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Short-term cropland responses to temperature extreme events during late winter

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Abstract

In recent years, several studies have focused on terrestrial ecosystem response to extreme events. Most of this research has been conducted in natural ecosystems, but few have considered agro-ecosystems. In this study, we investigated the impact of a manipulated warmer or cooler late winter-early spring on the carbon budget and final harvest of a soybean crop (*Glycine max* (L.) Merr.). Soil temperature was altered by manipulating soil albedo by covering the soil surface with a layer of inert silica gravel. We tested three treatments: cooling (Co), warming (W), mix (M) and control (C). An automated system continuously measured soil heterotrophic respiration (R_h), soil temperature profiles, and soil water content across the entire year in each plot. Phenological phases were periodically assessed and final harvest was measured in each plot. Results showed that treatments had only a transient effect on daily R_h rates which did not result in a total annual carbon budget significantly different from control, even though cooling showed a significant reduction in final harvest. We also observed anticipation in seed germination in both W and M treatments and a delay in germination for Co. Moreover, plant density and growth increased in W and M and decreased in Co.

1 Introduction

Soil respiration (R_s) is the second largest carbon flux in most ecosystems (Davidson et al., 2002). Thus, the possible increase in R_s due to climate warming and the consequent feedbacks on climate change have led to a growth in concern about the effects of climate change on soil organic matter dynamics (Cox et al., 2000; Jones et al., 2003; Knorr et al., 2005; Davidson and Janssens, 2006; Heimann and Reichstein, 2008).

The soil carbon pool is reported to be quite considerable (from 1220 to 1576 Pg C for the 0–100 cm layer; Tarnocai et al., 2009), while estimated global R_s in 2008 amounted to 98 ± 12 Pg C, with an increasing rate of 0.1 Pg C yr^{-1} between 1989 and 2008, implying a global R_s Q_{10} of 1.5 (Bond-Lamberty and Thomson, 2010). Hence, understanding the sensitivity of respiratory processes to temperature is central for quantifying the climate-carbon cycle feedback (Mahecha et al., 2010).

So far, several studies have focused on the effects of gradual climatic trends (e.g. global warming, increasing atmospheric CO_2 concentration; Jentsch et al., 2007), but in recent years there has been a growing interest in the impacts of climate extremes and climate variability on the carbon cycle (Easterling et al., 2000; Jentsch et al., 2007). In fact, such extreme events can have an even greater influence on ecosystems and societies than gradual shifts in mean temperatures and precipitation regimes (Jentsch and Beierkuhnlein, 2008). Moreover, there is general agreement about the fact that there will be an increase in both mean values and overall variability of occurrence of extreme weather events (Meehl et al., 2000; Jentsch et al., 2007; Jentsch and Beierkuhnlein, 2008). In particular, temperature extremes (heat waves) are predicted to become more frequent, intense and longer lasting (Karl and Trenberth, 2003; Meehl and Tebaldi, 2004), especially in certain areas like central-western Europe, where the length of summer heat waves has doubled and the frequency of hot days has almost tripled in recent decades (Della Marta et al., 2007). Regarding cold extremes, instead, a recent paper foresees an increased likelihood of cold in the European region (Fereday et al., 2012).

Since the total global cropland area amounted to 1.53×10^9 ha at the end of the last millennium (Biradar et al., 2009), and agriculture has been estimated to account for 10–12 % of total anthropogenic greenhouse gas emissions in 2005 (Loubet et al., 2011), it is clear that studying the effects of climate change and extremes on agro-ecosystems is a key issue in carbon dynamics and climatic research. Here, we investigate the response of soil respiration and ecosystem productivity to soil temperature manipulation (warming and cooling) in an agro-ecosystem during late winter-early spring, when soils are usually ploughed and soil organic matter is more accessible for micro-organisms (Dungait et al., 2012). In particular, the specific objective of this work is to assess the response of a soybean crop (*Glycine max* (L.) Merr.) to a manipulated warmer or colder late winter-early spring, particularly focusing on soil heterotrophic respiration (R_h) and final harvest. Our experimental hypotheses were that warm extreme

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events do not affect crop carbon input (C_{input}), while a warmer late winter-early spring leads to an increase in R_h (carbon output; C_{output}) and, consequently, to a detectable loss of soil carbon (C_{budget}). On the contrary, we hypothesized that a colder late winter-early spring leads to lower C_{output} and thus a higher C_{budget}.

2 Methods

2.1 Study site and experimental design

The experiment was carried out in Beano (46° N 13°01′ E, 65 m a.s.l.), north-eastern Italy. Mean annual temperature at the site is 13.7 °C and mean annual precipitation is around 1200 mm (2000–2007). An analysis of the occurrence of local climate extremes was performed using data for two decades (1991–2000 and 2001–2010) at a meteorological station close to the study field (~ 10 km). In particular, the average and standard deviation (σ) of the daily maximum (T_{max}) and minimum temperature (T_{min}) in the winter-early spring period (from January to April) were calculated. Then, similarly to De Boeck et al. (2010), we considered heat waves as periods encompassing at least 7 consecutive days above $T_{max} + \sigma$ and cold waves as periods encompassing at least 7 consecutive days below $T_{min} - \sigma$. The mean length of extreme events was expressed as the number of days above or below temperature threshold divided by the number of events.

The location is characterized by intensive, fertilized and irrigated farming. Soil is classified as a Chromi-Endoskeletic Cambisol (FAO, 2006) with the following characteristics in the 0–30 cm horizon: total soil organic carbon (SOC) = 48.4 ± 8.5 t C ha^{-1}, total N = 4.2 ± 1.1 t N ha^{-1}, soil bulk density = 1.25 ± 0.15 g cm^{-3}, soil field capacity = 23 % v/v, wilting point = 12 % v/v, and pH = 7.1 ± 0.02 (Alberti et al., 2010). In this field, irrigated maize (*Zea mays* L.) has been cultivated during the last 30 yr. In winter, the soil is ploughed to a depth of 0.35 m, while in spring, soils are ploughed to 0.05 m in preparation for sowing.

The experiment started on 1 March 2011 and lasted 1 yr until 28 February 2012 in order to complete the annual carbon budget. A soybean crop (*Glycine max* (L.) Merr.) was sown on 4 May 2011 (DOY 124), during the effective treatment period (see below for details).

The experiment setup consisted in 12 plots (3 replicates × 4 treatments): 9 plots of 5 × 2.5 m (treated) and 3 control plots of 10 × 10 m deriving from a previous experiment (Alberti et al., 2010). The plots were arranged in three blocks. Soil respiration measurements were performed every 2 h using three closed dynamic soil respiration systems based on the measurement of the increase in CO_2 concentration within an automated chamber during a fixed amount of time using a non linear regression method (Delle Vedove et al., 2007; Alberti et al., 2010). Heterotrophic respiration (R_h) was measured using two automated chambers per plot. Soil below the chambers was isolated with a root exclusion stainless-steel cylinder opened at both ends (32 cm diameter, 40 cm height). The steel cylinders were placed in the field after sowing and removed after final harvest. Soil temperature profiles (four type-T thermocouples for each depth: 0, 2.5, 5 and 10 cm depth, the superficial ones protected from direct solar radiation) and soil water content (Decagon EC-5; 5–10 cm depth) were also continuously monitored in each plot. All variables were measured at 0.1 Hz and then averaged half hourly. Air temperature, humidity (HMP45AC, Vaisala), and precipitation were measured at a nearby weather station (Alberti et al., 2010).

2.2 Warming–cooling method

We adopted a passive method to alter soil temperature, which consisted of changing soil surface albedo by covering it with a layer (0.5 cm thickness) of inert silica gravel (95.7 % SiO_2; pH 7–8 in water solution; density 2.65 g cm^{-3}; granulometry 1.2–1.8 mm). Using gravel of two different colours (black and white), we set up 4 treatments: Cooling (Co; white gravel), Warming (*W*; black gravel), Mix (*M*; 4 : 1 black and white gravel) and Control (*C*; bare soil). The main advantages of this system are the low cost and the fact that no electrical power is required, while the main disadvantage is the inability to determine, a priori, a soil temperature range. Moreover, since this method depends on incident radiation over soil, treatments were not effective at night time, on cloudy-rainy days, or after complete crop canopy closure. However, the aim of the experiment was to test the effects of soil temperature manipulation mainly outside the growing season (i.e. late winter-early spring).

2.3 Phenology and ecosystem productivity

Seed germination was monitored in each plot and seed birth trend for each treatment interpolated through a logistic function. The day when the first derivative of the logistic curve (i.e. seed birth rate) was at a maximum was assumed to be the day of germination for the treatment. Moreover, during the growing season, the height and phenological phases of the crop, according to Fehr et al. (1971), were periodically assessed, in order to detect if there were differences in crop development due to treatments.

Crop productivity and crop yield were assessed at final harvest by destructive sampling on 22 September 2011 (DOY 265). All plants in a 1.7 × 1.0 m subplot per plot were collected. After oven-drying at 70 °C for 48 h, above- and below-ground dry biomass and dry grain yield were determined. Furthermore, on a subsample of 10 plants, root : shoot ratio and harvest index were calculated. Crop residues after harvest were estimated on a 1 m^2 subplot for each plot.

Considering that we are dealing with a crop rotation, the carbon input to the ecosystem (C_{input}) was assumed to be equal to the sum of the crop residues of the previous crop year (CR_{yr-1}; 2010) and those of the studied crop year (CR_{yr}; 2011), minus the amount of carbon respired between the harvest of the previous year and the beginning of the experiment ($R_{hyr\text{-}1}$; already monitored in control plots by the same soil respiration systems):

$$C_{input} = CR_{yr-1} + CR_{yr} - R_{hyr\text{-}1} \quad (1)$$

Assuming that the carbon losses from the ecosystem (C_{output}) during the study year were equal to the cumulative heterotrophic respiration (R_{hyr}), the total carbon budget

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(C_{budget}) was calculated as follows:

$$C_{budget}=C_{input}-C_{output}=CR_{yr-1}+CR_{yr}-R_{hyr\text{-}1}-R_{hyr} \quad (2)$$

2.4 Data analysis

Measured soil respiration data were averaged across four periods during the day (00:00–06:00; 06:00–12:00; 12:00–18:00; 18:00–24:00). Days without at least three periods of data were discarded from further analysis so as not to under- or overestimate soil respiration since a complete daily trend was not available. Moreover, data for days when all three replicates per treatment were not available were also discarded. In total, 14 % of days were not considered in the analysis. Missing data were then gap-filled using surface temperature according to van't Hoff equation (Lloyd and Taylor, 1994):

$$R_h = Ae^{kT} \quad (3)$$

where R_h is soil heterotrophic respiration and T is soil surface temperature (Pavelka et al., 2007). Coefficients A and k were derived by non-linear regression. Sensitivity of soil respiration to soil temperature (Q_{10}) was then calculated as:

$$Q_{10} = e^{10k} \quad (4)$$

Data were analyzed at the end of the year and independently for the following five periods: period I, pre-treatment (DOY 60–67); period II, effective treatment period (from treatment application to complete crop canopy closure, DOY 68–158); period III, after complete crop canopy closure (from complete crop canopy closure to final harvest, DOY 159–264); period IV, after final harvest period (from final harvest to ploughing, DOY 265–326); period V, after ploughing (DOY 327–60). The slope of the cumulative soil respiration curve of each period was considered as the mean daily heterotrophic respiration rate of that period.

The effects of the various treatments on soil albedo, soil temperature, and water content were tested by repeated measures ANOVA with post-hoc tests (Tukey test), while the effects of treatments on daily heterotrophic respiration rates and ecosystem productivity were tested by one-way ANOVA (post-hoc Tukey test). Analyses were performed with SPSS (©IBM Corp.). All errors presented in text and graphs are standard error of the mean unless reported otherwise.

3 Results

3.1 Soil temperature and soil water content

Both maximum and minimum mean air temperatures (T_{max}, T_{min}) and their standard deviations were larger over the period 2001–2010 in comparison to 1991–2000 (T_{max} increased from 12.2 ± 5.3 to $13.0 \pm 5.6\,^{\circ}$C, T_{min} from 1.8 ± 4.5 to $2.8 \pm 4.6\,^{\circ}$C [mean ± standard deviation]). The occurrence of heat waves and their mean length also increased, growing from 6 heat waves lasting 9 days in 1991–2000 to 9 heat waves with a duration of 14 days in 2001–2010. Cold waves also increased from 4 to 8 events per decade, however their mean length decreased from 13 to 10 days. Thus, average temperatures, their variability and the occurrence of heat and cold waves during late winter-early spring increased in the last decade, in agreement with the expected climatic trends.

All treatments significantly modified soil surface albedo in comparison to *C* ($P < 0.001$; Mean albedo: Co 62.6 %; *W* 9.6 %; *M* 15.7 %, *C* 22.5 %). Thus, while there were not any significant differences in soil temperature at any depth among treatments before gravel application (DOY 60–67; $P > 0.05$), changes in soil albedo significantly modified soil temperatures during effective treatment periods (period II; $P < 0.001$; Fig. 1a). In particular, maximum soil temperature deviations from control were obtained at the soil surface and were equal to $-6.8\,^{\circ}$C for Co and $+5.7\,^{\circ}$C for *W* treatment, while the mean differences in soil temperature at 5 cm depth during period II amounted to

−3.00 ± 0.12, +2.06 ± 0.08 and +1.24 ± 0.09 °C for Co, *W* and *M*, respectively. During this period, all treatments created a quite homogeneous soil temperature alteration along the soil profile, at least up to 10 cm depth (data not shown). Soil temperature diurnal fluctuations were wider in *W* and narrower in Co (compared to *C*), but in all treatments they were gradually smaller as depth increased.

After complete crop canopy closure (period III; DOY 159–264), there were no significant differences in soil temperature among treatments, except for Co, which had significantly lower soil temperatures compared with *C* ($P = 0.008$) during the first days of this period due to a delay in crop development (see below). In the first days after final harvest (period IV; DOY 265–326), soil temperature of treatments *W* and *M* were significantly ($P < 0.001$) higher than *C* as harvest residues had not been redistributed over the soil yet, since plants were collected for laboratory measurements. Finally, after ploughing (period V; DOY 327–60), no significant differences in soil temperature were detected ($P > 0.05$).

Regarding soil moisture, during both period I and II, no significant differences were detected among treatments ($P > 0.05$). Unfortunately, just after canopy closure lightning damaged most of the soil water content sensors. Thus we were not able to assess if there was a difference in soil water content or not in the subsequent periods. However, because the crop is irrigated (a total of 310 mm during period II and III), soil water content was always close to field capacity (0.25 ± 0.04 [mean ± standard deviation] considering period III, IV and V; data from TDR at the weather station).

3.2 Heterotrophic respiration

Daily soil heterotrophic respiration ranged from 0.15 to 7.95 $\mathrm{g\,C\,m^{-2}\,d^{-1}}$ with an annual average equal to 1.77 ± 0.07, 1.27 ± 0.05, 1.96 ± 0.23 and 1.48 ± 0.08 $\mathrm{g\,C\,m^{-2}\,d^{-1}}$ in *C*, Co, *W* and *M*, respectively. There were no statistically significant differences in mean daily R_h rates before gravel application (i.e. slope of the cumulative respiration; $P > 0.05$), while during period II R_h rates in Co and *W* were less than and greater than *C*, respectively ($P = 0.117$ and $P = 0.007$; Fig. 1b). In this period, mean daily R_h rates were 2.81 ± 0.13 in C, 2.20 ± 0.21 in Co, 3.73 ± 0.43 in W and 2.78 ± 0.20 $\text{g C m}^{-2}\,\text{d}^{-1}$ in M. In period III, Co and M treatments had significantly lower daily R_h rates compared with C ($P < 0.01$). R_h rates presented the same trend in all treatments: an increase from period I to period II followed by a decrease during periods III, IV and V. For all treatments, maximum daily R_h rates were found in period II.

R_h increased exponentially with soil temperature in all treatments, however the van't Hoff equation explained only a small part of variance (C: $R^2 = 0.46$; Co: $R^2 = 0.09$; W: $R^2 = 0.28$; M: $R^2 = 0.12$; $P < 0.0001$). Calculated Q_{10} values were equal to 1.63 ± 0.12, 1.20 ± 0.07, 1.50 ± 0.10 and 1.28 ± 0.07 for C, Co, W and M, respectively. Q_{10} of Co was significantly lower than the Q_{10} of C. Seasonal patterns of R_h were similar for all treatments: we observed an increase in spring as temperature increased, a decrease thereafter to values around 1–2 $\text{g C m}^{-2}\,\text{d}^{-1}$ and a further decline in autumn after final harvest.

3.3 Phenology and ecosystem carbon budget

Treatments had a transient effect on crop development (i.e. on succession of phenological phases). Cooling treatment caused a lower plant density compared to C at all sampling dates (Fig. 2a), even if not significant ($P > 0.05$), while in W, plant density was always higher than C (significantly only on 13 May, 9 days from sowing; $P = 0.015$). However, at the end of growing season, plant density was not significantly different between any of the applied treatments and C ($P > 0.05$).

Concerning seed germination (first stage of Fehr-Caviness scale; Fehr et al., 1971), soil temperature manipulation led to earlier germination in comparison to C in both W and M treatments (−4 days), whilst germination was delayed by 3 days in Co (Fig. 2b). The survey of crop development through phenological phases (Table 1) showed that treatments C and W approximately followed the timetable for phenological phases reported by Fehr and Caviness (1971) in Setiyono et al. (2010). Conversely, in the cooling treatment, phase VE was delayed by 8 days, V6 by 22 days, R5 by 27 days and finally

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R6 by 12 days. In comparison to C, Co presented a delay of one or more stages during the entire growing season. Nevertheless, at the end of the crop year, plants reached full maturity in all treatments.

Regarding crop height, plants were significantly smaller in Co than C from 30 May ($P < 0.05$), while plant height was not significantly different from C in W on any sampling date ($P > 0.05$). Finally, plant height was significantly lower in M compared to C only during the last part of the growing season (from 3 August; $P < 0.05$).

As for the carbon budget (Fig. 3), there were no significant differences in C_{input} among treatments ($P = 0.46$), even if a significant reduction in harvest was recorded for Co in comparison to C at the end of the growing season (−37.5 %; $P = 0.02$), while in W and M final harvest was not significantly different from C (final harvest: 4.0 ± 0.3 in C, 2.5 ± 0.1 in Co, 4.0 ± 0.4 in W and 3.4 ± 0.1 t DM ha^{-1} in M). Annual total R_h (C_{output}) and total carbon budget (C_{budget}) of all treatments did not differ significantly from C ($P > 0.05$).

4 Discussion and conclusions

In this study we were able to enhance/decrease soil temperatures in a realistic way, thus mimicking the effects that might be associated to extreme events (i.e. both cold and heat waves; Meehl et al., 2000; Jentsch and Beierkuhnlein, 2008).

There is a large consensus that future increases in temperature will lead to an increase in heterotrophic soil respiration, suggesting that an overall increase in the frequency of extreme temperature events (heat waves) might lead to a substantial emission loss of soil carbon from croplands to the atmosphere. This could eventually lead and to a positive biospheric feedback to global warming (Granier et al., 2007; Heimann and Reichstein, 2008; Ciais et al., 2005). On the other hand, the occurrence of cold waves, especially during late winter-early spring, might have opposite effects.

The overall net effect of extreme events on the carbon balance of a cropping system is the result of the difference between carbon gains and losses. When soil water is in ample supply, as in irrigated systems, an increase in temperature may indeed translate into increased soil carbon losses. Our results show that heterotrophic respiration was stimulated by soil warming possibly leading to a rapid depletion of the most labile soil carbon stock. As a consequence, the enhanced respiration pulse was followed by reduced respiration rates when the substrate, and not the temperature, subsequently became limiting (Fig. 4). It is also interesting to consider that a higher soil temperature promoted initial growth of the crop by affecting, to some extent, its phenology: crop germination was brought forward by 4 days in response to soil warming, in agreement with Menzel et al. (2006) who predicted an earlier onset of germination of 2.5 days $^{\circ}C^{-1}$ in a future global warming scenario. However, this did not translate into an earlier flowering date and, more importantly, into a larger biomass and crop yield at the end of the growing season, an effect that was also observed in the warming experiments analyzed by Rustad et al. (2001) and, more recently, by Wu et al. (2011). Our hypothesis is that the faster soil organic matter decomposition, which is driven by increased soil temperature, leads to a faster mineralization in a period in which the crop, and its rooting system, is still unable to uptake most of the nutrients that can become available in the soil. This was demonstrated in the current study given the fact that the net carbon balance ($C_{input} - C_{output}$) of the crop grown on artificially warmed soil was the same as that in the control (Fig. 3). This suggests substantial homeostasis exists in the carbon balance when observed on a seasonal timescale, that finally restricts the effect of heat waves occurring during late winterearly spring mainly because of substrate limitations to respiration in the last part of the season (Kirschbaum, 2004; Eliasson et al., 2005; Knorr et al., 2005; Davidson and Jenssens, 2006; Hartley et al., 2007). However, such an effect may also be attributed to changes in microbial diversity and physiology (Allison et al., 2010), but this second hypothesis is unlikely due to the short duration of the warming effect that was considered in this study. It is worth noting, that this result is of interest for other types of investigations and in particular for ongoing studies that are trying to address the effect of changes in soil surface albedo on the carbon balance and crop productivity. For instance, the agricultural use of biochar, the dark carbonaceous

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residue of biomass pyrolisis, may in fact have similar effects to our soil warming treatment as its application prior to sowing can lead to a substantial decrease in surface albedo in the period that precedes full canopy cover (Genesio et al., 2012). Our study shows that such changes in the surface energy balance do in fact alter soil temperature, cause detectable priming of soil organic matter decomposition and enhance soil CO_2 efflux during late winter-early spring. However, on a seasonal timescale, there is hardly any affect on the overall carbon budget of the crop, unless other effects of the amendant (i.e. increased water holding capacity or improved plant nutrition) cause an increase in crop yields.

As expected, heterotrophic respiration was slightly diminished in the soil cooling treatment, and the overall carbon savings that were made during late winter-early spring could not be compensated by higher respiration rates during the crop growing period. In fact, when the soil warmed up and its temperature became comparable to that of the control, heterotrophic respiration remained lower. The most likely interpretation for such an effect is that the large albedo-driven decrease in soil temperature that was observed in the period before complete crop cover (up to −5.3 °C at 5 cm depth on DOY 131) may cause changes in the soil microbial functions, leading to reduced organic matter decomposition rates (Muhr et al., 2009). On the other hand, soil cooling also caused decreased harvest that did not affect overall C input. This was not due to changes in phenology, which was scarcely affected by soil cooling, but rather to a decrease in the number of germinating seeds that led to a decrease in plant density and, possibly, a reduction in soil nutrient availability in response to lower SOM mineralization rates. The observation that cold spells may lead to reduced crop yields is not novel (Fuller et al., 2007) but the effect of extreme cold events in the late winterearly spring on carbon accumulation in soils poses some interesting considerations. Recent studies on alternative tillage practices in crop management (Licht et al., 2005; Al-Kaisi et al., 2005) have already reported a decrease in soil temperature and an increase in carbon accumulation driven by no-tillage, even though they did not relate the increase in carbon storage to the decrease in soil temperature. Such an association is especially important in the light of recent climate modelling studies that support the idea of an increased likelihood of cold in Europe as a direct consequence of ice cover reduction in the arctic (Fereday et al., 2012). The preliminary nature of our results and the large uncertainty associated with such climate predictions (based on arctic ice melting effects) prevents excessive generalization of the idea of a complex feedback mechanism by which global warming will eventually cause ice cover reduction, translating into a higher frequency of cold winters over Europe and thus eventually leading to a net carbon sequestration in agricultural soils. But this idea certainly calls for new and more extensive field studies that can actually address the mechanisms associated with a decrease in soil temperature and the conservation of soil carbon stocks in croplands.

A final consideration examines the likely consequences of an increase in the amplitude and frequency of warming and cooling extreme events on the carbon balance of crop systems. Our study highlights that late winterearly spring heat waves are unlikely to cause depletion of soil carbon as resource supply rather than reaction kinetics appears to be the key limiting factor for heterotrophic respiration; on the other hand, substantial soil cooling occurring at the same stage in crop development may cause net carbon accumulation in soils. When combined, an increase in the frequency of both types of extreme events (Meehl and Tebaldi, 2004; Fereday et al., 2012) is therefore unlikely to have large effects on the soil carbon balance of European irrigated croplands. A conclusion that certainly warrants further investigation, involves the use of validated simulation models capable of capturing short-term soil warming and cooling effects on the dynamics of soil organic matter, soil carbon fluxes and stocks, and their critical determinants.

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Table 1. Cultural practices and phenological phases according to Fehr–Caviness scale (Fehr et al., 1971). Phenological phase abbreviations: VE = emergence; V1 = first node; V2 = second node; V*n* = *n*th node; R1 = beginning bloom; R2 = full bloom; R3 = beginning pod; R4 = full pod; R5 = beginning seed; R6 = full seed.

Date	Days from sowing	Phenological Phase Control	Cooling	Warming	Mix
11 May 2011	7	VE	–	VE	VE
13 May 2011	9	V1	–	V2	V1
17 May 2011	13	V2	VE	V2	V2
24 May 2011	20	V2	V1	V3	V2
30 May 2011	26	V3	V2	V3	V3
9 Jun 2011	36	V4	V3	V5	V5
14 Jun 2011	41	V5	V3	V6	V5
20 Jun 2011	47	V6	V4	V6	V5
30 Jun 2011	57	R1	V6	R1	R1
3 Aug 2011	91	R5	R4	R5	R5
9 Aug 2011	97	R5	R4	R5	R5
17 Aug 2011	105	R6	R5	R6	R6
24 Aug 2011	112	R6	R6	R6	R6
		Cultural practices			
19 Apr 2011	−15	Weed control: 5 $kg\,ha^{-1}$ Ammonium sulphate (N 21 %) + 2.5 $kg\,ha^{-1}$ Glifosate 36 %			
4 May 2011	0	Soybean sowing: Nikko Dekalb 1-			
6 May 2011	2	Weed control: 1.2 $L\,ha^{-1}$ S-metolachlor 86,5 % (960 $g\,L^{-1}$) + 0.8 $L\,ha^{-1}$ Linuron 36,5 % (425 $g\,L^{-1}$)			
10 May 2011	6	Pest control: 2 $kg\,ha^{-1}$ Metaldehyde 4.9 % + 2 $kg\,ha^{-1}$ Metaldehyde 3.5 %			
11 Jun 2011	39	Weed control: 2.2 $L\,ha^{-1}$ Cicloxidim 21 % (200 $g\,L^{-1}$) + 7 $g\,ha^{-1}$ Methyl Tifensulfuron 75 % + 1 $L\,ha^{-1}$ Imazamox 3,7 % (40 $g\,L^{-1}$)			
22 Sep 2011	145	Harvest			
23 Nov 2011	203	Plowing (35 cm depth)			

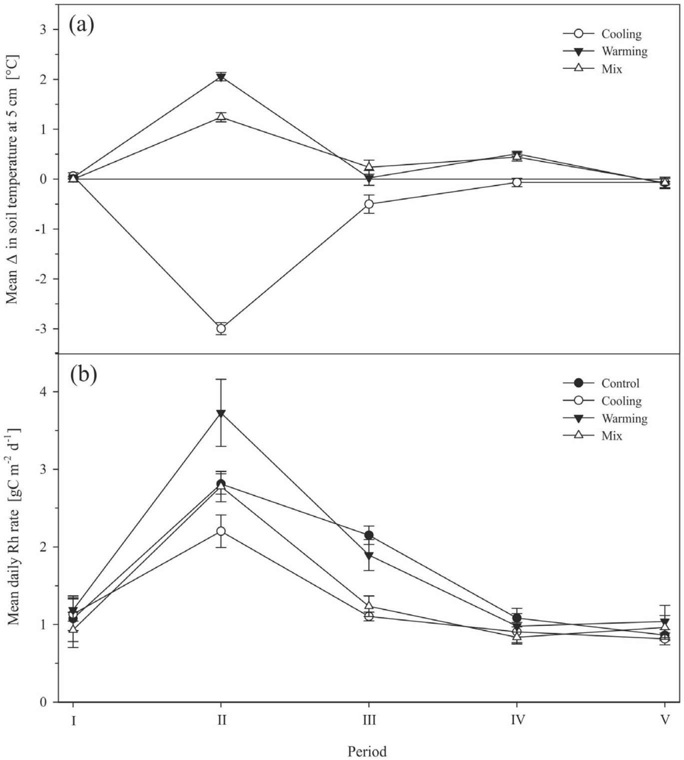

Fig. 1. Mean difference in soil temperature at 5 cm depth (treatment – control; **(a)**) and mean daily heterotrophic respiration rates by treatment **(b)** for each of the study periods considered (**I** to V). Period **I**: pre-treatment (DOY 60–67); Period **II**: effective treatment period (from treatment application to crop canopy closure, DOY 68–158); Period **III**: after crop canopy closure (from crop canopy closure to harvest, DOY 159–264); Period IV: after harvest period (from harvest to ploughing, DOY 265–326); Period V: after ploughing (DOY 327–60). Vertical bars represent standard error ($n = 3$).

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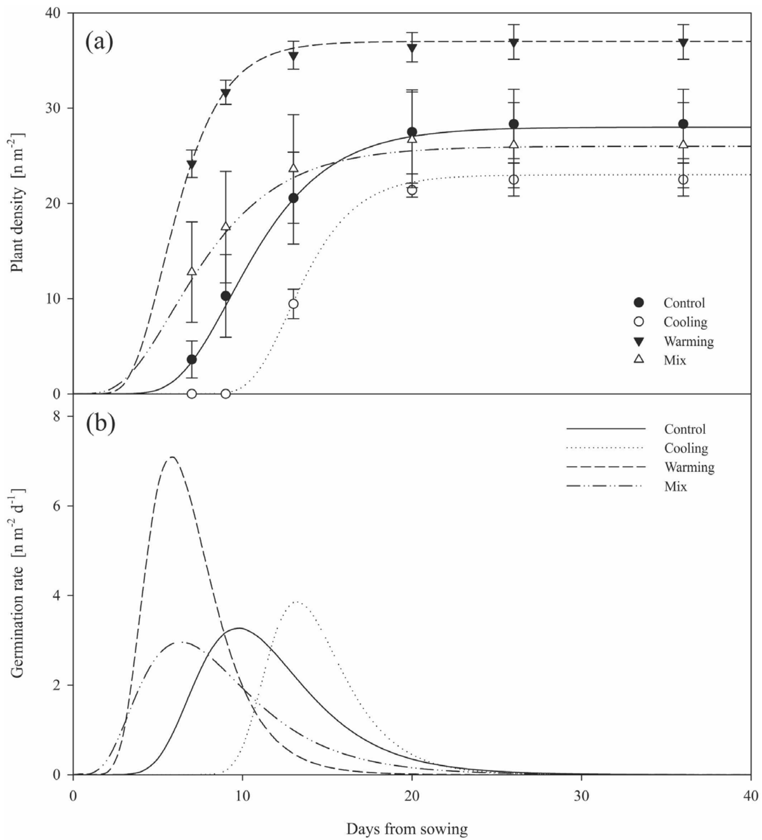

Fig. 2. Crop development: plant density **(a)** and germination rate **(b)**. Vertical bars represent the standard error ($n = 3$).

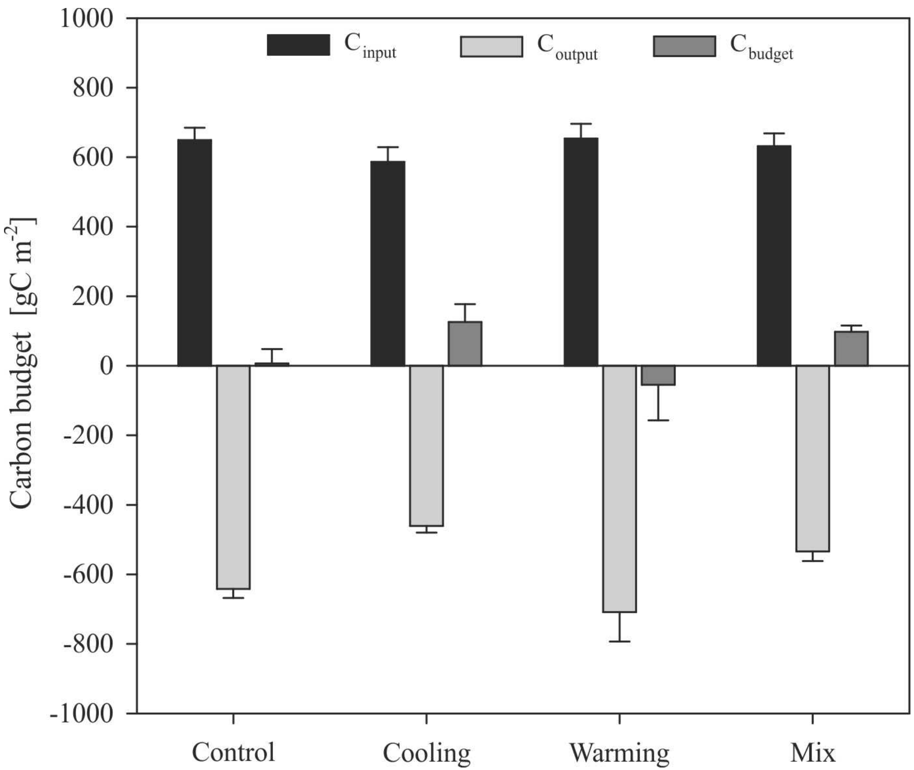

Fig. 3. Total carbon input (C_{input}), carbon output (C_{output}) and carbon budget (C_{budget}) of the studied agro-ecosystem. Negative values represent carbon losses. Vertical bars represent the standard error ($n = 3$).

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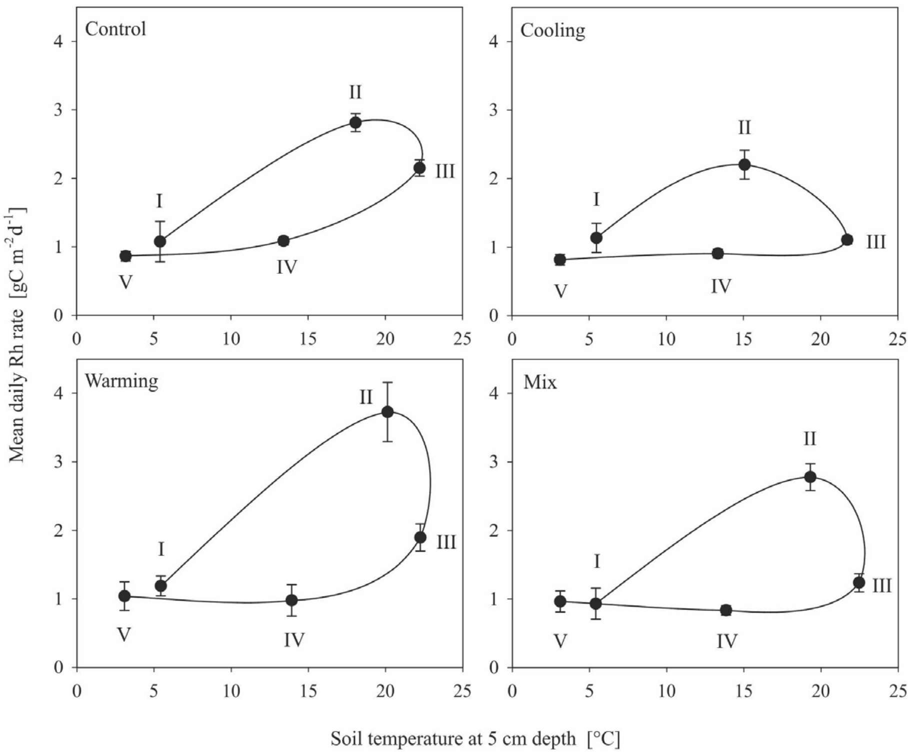

Fig. 4. Heterotrophic respiration rates vs. soil temperature at 5 cm by treatment and period (I to V). Vertical and horizontal bars represent the standard error ($n = 3$).

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