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# Positive feedback of elevated CO<sub>2</sub> on soil respiration in late autumn and winter

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## Abstract

Soil respiration of terrestrial ecosystems, a major component in the global carbon cycle is affected by elevated atmospheric CO<sub>2</sub> concentrations. However, seasonal differences of feedback effects of elevated CO<sub>2</sub> have rarely been studied. At the Giessen Free-Air CO<sub>2</sub> Enrichment (GiFACE) site, the effects of +20% above ambient CO<sub>2</sub> concentration (corresponds to conditions reached 2035–2045) have been investigated since 1998 in a temperate grassland ecosystem. We defined five distinct annual periods, with respect to management practices and phenological cycles. For a period of three years (2008–2010), weekly measurements of soil respiration were carried out with a survey chamber on vegetation-free subplots. The results revealed a pronounced and repeated increase of soil respiration during late autumn and winter dormancy. Increased CO<sub>2</sub> losses during the autumn period (September–October) were 15.7% higher and during the winter period (November–March) were 17.4% higher compared to respiration from control plots.

However, during spring time and summer, which are characterized by strong above- and below-ground plant growth, no significant change in soil respiration was observed at the FACE site under elevated CO<sub>2</sub>. This suggests (i) that soil respiration measurements, carried out only during the vegetative growth period under elevated CO<sub>2</sub> may underestimate the true soil-respiratory CO<sub>2</sub> loss (i.e. overestimate the C sequestered) and (ii) that additional C assimilated by plants during the growing period and transferred below-ground will quickly be lost via enhanced heterotrophic respiration outside the main vegetation period.

## 1 Introduction

The atmospheric concentration of CO<sub>2</sub> has increased from pre-industrial values of 275–285 ppm (Raynaud and Barnola, 1985) to 400 ppm in 2013 (Monastersky, 2013). Projections of future atmospheric CO<sub>2</sub> concentration in the year 2100 range between

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490 and 1370 ppm depending on representative concentration pathways (Moss et al., 2010). As the major radiative forcing component (IPCC, 2013), atmospheric CO<sub>2</sub> is positively correlated with air temperature and is therefore an important component for global warming. Additionally, indirect effects of elevated atmospheric CO<sub>2</sub> (eCO<sub>2</sub>), which are altering carbon (C) fluxes in ecosystems, may impose a feedback to climate change. About half of photosynthetically assimilated C returns immediately to the atmosphere as plant-respired CO<sub>2</sub> (autotrophic respiration) (Chapin et al., 2002). Portions of the net carbon gain (net primary production) are transferred to the soil via root exudates, fine root growth and -turnover or other litter, providing the substrate for soil organic carbon (SOC) buildup (Kirschbaum, 2000).

Soil functions as an important C reservoir within the global carbon cycle and stores about 1500 Gt of C (Amundson, 2001; Lal, 2004; Batjes, 1996), which is about twice the amount of C in the atmosphere (Schils et al., 2008).

Soil respiration, the sum of autotrophic root respiration and heterotrophic respiration from microorganisms and soil meso- and macrofauna, accounts for two thirds of the total C loss from terrestrial ecosystems (Luo, 2006). Enhanced net C losses under eCO<sub>2</sub> cause a positive feedback.

Many past studies focused on soil–atmosphere CO<sub>2</sub> exchange during the growing season. However, soil respiration during vegetation dormancy may represent a significant component of the annual C budget and contributes to the observed winter CO<sub>2</sub> maximum in the atmosphere (Raich and Potter, 1995). Accordingly, analysis of CO<sub>2</sub> data from an air sampling network identified seasonal oscillation with highest concentrations occurring each winter when respiration exceeds photosynthesis (Keeling et al., 1996). This emphasizes the necessity to study seasonal dynamics of soil respiration under future CO<sub>2</sub> conditions to gain a better understanding of how soil respiration responds to changing atmospheric CO<sub>2</sub> concentrations.

A meta-analysis of Zak et al. (2000) revealed a 51 % increase of soil respiration as a mean response in a grassland ecosystem under elevated CO<sub>2</sub>, Janssens and Ceulemans (2000) provided evidence for consistent stimulation of soil respiration un-

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der a variety of tree species. However, the majority of studies, to date, are based on short-term exposure (less than five years) with  $e\text{CO}_2$ , often using open-top chamber experiments (Zak et al., 2000). Results from these experiments should be analyzed with appropriate caution because of the known “chamber effect” on the microclimate (Leadley and Drake, 1993) and their relevance to natural ecosystems in which longer-term biogeochemical feedbacks operate (Rastetter et al., 1991). Since soil respiration is a product of several rhizospheric processes i.e. root exudation, root respiration, and root turnover, as well as decomposition of litter and bulk soil organic matter from various pools with different characteristic turnover times, short- and long-term responses to  $e\text{CO}_2$  may be quite different (Luo et al., 2001).

The most suitable approach for conducting ecosystem  $\text{CO}_2$  experiments under natural conditions are FACE experiments, where intact ecosystems are exposed in-situ to a higher atmospheric  $\text{CO}_2$  concentration. However, it has been reported that the sudden increase in atmospheric  $\text{CO}_2$  ( $\text{CO}_2$  step increase) at the beginning of a  $\text{CO}_2$ -enrichment, may cause certain short-term responses of the ecosystem that differ from long-term responses (Luo, 2001; Newton et al., 2001). Accordingly, Kammann et al. (2005) showed that yield responses to  $e\text{CO}_2$ , in the Giessen Free-Air  $\text{CO}_2$  Enrichment (GiFACE), were different in the initial compared to the subsequent years. Moreover, plants may undergo micro-evolutionary changes in response to  $e\text{CO}_2$  (Ward and Kelly, 2004), which may also be reflected in belowground processes (Klironomos et al., 2005). Consequently, to avoid misinterpretations due to insufficient experimental durations, results from long-term exposure studies are required. In the GiFACE this was after approximately 5–6 years (Kammann et al., 2005). In the following we use the expression “short-term” for  $\text{CO}_2$  enrichment durations  $< 5$  years and “long-term” for durations  $> 5$  years.

Based on a literature overview, we found 13 other FACE studies, from a wide variety of ecosystems, where in-situ soil respiration under  $e\text{CO}_2$  has been investigated. All of these FACE studies operated at higher  $\text{CO}_2$  enrichment concentrations than the GiFACE experiment (with +20%  $\text{CO}_2$  above ambient), i.e. they imposed larger initial

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step increases (Klironomos et al., 2005). Klironomos et al. (2005) have demonstrated that ecosystem responses to eCO<sub>2</sub> may differ between using a sudden step increase and a gradual rise in the CO<sub>2</sub> concentration. However, in any CO<sub>2</sub> enrichment study a step increase – also if lower than usual – cannot be avoided. Thus, experimental FACE results are more indicative for future predictions. However, experimental studies with duration of > 10 years are scarce (Carol Adair et al., 2011; Jackson et al., 2009). To our knowledge, 10 of the 16 investigations on soil respiration across these 13 FACE studies were carried out within the first five years of exposure, thus reporting short-term responses (Craine et al., 2001; King et al., 2001; Allen et al., 2000; Andrews and Schlesinger, 2001; Selsted et al., 2012; Masyagina and Koike, 2012; Soe et al., 2004; Lagomarsino et al., 2013; Liu et al., 2006; Nakayama et al., 1994). All short-term study results pointed towards a consistent stimulatory effect of eCO<sub>2</sub> on soil respiration. The average increase ranged from 12 % under a sweetgum plantation (King et al., 2004) to 70 % under a mixed plantation of *Populus* species (Lagomarsino et al., 2013). In two of the short-term studies, significant effects were only observed on days with high photosynthetic activity (Masyagina and Koike, 2012; Soe et al., 2004); measurements during dormancy were not carried out.

Three of the short-term studies conducted measurements during winter dormancy with contrasting results (Allen et al., 2000; Andrews and Schlesinger, 2001; Selsted et al., 2012; Lagomarsino et al., 2013). In a temperate heathland (CLIMAITE study), soil respiration was significantly increased under eCO<sub>2</sub> during three consecutive winter periods (Selsted et al., 2012). Allen et al. (2000) detected a significant effect of eCO<sub>2</sub> on soil respiration during December 1997 in the Duke Forest FACE study but not during the previous growing season beneath the loblolly pine forest. Andrews and Schlesinger (2001) reported from the same site greater increases of soil respiration during fumigation periods (26–59 %) than during non-fumigated periods (8–15 %). Fumigation was stopped when ambient air temperature dropped below 5 °C for more than one hour. In line with these results, much larger percentage enhancements of the soil CO<sub>2</sub> efflux were observed during the growing season (up to 111 %) than during dormant sea-

son (40%) from a mixed plantation of *Populus* species exposed to  $e\text{CO}_2$  (EuroFACE) (Lagomarsino et al., 2013).  $\text{CO}_2$  enrichment was provided from bud burst to leaf fall at this site.

Out of six long-term studies on soil respiration (Carol Adair et al., 2011; Pregitzer et al., 2008; Jackson et al., 2009; Pendall et al., 2001; Bader and Körner, 2010; Dawes et al., 2013), only one study reported measurements throughout the dormant season, showing that after 10 years of  $e\text{CO}_2$  during the growing season at a loblolly pine forest (Duke FACE) soil respiration was consistently higher in midsummer to early fall and diminished or disappeared in winter (Jackson et al., 2009). This was explained by a reduction in assimilation and hence available root exudate during dormancy. If the fumigation may continue during the dormant season in an ecosystem with a green canopy e.g. in a permanent grassland, the stimulation may theoretically continue on a higher level.

Reports from other long-term FACE studies in temperate ecosystems (disregarding the dormant season) were consistent by reporting an increase in soil respiration under  $e\text{CO}_2$ , with the exception of the Swiss Canopy Crane experiment in an old-growth, mixed deciduous forest. Bader and Körner (2010) reported that soil respiration from the site was only stimulated when volumetric water content was  $\leq 40\%$  at soil temperatures above  $15^\circ\text{C}$ .

In summary, only fragmented information is available on how soil respiration responds to  $e\text{CO}_2$  during vegetation as well as dormant periods after long-term  $e\text{CO}_2$ . To our knowledge, no long-term FACE study in a grassland ecosystem exists which has investigated soil  $\text{CO}_2$  fluxes across several years. Consequently, it is difficult to generalize temporal patterns of soil respiration under  $e\text{CO}_2$ , and thus the soil respiratory response to  $e\text{CO}_2$  at all.

Based on the available studies and earlier observations at our site, where whole-ecosystem respiration including the green canopy was increased under  $e\text{CO}_2$ , mainly during non-growing season (Lenhart, 2008), we hypothesized that (i) long-term ( $> 10$  years) moderate  $\text{CO}_2$  enrichment will cause increased soil respiration, (ii) soil respira-

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tion will be more enhanced in the vegetation than dormant period and (iii) soil respiration will still be significantly enhanced in the dormant period (winter) under  $e\text{CO}_2$  in the GiFACE where the  $\text{CO}_2$  enrichment is continuing during winter.

## 2 Materials and methods

### 2.1 Study site and design

The Giessen Free Air Carbon Enrichment (GiFACE) experiment is located on permanent semi-natural grassland. It is situated near Giessen, Germany ( $50^\circ 32' \text{ N}$  and  $8^\circ 41.3' \text{ E}$ ) at an elevation of 172 m a.s.l.

The set-up and performance of the GiFACE system has been described in detail by Jäger et al. (2003). In brief, from May 1998 until present, atmospheric  $\text{CO}_2$  concentrations were enriched by 20 % above ambient, all-year-round during daylight hours. At present the GiFACE experiment is still ongoing.

The  $\text{CO}_2$  enrichment was applied in three rings, each eight meter in diameter (E plots). Three equally sized control plots were maintained at ambient atmospheric  $\text{CO}_2$  levels (A plots). The experimental design was a randomized block design. A block consisted of two plots to which ambient and  $e\text{CO}_2$  treatments were randomly assigned. A characteristic attribute of the study site is a soil moisture gradient, resulting from a gradual terrain slope ( $2\text{--}3^\circ$ ) and varying depths of a subsoil clay layer. Within each of the three blocks, soil moisture conditions were relatively homogeneous (Jäger et al., 2003).

The vegetation is an Arrhenatheretum elatioris Br.Bl. Filipendula ulmaria subcommunity, dominated by *Arrhenaterum elatium*, *Galium mollugo* and *Geranium pratense*. At least 12 grass species, 15 non-leguminous herbs and 2 legumes are present within a single ring. For at least 100 years, the grassland has not been ploughed. Since several decades, it was managed as a hay meadow with two cuts per year, and fertilized in mid-April with granular mineral calcium-ammonium-nitrate fertilizer at the rate of

40 kg N ha<sup>-1</sup> yr<sup>-1</sup>. Before 1996, fertilizer was applied at a rate of 50–100 kg N ha<sup>-1</sup> yr<sup>-1</sup> (Kammann et al., 2008).

The soil of the study site is classified as a Fluvisol (FAO classification) with a texture of sandy clay loam over a clay layer (Jäger et al., 2003).

Observations in this study were carried out from January 2008–December 2010 (i.e. more than 9 years after the onset of CO<sub>2</sub> enrichment). During the observation period the mean annual temperature was 9.2 °C and mean annual precipitation was 562 mm which was identical to the average rainfall since the beginning of recording in 1995. Rainfall was recorded at the site in 30 min intervals with 20 randomly distributed “Hellmann” samplers. Air temperature was recorded continuously at two locations at the site in 2 m height and averaged 9.5 °C since 1995.

## 2.2 Measurement of soil CO<sub>2</sub> fluxes at the field site

In each of the six FACE plots, soil respiration rates were measured using an automated closed dynamic chamber system with an infrared gas analyzer (LI-COR 8100, LI-COR, Inc., Lincoln, Nebraska, USA) with a patented vent for pressure equilibration between the closed chamber and the atmosphere (McDermitt et al., 2005). Carbon dioxide fluxes were reported in μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>. The measurements were performed at four permanently installed PVC soil collars per FACE ring, to cover the spatial heterogeneity within each ring. The soil collars had a diameter of 20.3 cm (8 inch) and were about 11 cm high. A beveled edge at one end facilitated the insertion into the soil, which took place on 9 May 2006 and the vegetation cover, including surficial rhizomes, was removed manually. Subsequently, the surface was held vegetation-free by removing germinated seedlings weekly. Due to uneven soil conditions, soil collars varied ±1 cm in their insertion depth. Generally, the insertion was chosen to be as shallow as possible, minimizing the trenching effect (Heinemeyer et al., 2011) while maintaining an airtight connection between soil and chamber. A foam gasket and rubber seal between the bottom of the chamber and the top of the soil collar minimized leaks between

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the collar and the chamber. Before each measurement, the distance between the soil surface and the top of each soil collar (i.e. chamber offset) was measured and entered into the LICOR-software to enable correct flux calculations (= total chamber volume). After installation in May 2006, soil CO<sub>2</sub> efflux measurements were carried out over a period of one month to record the insertion and disturbance effects (Fig. S1). The investigation period spanned over three years (January 2008 until December 2010), after the collars were well established and held vegetation free for 1.5 years, allowing a die-back and decomposition of trenched roots, and in-growth of new roots from the outside vegetation. This ensured that soil respiration measurements in a dense, closed grassland canopy were taken as unbiased as possible. Measurements of soil respiration were made weekly in the evening, except from May to July and from October to December 2010, where measurements were carried out every second week.

During the measurement, a pump provided circulating air flow from the closed chamber on its collar to the infrared gas analyzer for thorough mixing of the systems' inner volume. Chamber closure time was between 1 and 3 min, depending on the season (i.e. the strength of the CO<sub>2</sub> efflux and thus the detection limit). CO<sub>2</sub> and H<sub>2</sub>O concentrations were measured simultaneously. The software calculated soil respiration rates by using the changes in CO<sub>2</sub> concentration over a period of time, taking the dilution of water vapor into account. Rates were calculated either by linear regression (lin\_flux) or as the efflux rate at time  $t_0$  at chamber closure using an exponential CO<sub>2</sub> efflux function (exp\_flux) (LI-COR, 2007). The latter takes the diminishing CO<sub>2</sub> concentration gradient between the soil and the chamber headspace into account (Hutchinson and Mosier, 1981) and is implemented by LI-COR in the LI-8100 to avoid underestimations of the CO<sub>2</sub> efflux. We used the following algorithm to choose between these two types of flux calculation for the subsequent processing of all obtained flux data. The use of the exp\_flux calculation was only allowed when (1) the  $R^2$  of the exp\_flux calculation was better than that of the lin\_flux calculation, and (2) when the number of iterations necessary for the exp\_flux calculation was lower than 5. By applying these comparatively strict criteria (stricter than those that are inbuilt by the manufacturer) we

minimized miscalculations caused either by large initial CO<sub>2</sub> concentration fluctuations at chamber closure (when the exp\_flux calculation is used) or underestimations of the true soil CO<sub>2</sub> efflux (when only the lin\_flux calculation is used). The algorithm was applied to each measurement with the same settings. In general, CO<sub>2</sub> flux rates with an  $R^2$  below 0.90 were excluded. This was the case in 0.6% of all measurements taken in this study throughout the three year investigation period.

Soil moisture was measured in each FACE plot as the volumetric water content (VWC) with time-domain-reflectometric (TDR) probes (Imko, Ettlingen, Germany, type P2G). The probes were permanently installed (in March 1998) within the top 15 cm. The probes were monitored manually once a day, except on weekends or holidays. Soil temperature was logged in every plot at 10 cm depth as 30 min means (Imko, Ettlingen, Germany, Pt-100 sensors).

### 2.3 Data analyses

In order to describe changes in soil respiration during different seasons and to test for differences in soil respiration between ambient and elevated CO<sub>2</sub>, we performed a linear mixed-effect model analysis with SPSS version 18. We used all observational data of three years for the linear mixed-effect model analysis. CO<sub>2</sub> treatment was considered as a fixed effect in the model. Coding variables were introduced to indicate the hierarchical order of the data. The six mean fluxes taken in one measurement cycle received the same numerical code; this variable (“measurement cycle”) was considered as a random effect in the linear mixed effect model. A further variable (“ringreplicate”) was introduced to define the ring where the measurement was taken (1–6). “Ringreplicate” was selected as a repeated measure in the SPSS software using linear mixed effect model analysis. Maximum likelihood was used as the estimation method for the parameters in the model. The total observational data set was split by season to analyze seasonal CO<sub>2</sub>-response patterns. Therefore, we distinguished the following five periods (1–5), depending on major dates of phenology and management practices at the grassland study site (Fig. 1): 1 = *winter* (November–March); 2 = *start of veg-*

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etation period up to the date of spring fertilizer application (March–middle of April); 3 = spring until first biomass harvest (middle of April–end of May); 4 = regrowth and summer growing period (end of May–beginning of September); 5 = regrowth and autumn growing period (beginning of September–end of October).

The start of the vegetation period for the grassland ecosystem was identified according to the calculations defined by Wasshausen (1987). The date of leaf discoloration of *Quercus robur* in the nearby phenological garden was used to identify the beginning of winter dormancy. All other dates were chosen according to the management practices at the study site (Fig. 1); the exact dates varied by a few days between the years.

## 2.4 Soil respiration model

In order to describe the dependence of soil respiration on temperature, a function was fitted according to Lloyd and Taylor (1994) (Eq. 1) to 20% of the data that were randomly selected. We defined values for coefficients  $E0$  (= 62.16),  $T0$  (= 262.47) and  $R10$  (= 2.85) for the first run of the model. Subsequently,  $E0$ ,  $T0$  and  $R10$  were fitted for each treatment (ambient and  $eCO_2$ ) by using the dynamic fit function in the SigmaPlot 11.0 software package (Systat Software, San Jose, CA, 2008). Mean soil temperature values were converted from °C to K.

$$f = R10e^{E0\left(\frac{1}{(283.15-T0)} - \frac{1}{(x-T0)}\right)} \quad (1)$$

with  $E0$  = activation-energy-type empirical coefficient,

$T0$  = lower temperature limit for soil respiration in K,

$R10$  = respiration rate at 10 °C.

Consequently, the quality of the soil respiration model was evaluated by plotting modelled against observed respiration values to test if the linear trend line meets the requested slope of 1.

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## 2.5 Gap filling of soil respiration data

To obtain annual sums of soil respiration, a gap filling procedure was applied. Therefore modelled soil respiration rates were calculated, based on the almost continuous data set of soil temperature in 10 cm depth measured at 2–3 positions per ring. We received modelled fluxes for every 15 min over the three year period for all gaps where no observational data were available. Estimates of annual sums were then calculated with the observational data and the modelled data. Differences in annual soil respiration between the CO<sub>2</sub> treatments were tested by using a paired *t* test. Further, the absolute difference and relative change of monthly mean soil respiration rates under *e*CO<sub>2</sub> were calculated in comparison to soil respiration under ambient CO<sub>2</sub>, based on observational and modelled data. For calculating the relative change ambient soil respiration was set to 0%.

## 3 Results

### 3.1 Annual variability of soil respiration

From 2008 to 2010, soil respiration rates at the GiFACE experiment showed distinct annual dynamics, following the seasonal temperature cycle with lowest soil respiration effluxes during winter months and highest effluxes during mid-summer (Fig. 2c and f). Thus, soil respiration rates responded to abiotic factors in particular temperature and moisture. This is exemplified by the high CO<sub>2</sub> efflux rates in June 2009 which occurred shortly after a period of high precipitation while soil temperatures were > 20 °C (Fig. 2f).

The relative and absolute change of soil respiration under *e*CO<sub>2</sub> (Fig. 2d and e) followed a seasonal pattern with greatest increases under *e*CO<sub>2</sub> during *autumn* and *winter*. During midsummer, when the largest absolute soil respiration rates occurred, the relative increase due to the CO<sub>2</sub> enrichment was lowest or non-existent. A linear mixed effect model analysis confirmed that soil respiration rates under *e*CO<sub>2</sub> were sig-

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nificantly higher compared to rates under ambient CO<sub>2</sub> during *autumn* (15.7%) and *winter* (17.4%) (Fig. 3). During all other seasons (*beginning of vegetation period* (season 2), *spring* (season 3) and *summer* (season 4)), covering most of the vegetation period, a trend towards higher soil respiration, but no significant CO<sub>2</sub> effect was observed with eCO<sub>2</sub> (Fig. 3).

### 3.2 Model performance and parameter estimation

By comparing modelled soil respiration with observed soil respiration for all observation dates from 2008–2010 a significant linear relationship was observed with a slope of 1.03 (Fig. 4).

Based on the temperature-respiration function by Taylor and Lloyd (1994), soil respiration was significantly correlated to soil temperature under ambient as well as eCO<sub>2</sub> ( $p \leq 0.0001$ ). From 2008 to 2010, 75% of the variability of soil respiration rates was explained by soil temperature under ambient CO<sub>2</sub> and 82% under eCO<sub>2</sub> (Table 1). Soil respiration rates did not differ in their relationship to soil temperature between the treatments (Fig. 5a). In Fig. 5b we plotted the temperature relationship of soil respiration, visualizing the different seasons, which indicated that soil CO<sub>2</sub> efflux data from *autumn* imposed a different relationship to soil temperature compared to data from other seasons. During *autumn*, soil temperatures were within the same range as during *spring* and *summer*, but soil respiration was on average lower (Fig. 2).

### 3.3 Annual sums of soil respiration

Comparing annual sums of soil respiration, no mean treatment effect of elevated CO<sub>2</sub> (over all seasons) was observed in any of the observation years (Table 2, Fig. 6). Mean annual estimates of soil respiration under ambient CO<sub>2</sub> ranged from 1282.48 to 1344.00 g C [CO<sub>2</sub>] m<sup>-2</sup> yr<sup>-1</sup> and under eCO<sub>2</sub> from 1300.15 to 1351.56 g C [CO<sub>2</sub>] m<sup>-2</sup> yr<sup>-1</sup>.

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## 4 Discussion

### 4.1 Annual sums of soil respiration

In contrast to our initial hypotheses, annual estimates of soil respiration were not different between the CO<sub>2</sub> treatments (Table 2, Fig. 6). Mean annual sums of soil respiration were 1316.76±18.10 g C m<sup>-2</sup> yr<sup>-1</sup> under ambient CO<sub>2</sub> and 1330.58±15.57 g C m<sup>-2</sup> yr<sup>-1</sup> under elevated CO<sub>2</sub>. Raich and Schlesinger (1992) estimated much lower rates of annual soil respiration, reporting 400 to 500 g C m<sup>-2</sup> yr<sup>-1</sup> for temperate grasslands. Annual soil respiration sums from a sandstone and serpentine grassland were 485 and 346 g C m<sup>-2</sup> yr<sup>-1</sup> (Luo et al., 1996). Other recent studies reported higher rates of annual soil respiration which are closer to our estimates; however climatic factors are different from our site: in a tallgrass prairie of Oklahoma annual soil respiration rates were 1131 and 877 g C m<sup>-2</sup> yr<sup>-1</sup> in 2002 and 2003 respectively (Zhou et al., 2006). In a Texas grassland annual soil respiration rates increased with annual precipitation and were 1600, 1300, 1200, 1000, 2100 and 1500 g C m<sup>-2</sup> yr<sup>-1</sup> in 1993 through 1998 respectively (Mielnick and Dugas, 2000).

### 4.2 Seasonality of soil respiration

Also, contrary to our initial hypotheses is the observation that soil respiration was not significantly affected during the vegetation period (*start of vegetation period, spring and summer*) by the moderate long-term CO<sub>2</sub> enrichment. This indicates that any increase in the ecosystem respiration (Lenhart, 2008) during this period will not have been due to enhanced soil (root-derived) respiration but rather to increases in the respiration of the green canopy.

The majority of long-term FACE studies reported significantly increased soil respiration under eCO<sub>2</sub> during the growing season (Pregitzer et al., 2008; Jackson et al., 2009; Pendall et al., 2001; Dawes et al., 2013; Carol Adair et al., 2011), whereas Bader and Körner (2010) reported that seven years of eCO<sub>2</sub> failed to stimulate cumulative soil

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respiration significantly during the growing season. Among the mentioned long-term FACE experiments, the GiFACE operates at the lowest CO<sub>2</sub> enrichment step increase (20 % above ambient CO<sub>2</sub>), which may have contributed to this result.

However, in line with our hypotheses, the results revealed that 10 years of moderate CO<sub>2</sub> enrichment increased soil respiration during *winter* and *autumn* (Fig. 3). These seasonal stimulations of soil respiration under *e*CO<sub>2</sub> were not observed by comparing the annual sums of soil respiration (Fig. 6). This may be because soil respiration fluxes were lower in *winter* and *autumn* compared to fluxes from the other seasons where no differences in soil respiration between the CO<sub>2</sub> treatments were observed. However, within the *winter* and *autumn* season differences in soil respiration may play an important role concerning the global C balance. Increased rates of winter soil respiration under *e*CO<sub>2</sub> may increase the observed winter CO<sub>2</sub> maximum in the atmosphere (Raich and Potter, 1995; Keeling et al., 1996) when respiration exceeds photosynthesis. Another reason why annual sums of soil respiration were not different between the CO<sub>2</sub> treatments may be that our model underestimated high soil respiration fluxes (> 10 μmol m<sup>-2</sup> s<sup>-1</sup>). However these fluxes occurred only in 1.72 % of all observations. Our model did not take soil moisture into account. The high variability of observed soil respiration during summer may be partly due to differing soil moisture conditions, which were not significantly different between ambient and *e*CO<sub>2</sub> plots (Kammann et al., 2005, 2008).

In most FACE studies which reported the effect of *e*CO<sub>2</sub> on soil respiration, the winter was excluded since fumigation during this period was mostly switched off (often in response to sub-zero freezing temperatures or deciduous forest ecosystems). This was the case in the Swiss FACE study, where seeded grassland was exposed to 600 ppm CO<sub>2</sub> (de Graaff et al., 2004), the BioCON FACE, also a grassland study (Craine et al., 2001; Carol Adair et al., 2011), the Aspen FACE, an aspen forest enriched with *e*CO<sub>2</sub> (Pregitzer et al., 2008; King et al., 2001), a Japanese model forest ecosystem exposed to 550 ppm CO<sub>2</sub> (Masyagina and Koike, 2012) and in a 9 year FACE study of an alpine treeline ecosystem (Dawes et al., 2013). In the Swiss Canopy

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Crane study soil respiration was measured during the beginning of the dormant season but not over the complete dormant season while fumigation was switched off (Bader and Körner, 2010). In the Maricopa FACE, where a wheat field was exposed to  $e\text{CO}_2$ , no winter measurements were carried out because this season was a fallow season (Pendall et al., 2001). Outside the cultivation period no soil respiration measurements were made on a cotton plantation exposed to  $e\text{CO}_2$  (Nakayama et al., 1994).

Increased winter soil CO<sub>2</sub> fluxes are in line with results from Selsted et al. (2012), who reported stimulated rates during three consecutive winter periods in a Danish N-limited *Calluna-Deschampsia*-heathland exposed to FACE at 510 ppm (CLIMAITE study). Fumigation was carried out all year-round except during periods with full snow cover. Contrary to our results, in the CLIMAITE study, the stimulatory effect of  $e\text{CO}_2$  on soil respiration persisted throughout most of the year, i.e. also in summer and not only during winter. However, in the CLIMAITE study, monthly soil respiration measurements were carried out within the first three years after the experimental start and may therefore reflect short-term responses, driven by the initial CO<sub>2</sub> step increase (Klironomos et al., 2005). Thus the results are not completely comparable to this study where measurements were carried out in the 11th–13th year of CO<sub>2</sub> enrichment.

To our knowledge, the Duke Forest FACE is the only other FACE experiment where soil respiration was measured in an evergreen ecosystem year-round for several years and after long-term fumigation with  $e\text{CO}_2$  (+200 ppm). On average, soil respiration was significantly higher by 23% under  $e\text{CO}_2$ . Jackson et al. (2009) summarized, after 10 years of CO<sub>2</sub> enrichment, that the greatest stimulation of soil respiration under  $e\text{CO}_2$  occurred from midsummer to early fall, in contrast to our observations, during winter the CO<sub>2</sub> response of soil respiration was weakest. However, fumigation was stopped at the Duke Forest FACE when ambient air temperature dropped below 5 °C for more than one hour.

After short-term enrichment with  $e\text{CO}_2$  (550 ppm) on a mixed plantation of *Populus* species (EuroFACE; in the 4th and 5th year of enrichment), Lagomarsino et al. (2013) recorded much larger stimulation of soil respiration during the vegetation (up to



111 % enhancement) than dormant season (40 % enhancement), when fumigation was stopped, which is also contrary to our results. However, experimental setup and climate differed from our site. While minimum soil temperatures reached  $-1.7^{\circ}\text{C}$  in the GiFACE experiment during winter (Fig. 2b), comparably warm and mild winters without sub-zero temperatures were typical at the EUROFACE site located in Italy. Moreover, the *Populus* plantation was a fertilized agro-ecosystem, where coppicing was carried out every three years, while the GiFACE was an old established, species-rich ecosystem where N-supply was limited.

In line with results from the EuroFACE but in contrast to our findings, Volk and Niklaus (2002) did not observe any wintertime increase in the ecosystem  $\text{CO}_2$  efflux from a calcareous grassland in response to three years of  $\text{CO}_2$  enrichment (600 ppm) with a screen-aided  $\text{CO}_2$  enrichment facility.

Investigations from the GiFACE experiment showed that  $\text{N}_2\text{O}$  emissions also exhibited a “seasonality response”, with the greatest stimulation of  $\text{N}_2\text{O}$  emission under  $e\text{CO}_2$  being observed in late-summer and autumn (Kammann et al., 2008). These findings are in line with the hypothesis that the driving mechanism of the  $e\text{CO}_2$  seasonality responses of enhanced microbial activity may have been related to the mineralization of previously accumulated organic matter, fuelling denitrification (Kammann et al., 2008).

### 4.3 Root derived soil respiration

Increased root biomass was frequently recorded under  $e\text{CO}_2$  (Rogers et al., 1994; Jastrow et al., 2000; Lukac et al., 2009), potentially affecting soil respiration rates (Zak et al., 2000). However, at the GiFACE, root biomass, picked with forceps (for set time intervals per sample,  $n = 3$  per FACE ring), was only different in December 2005 between the  $\text{CO}_2$  treatments but not at other dates during 2004–2007 (Lenhart, 2008) or in November 2011 (unpublished results). Lenhart (2008) observed in the GiFACE  $e\text{CO}_2$  plots, using Keeling plots and two-component mixing models that the fraction of root-derived  $\text{CO}_2$  (root- and root-exudate respiration and fine root decay), as part of the

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total soil CO<sub>2</sub> efflux was lower in winter than during the vegetation period. Accordingly, during winter times, the soil CO<sub>2</sub> efflux originated mainly from microbial soil respiration.

Higher fine root turnover under *e*CO<sub>2</sub>, resulting in higher C input via root necromass could explain increased *autumn* soil respiration but unlikely the wintertime increase in soil CO<sub>2</sub> efflux at the GiFACE since root necromass was not changed under *e*CO<sub>2</sub> in November 2011 (unpublished results). Alternatively, differences in the root necromass could already have been decomposed at this time of sampling or may be observed later in the year, so that “enhanced fine root decomposition” as cause of the *autumn* and *wintertime* soil respiration increase under *e*CO<sub>2</sub> cannot be ruled out.

#### 4.4 Temperature dependence of soil respiration

We observed that the temperature dependence of soil respiration was different in *autumn* compared to other seasons, whereas *e*CO<sub>2</sub> did not change the relationship of soil respiration to temperature. During *autumn*, soil temperatures were at the same range as during *spring* and *summer*, but soil respiration was on average lower (Fig. 5a). This pattern could reflect the higher proportion of root respiration (due to active root growth and assimilate allocation to exudates) during *spring* and *summer*, as observed by Lenhart (Lenhart, 2008). Boone et al. (1998) found a greater temperature sensitivity of root respiration than microbial respiration, whereas, Bååth et al. (2003) contradicted this finding in a microcosm experiment where different fractions of soil respiration had the same *Q*<sub>10</sub> relationship. They suggested that the intensity of light, and thus the intensity of photosynthetic carbon gain and its availability for root-derived soil-respired C, may co-vary with temperature in field studies, probably explaining different temperature dependencies of soil respiration between seasons. In summary, the lack of a difference between ambient and *e*CO<sub>2</sub> soil respiration temperature functions suggests that there is no need to account for a special “*e*CO<sub>2</sub> temperature sensitivity effect” in larger scale models of temperate-grassland CO<sub>2</sub> exchange under future CO<sub>2</sub>-enriched atmospheres.

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## 4.5 N availability

Since soil microorganisms require C as well as N for maintenance and growth (De Graaff et al., 2006; Zak et al., 1993), N availability plays an important role in determining soil CO<sub>2</sub> efflux. Moreover, the build-up of stable humus compounds (C : N ratio of 10–11), as a potential negative (dampening) feedback of rising CO<sub>2</sub> atmospheres, requires sufficient quantities of N. Root respiration rates were observed to correlate with tissue nitrogen concentration (Burton et al., 1996, 1998), whereas nitrogen affected microbial respiration in a complex pattern (Magill and Aber, 1998; Saiya-Cork et al., 2002; Ågren et al., 2001). In the Giessen-FACE, eCO<sub>2</sub> caused reduced tissue N concentrations and higher C : N-ratios of aboveground plant biomass (Kammann et al., 2008). In line with these findings is the observation of Lenhart (2008), who found a lower fraction of root derived CO<sub>2</sub> on soil respiration with increasing atmospheric CO<sub>2</sub>. Furthermore, eCO<sub>2</sub> induced a shift of available NO<sub>3</sub><sup>-</sup> towards NH<sub>4</sub><sup>+</sup> at the study site (Müller et al., 2009), a typical feature of N-limited ecosystems to retain mineral N (Rütting et al., 2008; Huygens et al., 2008). Through freezing effects in winter, mineral N, which was immobilized into the microbial biomass shortly after fertilizer application in spring, became partly available again (Müller et al., 2003). It is possible that N, as a limiting factor in the temperate grassland, may partly be responsible for the increase in soil C loss during the *autumn* and *winter* season under eCO<sub>2</sub>.

## 4.6 Microbial community

Multiple observations from the GiFACE indicated that increases in winter soil respiration under eCO<sub>2</sub> were largely associated with microbial respiration (including rhizosphere microbiota). Recent studies from other FACE sites detected differences between microbial communities at eCO<sub>2</sub> compared to ambient CO<sub>2</sub> (Drigo et al., 2008, 2009). At the GiFACE, stimulated rhizosphere-C utilization by arbuscular mycorrhizal fungi were found under eCO<sub>2</sub> by a <sup>13</sup>C-PLFA study (Denef et al., 2007), which may have contributed to altered soil respiration. Recent measurements in 2013 did not in-

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dicating any differences in the abundance of bacteria and archaea between the ambient and  $e\text{CO}_2$  plots (K. Brenzinger, personal communication, 2013) so that this can be ruled out as a cause for differed soil respiration between the  $\text{CO}_2$  treatments if this observation persists throughout *autumn* and *winter*.

#### 4.7 Soil moisture

Several studies showed that  $e\text{CO}_2$  can affect soil moisture (Niklaus et al., 1998; Field et al., 1995; Hungate et al., 1997), which in turn regulates soil respiration. However, the GiFACE is a rather wet permanent grassland with a shallow water table, where no significant effect of  $e\text{CO}_2$  on the soil water content was observed after 13 years of enrichment (Meine, 2013). Consequently, a  $\text{CO}_2$ -induced soil moisture effect is unlikely governing increased soil respiration rates; but still, enhanced anaerobicity due to enhanced microbial activity, as experimentally produced e.g. by Sehy et al. (2004), cannot completely be ruled out. However any hypothetical aerobicity change, if present at all in the GiFACE, was not large enough to affect the performance and composition of the methanogenic community in the 11th year of  $\text{CO}_2$  enrichment (Angel et al., 2012), which is a sensitive indicator for aerobicity changes.

However, it can be assumed that annual dynamics of soil moisture with wettest conditions in winter, i.e. close to saturation, and driest conditions in summer (Fig. 2a) contributed to the seasonal dynamics of soil respiration under  $e\text{CO}_2$  due to diffusion limitations. Analysis of stable isotopes revealed a distinctive  $\delta^{13}\text{CO}_2$  gradient in soil during winter with decreasing signatures with depth but a homogenous  $\delta^{13}\text{CO}_2$  profile during vegetation period at our study site (Lenhart, 2008). The absence of a  $\delta^{13}\text{CO}_2$  gradient during summer was likely due to improved diffusive mixing of soil air in the profile during dry soil conditions. It appears that under dry conditions,  $\text{CO}_2$  from deeper soil layers diffused towards the surface and altered the  $\delta^{13}\text{C}$  gradient, which corresponded to trace gas dynamics observed in the same grassland soil (Müller et al., 2004). Accordingly,  $\text{CO}_2$  diffusion was slowed down at times of high soil moisture, coinciding with

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limited oxygen supply (Skopp et al., 1990). At these times, soil respiration was likely originating to a major part from the topsoil. However, increased *autumn* soil respiration under  $e\text{CO}_2$  cannot be attributed to this phenomenon since soil water content is relatively low at this season (Fig. 2a). We suggest that increased substrate supply under  $e\text{CO}_2$  from end-of-season dieback of roots and the root-associated microbiome may explain stimulated soil respiration rates in *autumn*.

#### 4.8 Freeze/thaw cycles

Freeze/thaw cycles are known to mobilize previously inaccessible C- and N-substrates (Goodroad and Keeney, 1984; Kammann et al., 1998; Röver et al., 1998; Müller et al., 2002; Edwards and Cresser, 1992), providing substrates for heterotrophic activity. Frost events occurred during the study at the GiFACE from end of December 2008 to February 2009 (Fig. 2c). The relative change of soil respiration under  $e\text{CO}_2$  was 17%, 12% and 5% from January to March 2009 respectively (Fig. 2d), showing a more pronounced stimulation in these periods than during the vegetation period, apart from October 2010 (12% increase under  $e\text{CO}_2$ ).

#### 4.9 Plant community

Another aspect which may have contributed to altered soil respiration rates under  $e\text{CO}_2$  is a shift in the plant community composition. Grüters et al. (2006) observed that summer-greens decreased, whereas evergreens increased under  $e\text{CO}_2$  in the GiFACE experiment. Since soil respiration is controlled by substrate supply via rhizodeposition (Verburg et al., 2004; Wan and Luo, 2003; Craine et al., 1999), higher photosynthetic activity in  $e\text{CO}_2$  plots during mild dormancy periods may have contributed to the observed increase in soil respiration. In addition, since the vegetative aboveground growth is dormant and does not provide an assimilate sink, the relative proportion of assimilate partitioned below-ground towards the root-associated micro-biota may increase, contributing to the relative increase under  $e\text{CO}_2$  during the off-season. The higher

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abundance of evergreens at  $e\text{CO}_2$  also underlines the importance of a year-round  $\text{CO}_2$  enrichment strategy in such ecosystems with the respective climatic conditions. To date, increased winter soil respiration at  $e\text{CO}_2$  was only found in FACE experiments with year-round fumigation and a photosynthesizing at least partly green canopy, i.e. in the CLIMAITE study (Selsted et al., 2012) and in this study.

## 5 Conclusions

In conclusion, our results demonstrated the importance of wintertime soil respiration measurements, by showing that soil respiration was increased during *autumn* and *winter* after moderate long-term  $e\text{CO}_2$ . Measurements and year-round  $\text{CO}_2$  enrichment should not be neglected, at least in winter-green temperate ecosystems. Studies in such ecosystems excluding measurements during the dormant season may thus underestimate the effect of  $e\text{CO}_2$  on annual soil-respiratory  $\text{CO}_2$  losses (i.e. leading to an overestimation of C sequestered). Consequently, winter soil  $\text{CO}_2$  fluxes may play a crucial role in determining the carbon balance and dynamics of temperate grassland ecosystems. Our results indicate that temperate European grasslands which are characterized by a greenhouse gas balance near zero (Soussana et al., 2007) may gradually turn into greenhouse gas sources with rising atmospheric  $\text{CO}_2$  due to enhanced  $\text{CO}_2$  losses during autumn and winter, in particular if  $\text{N}_2\text{O}$  emissions are significantly increased as observed in the GiFACE (Kammann et al., 2008; Regan et al., 2011).

To generalize and explain the variation in the temporal dynamics of soil respiration under  $e\text{CO}_2$  more studies of wintertime C dynamics under long-term  $e\text{CO}_2$  are required. For such future studies it is advisable to include frequent samplings of root biomass, including the fine root fraction and necromass, in particular during the autumn/winter period under  $e\text{CO}_2$ . Another beneficial research strategy may be combined (pulse) labelling of  $^{15}\text{N}$  and  $^{13}\text{C}$  to elucidate gross C and N turnover processes after long-term (> 10 years) of  $\text{CO}_2$  enrichment to study the C-N gross dynamics and associated carbonaceous gas losses.

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**Table 1.** Results of fitting the temperature-dependence model after Lloyd and Taylor (Lloyd and Taylor, 1994) to 20 % of our observation data under ambient and elevated CO<sub>2</sub>.

CO <sub>2</sub> treatment	<i>R</i>	Rsqr	Adj Rsqr	Standard Error of Estimate
Ambient CO <sub>2</sub>	0.87	0.75	0.75	1.35
Elevated CO <sub>2</sub>	0.91	0.82	0.82	1.19



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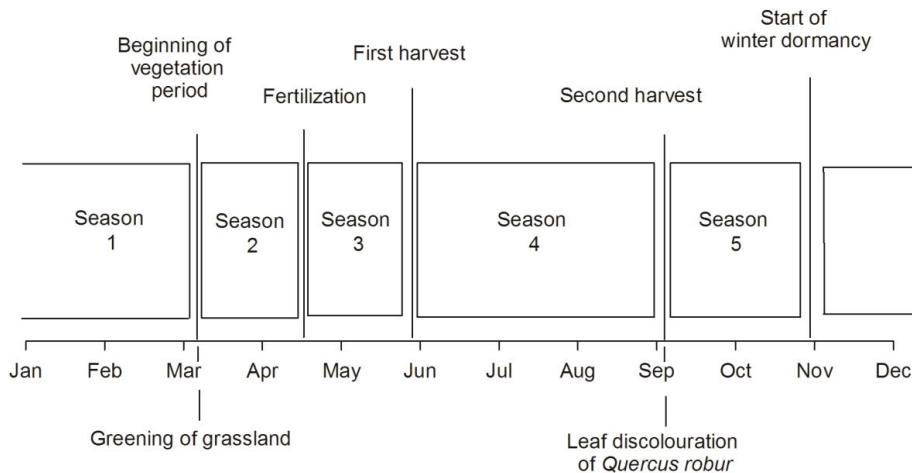
**Table 2.** Annual sums of soil respiration under ambient and eCO<sub>2</sub> from 2008–2010. Data are presented as averages ( $n = 3$ )  $\pm$  standard error (SE).

Year	CO <sub>2</sub> treatment	Mean annual sum of soil respiration (g CO <sub>2</sub> m <sup>-2</sup> yr <sup>-1</sup> )	Mean annual sum of soil respiration (g C[CO <sub>2</sub> ] m <sup>-2</sup> yr <sup>-1</sup> )	Relative change to control (%)	<i>P</i> value
2008	Ambient CO <sub>2</sub>	4853.93 $\pm$ 33.84	1323.80 $\pm$ 9.23	1.22	0.17
	Elevated CO <sub>2</sub>	4913.38 $\pm$ 14.20	1340.01 $\pm$ 3.87		
2009	Ambient CO <sub>2</sub>	4928.00 $\pm$ 48.34	1344.00 $\pm$ 13.18	0.56	0.64
	Elevated CO <sub>2</sub>	4955.74 $\pm$ 39.08	1351.56 $\pm$ 10.66		
2010	Ambient CO <sub>2</sub>	4702.44 $\pm$ 36.69	1282.48 $\pm$ 10.01	1.38	0.23
	Elevated CO <sub>2</sub>	4767.22 $\pm$ 11.47	1300.15 $\pm$ 3.13		

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**Figure 1.** Seasonal patterns and the five defined seasons at the GiFACE grassland study site.

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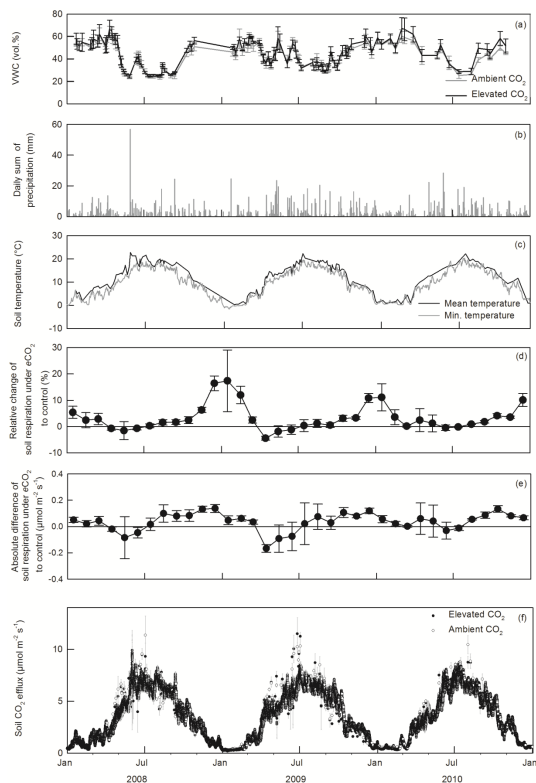
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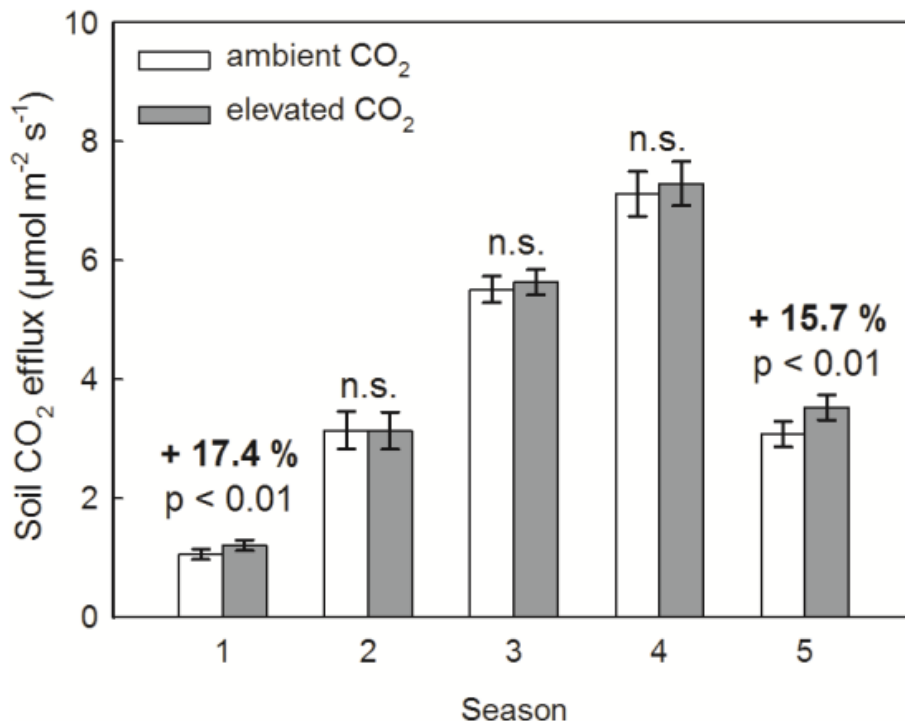
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**Figure 2.** Volumetric water content under ambient and elevated CO<sub>2</sub> (a), daily sums of precipitation at the GiFACE (b), mean soil temperature during soil respiration measurements and minimum daily soil temperature at 10 cm depth (c), the relative mean monthly change of soil respiration under elevated CO<sub>2</sub> based on observed and modelled data (d), the absolute mean monthly difference in soil respiration under elevated CO<sub>2</sub> based on observed and modelled data (e) and soil respiration under ambient and elevated CO<sub>2</sub> per measurement from 2008 to 2010 based on observed and modelled data (f). Data are presented as averages ( $n = 3$ )  $\pm 1$  SE.



**Figure 3.** Mean soil respiration rates during the five defined seasons under ambient and elevated CO<sub>2</sub> averaged over three years from 2008–2010; (1) = *winter dormancy*; (2) = *start of vegetation period*; (3) = *spring*; (4) = *summer*; (5) = *autumn* (for details see methods).

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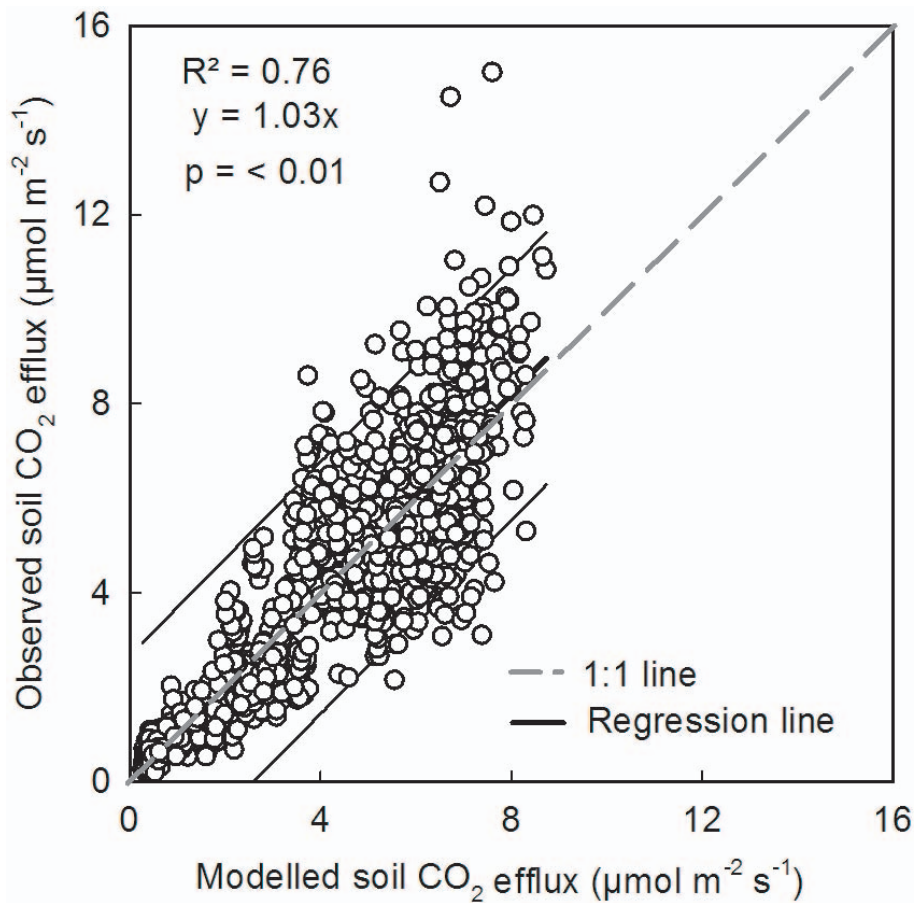
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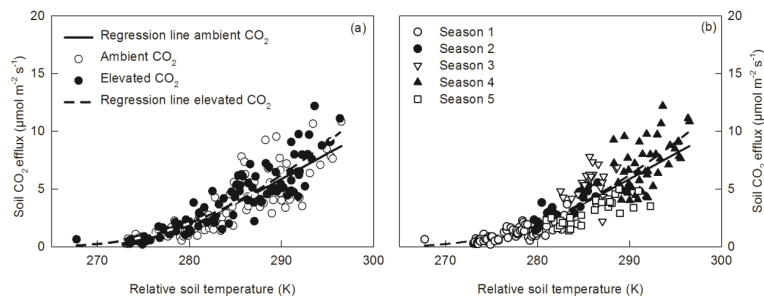




**Figure 4.** Observed vs. modelled soil respiration rates under ambient and elevated CO<sub>2</sub>.

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**Figure 5.** Relationship between soil respiration rate and soil temperature under ambient and elevated CO<sub>2</sub> (a) and temperature dependence of soil respiration under ambient and elevated CO<sub>2</sub> during different seasons (b). Equation of dynamic fit (Lloyd and Taylor, 1994):

$$f = R10e^{E0\left(\frac{1}{(283.15-T0)} - \frac{1}{(x-T0)}\right)}$$

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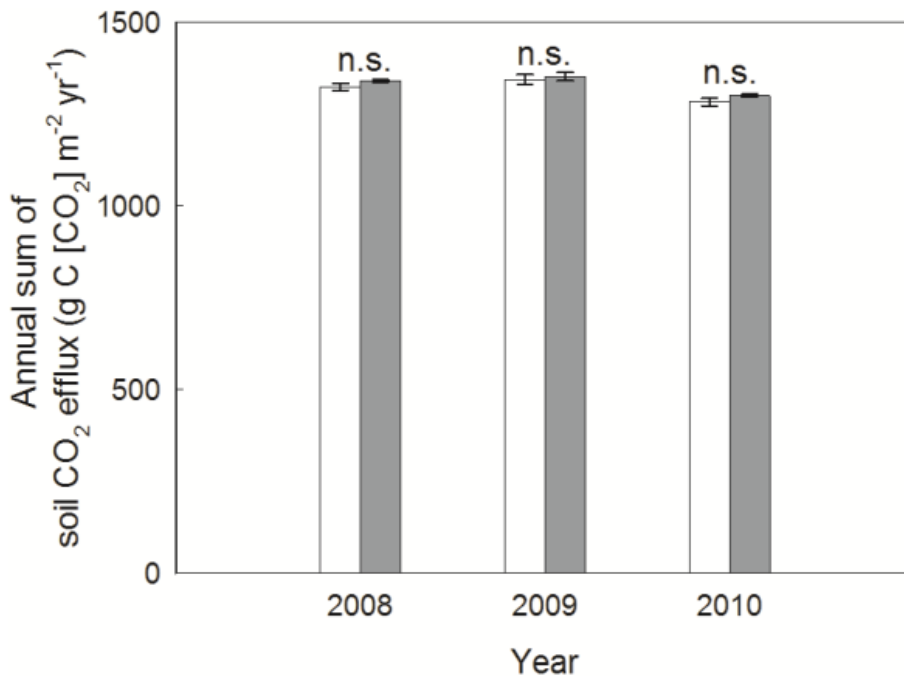
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**Figure 6.** Annual sums of soil respiration under ambient and elevated CO<sub>2</sub> for 2008–2010 based on observed and modelled data. Error bars represent ±1 SE of the mean.

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