011).

In the current study, addition of wheat residue increased SOC mineralization (Fig. S1) and this process may have enhanced the growth and activity of microbes and consequently immobilization of N (Giardina and Ryan, 2000; Wang et al., 2016). Furthermore, the increase in Michaelis-Menten parameter (Km) with a decrease in soil available nitrogen and immobilization (Eberwein et al., 2017) could have increased the Q_{10} values (German et al., 2012) for SOC mineralization in the residue treated Vertisol. Another probable mechanism could relate to the addition of low quality wheat residue (C:N = 85:1), which may increase the activation energy requirement for SOC mineralization with a corresponding increase for the Q_{10} values (Gershenson et al., 2009; Thiessen et al., 2013). However, our findings contradict the reports that addition of external organic inputs decreased Q_{10} of SOC mineralization (Wang et al., 2016).

In the control soil without residue addition, higher Q_{10} was observed in the Luvisol than Vertisol at temperature below 33°C. The Q_{10} of the control Vertisol was lower despite having higher SOC content and C:N ratio than the control Luvisol (Table 1). This could be probably due to higher SOC mineralization in the clay-poor Luvisol than the clay-rich Vertisol (Fig. S1). Soil texture is the primary driver for mineralization of SOC (Mtambanengwe et al., 2004; Xu et al., 2016). This could be because the higher specific surface area of clay minerals in the clay-rich Vertisol may physically and chemically protect SOC from microbial and enzymatic mineralization *via* organo-mineral interactions (Six et al., 2002; Xu et al., 2016).

The Q_{10} of SOC mineralization is significantly affected by temperature in both treated and control soils. A negative correlation was observed between Q_{10} and temperature. The greater temperature sensitivity of SOC mineralization at lower temperature range (13-23°C) than the higher temperature range (23-33 and 33-43°C) in our study is consistent with other studies (Bao et al., 2016; Benbi and Khosa, 2014; Gutinas et al., 2013; Karhu, 2010; Kirschbaum, 1995; Suseela et al., 2012). The decline in the Q_{10} of SOC mineralization with increase in temperature suggests that the stimulation effect of warming on SOC mineralization will be lower and can partly reduce C losses in these soils (Del Grosso et al., 2005). Therefore, this will result in a less positive feedback to climate change than previously expected for subtropical or semi-arid cultivated soils.

The Q_{10} values of control soils observed in our study, ranging from 2.57 to 1.29 (Luvisol) and 2.05 to 1.34 (Vertisol), agree with Q_{10} values reported by Fang et al. (2014) for similar soils in these regions. In the current study, a significant increase in Q_{10} with time was found at the lowest temperature range (13-23°C) in the residue treated and control soils. Our results partly agree with a previous incubation study that observed an increase in Q_{10} with time at both cold and warm temperatures (Thiessen et al., 2013). In the current study, the increase of Q_{10} values with time at low temperature could be the result of slow depletion of labile SOC and subsequent mineralization of resistant SOC fraction with higher activation energy and Q_{10} values at the later phase of incubation. Whereas, for temperatures above 23°C in the residue treated and control soils, the Q_{10}

dynamics either decreased or remained constant. Therefore, the trend of changes in Q_{10} dynamics seems to be influenced by incubation temperature and substrate quality (Curiel Yuste et al., 2007; Thiessen et al., 2013).

5. Summary

In conclusion, wheat residue addition increased the priming of SOC in two cultivated, subtropical or semi-arid, soils with contrasting organic C and clay contents. The magnitude of priming was higher for the low-C and clay-poor Luvisol than the high-C and clay-rich Vertisol at all temperatures, indicating that the Vertisol is more resistant to priming. On the other hand, the priming of SOC mineralization caused by wheat residue increased with temperature for the Vertisol but decreased with temperature for the Luvisol, which may be linked to the timing of microbial accessible resistant SOC fractions in the soils. Wheat residue addition significantly increased the Q_{10} of SOC mineralization at lower temperature ranges (13-23 and 23-33°C) for the Vertisol only. The significant negative correlation between Q_{10} and temperature for SOC and residue-C mineralization means a lower positive feedback response to climate change in high-C, smectite-rich soils relative to low-C kaolinitic soils.

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Table 1

Initial properties of the soils (0-10 cm) and wheat residue prior to the laboratory incubation. Standard error of mean (n=6) is shown in parenthesis.

	Luvisol	Vertisol	Wheat residue
TOC (%)	0.97 (±0.08)	2.03(±0.06)	*45.91(±0.2)
TN (%)	0.08 (±0.002)	0.15 (±0.003)	0.54 (±0.14)
C:N ratio	12	14	85
$\delta^{13}C$ (‰)	-25.48 (±0.74)	-19.05 (±0.17)	583.58 (±26.07)
Sand (%)	63 (±3.5)	11(±2)	
Silt (%)	12 (±2.3)	24 (±2.1)	
Clay (%)	25 (±1.2)	65 (±1.8)	
pH (1:2.5 water)	5.8 (±0.2)	7.0 (±0.3)	
B.D (Mg m^{-3})	1.3 (±0.3)	1.0 (±0.1)	

TOC: total organic carbon; TN: total nitrogen; C:N ratio: carbon to nitrogen ratio

*total carbon in wheat straw

Table 2

Averaged temperature sensitivity (Q_{10}) of SOC and residue-C mineralization over the incubation period of 52 days for the three temperature ranges. The number in parenthesis are the standard error of the mean (n=3).

	13-23°C	23-33°C	33-43°C
	SOC mineralization		
Luvisol			
Control	2.21 (±0.26)bA*	1.79 (±0.08)abA	1.42 (±0.06)aA
Treated	2.33 (±0.05)bA	1.51 (±0.03)aA	1.47 (±0.02)aA
Vertisol			
Control	1.75 (±0.01)cA	1.57 (±0.01)bA	1.41 (±0.02)aA
Treated	2.41 (±0.04)cB	2.04 (±0.01)bB	1.44 (±0.01)aA
	wheat residue-C mineralization		
Luvisol	1.66 (±0.01)cB	1.15 (±0.005)bB	0.81 (± 0.004)aB
Vertisol	1.53 (±0.01)bA	1.11 (±0.02)aA	1.11 (±0.01)aA

* Different lower case letters indicate significant differences between temperatures across each column; different upper case letters indicate significant differences between control and treated soil within rows for each soil type.

Table S1

Statistical significance (P values given) of the effects of incubation time, temperature, soil and their interactions on cumulative CO_2-C respired from SOC in control and treated soils, wheat residue-C and priming.

Source	Control SOC	Residue treated SOC	Residue-C	Priming
Time	0.0001	0.0001	0.0001	0.004
Temp	0.0001	0.0001	0.0001	0.025
Soil	0.0001	0.0001	ns	0.003
Time * Temp	0.0001	0.0001	0.0001	0.002
Time * Soil	0.0001	0.0001	0.0001	0.019
Temp * Soil	0.0001	0.0001	0.0001	0.005
Time * Temp * Soil	0.0001	0.0001	0.0001	0.018

ns, not significant

Table S2

Statistical significance (P values given) of the effects of incubation time, soil, temperature and their interactions on temperature sensitivity (Q_{10}) of SOC mineralization in control and treated soils and wheat residue-C.

Source	Q_{10} of SOC mineralization in control soil	Q_{10} of SOC mineralization in residue treated soil	Q_{10} Wheat residue C mineralization
Time	ns	0.0001	0.0001
Temp	0.001	0.0001	0.0001
Soil	0.030	0.011	0.001
Time * Temp	0.001	0.001	0.0001
Time * Soil	ns	0.005	0.001
Temp * Soil	ns	0.021	0.0001
Time * Temp * Soil	0.001	0.003	0.0001

ns, not significant

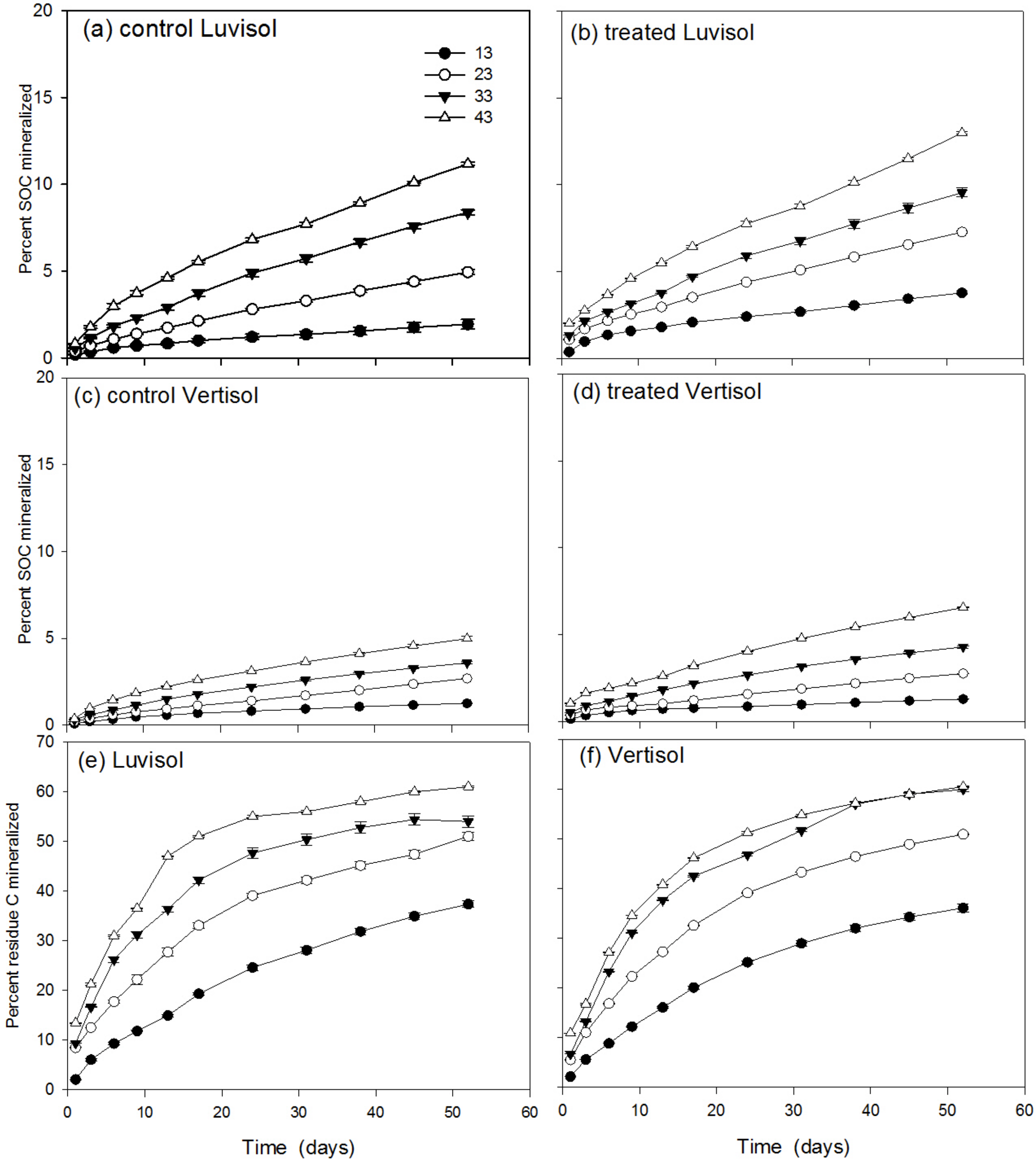

Fig. 1. Cumulative percent of SOC (a, b) and residue C (c) mineralized for the Vertisol and Luvisol during the whole incubation period for different incubation temperatures (13, 23, 33 and 43 °C). The plotted values are average of three replicates and standard errors are represented by error bars.

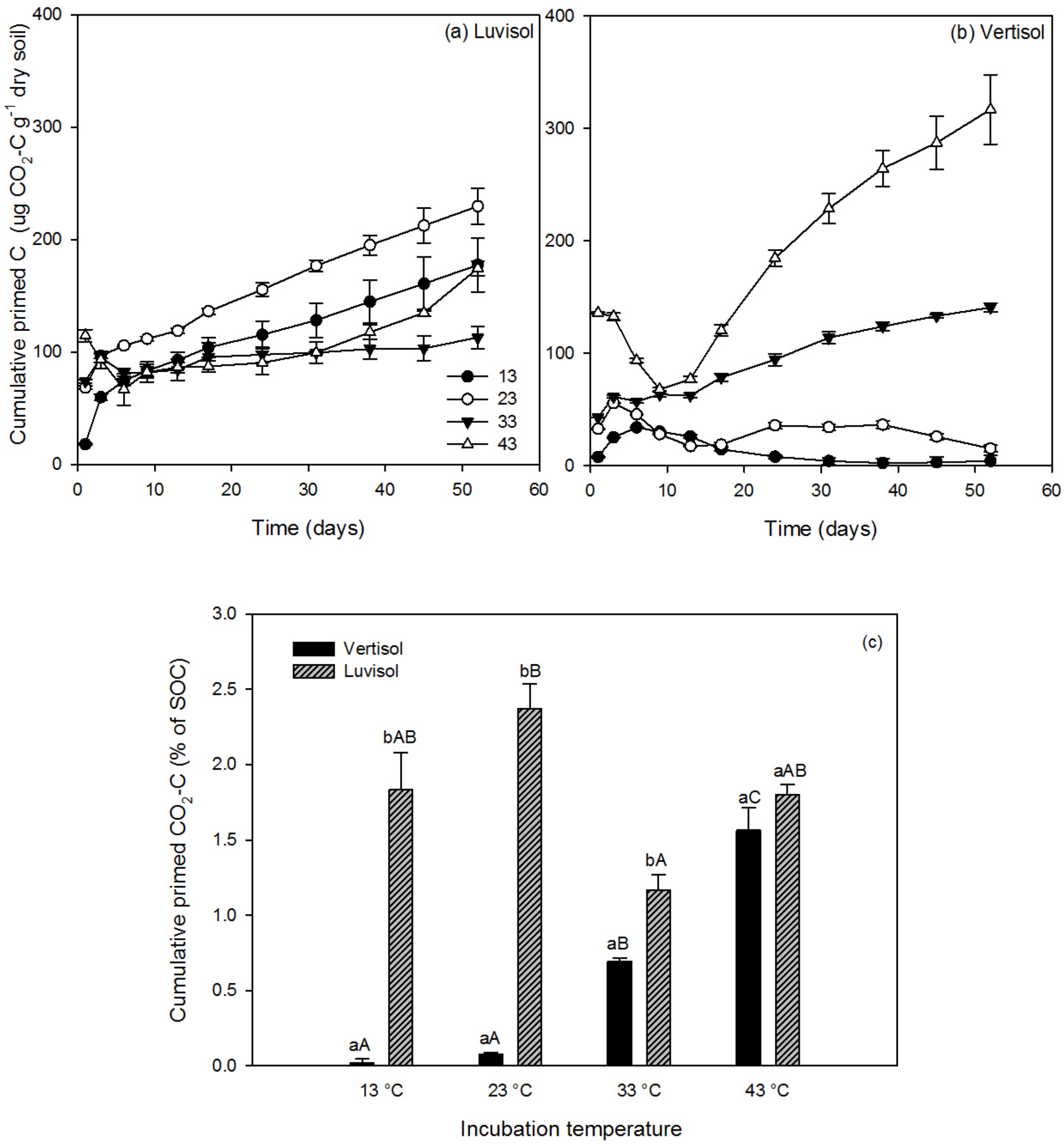

Fig. 2. Dynamics of cumulative primed C per unit of dry soil during the incubation period of 52 days (a, b) and cumulative percent of SOC primed for the Luvisol and the Vertisol at different incubation temperatures (c). The plotted values are average of three replicates and standard errors are represented by error bars. Different lower case letters above bars indicate significant differences between soil types across each temperature; different upper case letters above bars indicate significant differences between temperatures across each soil type ($p<0.05$).

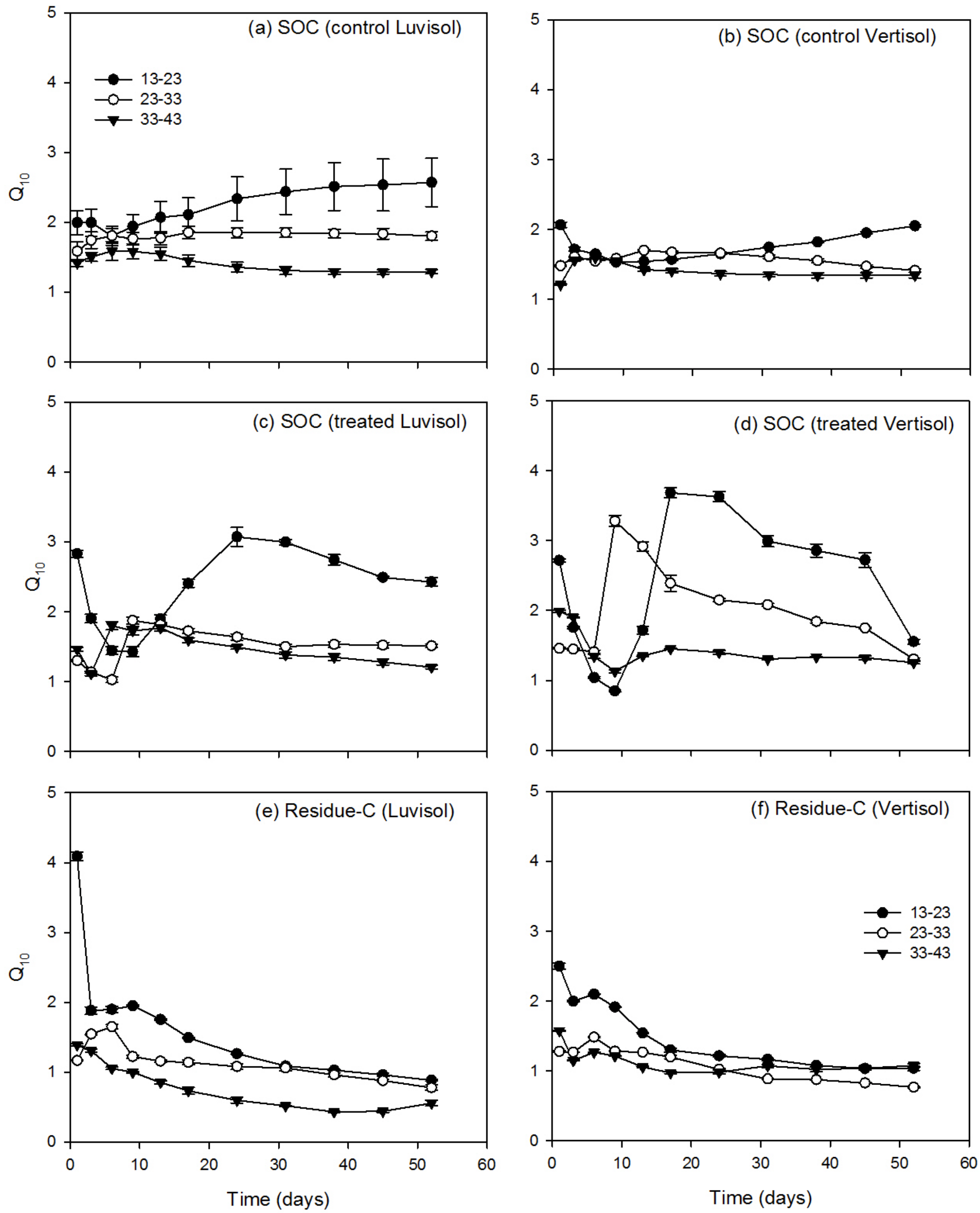

Fig. 3. Temperature sensitivity (Q_{10}) of SOC mineralization for the control and the treated Luvisol and Vertisol; Q_{10} of residue C mineralization for the Luvisol and Vertisol at different incubation temperatures during 52 days incubation period. The plotted values are average of three replicates and standard errors are represented by error bars.

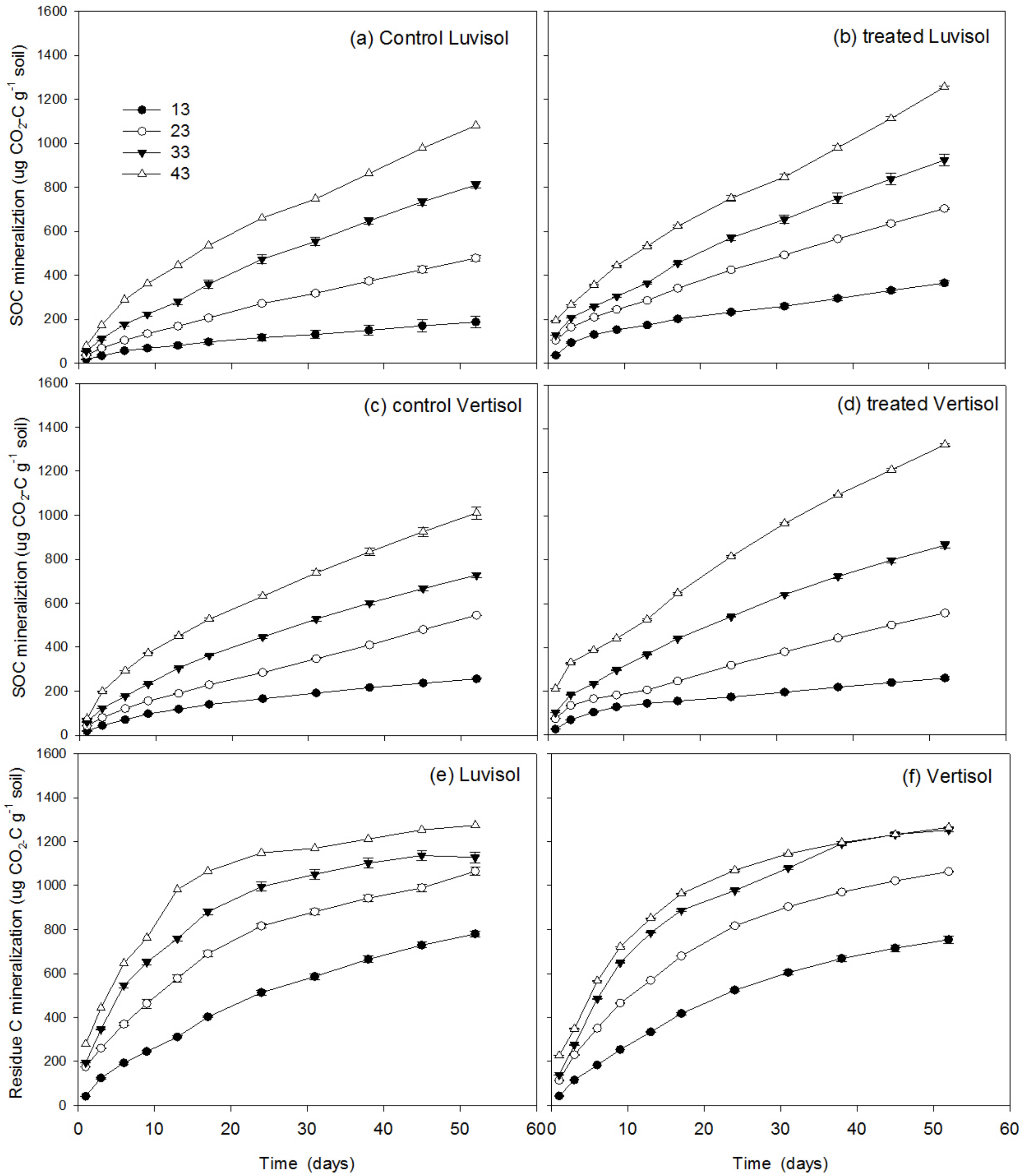

Fig. S1. Cumulative SOC and residue C mineralization during the incubation period at different incubation temperatures (13, 23, 33 and 43 °C) for the control and treated Vertisol and Luvisol. The plotted values are average of three replicates and standard errors are represented by error bars.