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Drought effects on soil CO_2 efflux in a cacao agroforestry system in Sulawesi, Indonesia

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Abstract

Climate change induced droughts pose a serious threat to ecosystems across the tropics and sub-tropics, particularly to those areas not adapted to natural dry periods. In order to study the vulnerability of cacao (*Theobroma cacao*) – *Gliricidia sepium* agroforestry plantations to droughts a large scale throughfall displacement roof was built in Central Sulawesi, Indonesia. In this 19-month replicated experiment, we measured soil surface CO_2 efflux (soil respiration) in three simulated drought plots compared with three adjacent control plots. Soil respiration rates peaked at intermediate soil moisture and decreased under increasingly dry conditions (drought induced), but also decreased when soils became water saturated, as evidenced in control plots. The simulated drought plots exhibited a slight decrease in soil respiration compared to the control plots (average 13% decrease). The strength of the drought effect was spatially variable – while some measurement chamber sites reacted strongly ("responsive") to the decrease in soil water content (up to R^2=0.70) (n=11), others did not react at all ("non-responsive") (n=7). The degree of soil CO_2 respiration drought response was highest around cacao tree stems and decreased with distance from the stem (R^2=0.22). A significant correlation was measured between "responsive" soil respiration chamber sites and sap flux density ratios of cacao (R=0.61) and *Gliricidia* (R=0.65). Leaf litter CO_2 respiration decreased as conditions became drier. During dry periods the litter layer contributed approximately 3–4% of the total CO_2 efflux and up to 40% during wet periods. A CO_2 flush was recorded during the rewetting phase that lasted for approximately two weeks, during which time accumulated labile carbon stocks mineralized. The net effect on soil CO_2 emissions over the duration of the experiment was neutral, control plots respired 11.1±0.5 Mg C ha^{-1} yr^{-1}, while roof plots respired 10.5±0.5 Mg C ha^{-1} yr^{-1}.

1 Introduction

In recent decades, Indonesia has experienced severe droughts that were related to El Niño Southern Oscillation (ENSO) events (Quinn et al., 1978; Sheffield and Wood, 2008). Some climate prediction models suggest that droughts in Indonesia may become more frequent and more severe in the future (Sheffield & Wood 2008; Timmermann et al., 1999). Changes in precipitation patterns due to climatic change, including droughts, will have direct effects on agricultural productivity (Sivakumar et al., 2005) and the terrestrial biosphere carbon cycle (Tian et al., 2000). Understanding how ecosystems and specifically carbon stock dynamics respond to droughts is important given the feedback potentials to the atmosphere from carbon dioxide (CO_2) emissions. Decreases in precipitation have been shown to affect plant root dynamics, litter fall, soil organic matter decomposition, nutrient mineralization rates, as well as soil aeration – which in turn affects gas diffusion and microbial processes (Davidson et al., 2004). Exactly how an ecosystem will react to drought conditions is largely dependent on the mechanisms it has available to adapt to droughts. The presence or absence of deep root systems is one such mechanism. Studies carried out in tropical forests of Latin America suggest that ecosystems with deep rooted trees are more capable to mitigate drought effects (Davidson et al., 2004; Nepstad et al., 1994).

Droughts in Indonesia pose a potential threat to both natural forest ecosystems and agricultural production systems such as cacao (*Theobroma cacao*). In the last 25 years, Indonesia has experienced a boom in cocoa production and has since become the third largest producer of cocoa beans worldwide (FAO, 2009). Nearly 80% of the cocoa beans produced in Indonesia are grown in Sulawesi. It is unknown how well cacao agroforestry plantations are adapted to drought conditions, although a recent socio-economic survey by Keil et al. (2008) in central Sulawesi found that cocoa production is vulnerable to drought. Unlike cacao trees which tend to have a shallow rooting architecture (Kummerow et al., 1982), agroforestry over-story trees such as *Gliricidia* (*Gliricidia sepium*) often have deeper root systems.

To date, little has been published on below-ground carbon dynamics in agroforestry systems (Bailey et al., 2009; Hergoualc'h et al., 2008; Oelbermann et al., 2006), and as far as we are aware, no soil CO_2 efflux measurements have been carried out in tropical agroforestry systems in relation to drought stress. In a replicated experiment, we investigated how a cacao – *Gliricidia* agroforestry plantation in central Sulawesi, Indonesia reacted to an experimental drought. In an earlier paper by Schwendenmann et al. (2009) it was shown that this agroforest was surprisingly resilient to drought which was explained by a combination of complementary use of soil water resources and acclimation. Here we report how the experimental drought affected soil CO_2 production and efflux. The specific research objectives for this study were twofold:

1. to determine how below-ground carbon dynamics (specifically CO_2 production) reacted to a simulated drought and the subsequent rewetting phase;
2. to identify the controls driving CO_2 production.

At the beginning of the experiment we suspected that this agroforestry system would be vulnerable to drought stress and we hypothesized that soil respiration rates will show strong decreases across the plantation with the severity and duration of the drought affecting the degree of the CO_2 drought response. Furthermore, if the drought becomes so severe that there is significant root mortality CO_2 emissions may become more difficult to predict, as a drought-induced reduction in root and heterotrophic respiration may be compensated for by an increase in dead roots which may lead to an increase in decomposition. Finally, during the rewetting phase following the drought we expected a strong increase in CO_2 production in the drought plots.

2 Materials and methods

2.1 Site description

The drought simulation experiment was conducted in a seven year old cacao agroforestry plantation on the western periphery of the Lore Lindu National Park (1.552° S, 120.020° E) in Central Sulawesi, Indonesia at an elevation of 560 m above sea level (a.s.l.). Established in December 2000, the plantation was composed of a *Gliricidia* (*Gliricidia sepium* (Jacq.) Kunth ex Steud.) overstory (~330 trees ha^{-1}) and a cacao (*Theobroma cacao* L.) understory (~1030 trees ha^{-1}). The ground was largely devoid of undergrowth herbs and grasses except for a few patches of grass in open areas. We selected a site that was located on a gentle slope (8–12°), where the ground water table (>4.5 m) was deeper than the tree rooting zone. The region experiences two mild rainy seasons per year. The average annual precipitation at the Gimpu meteorological station (417 m a.s.l.) five kilometers south of the experiment site was 2092 mm. The mean annual temperature for 2002–2006 was 25.5 °C (Schwendenmann et al., 2009).

The soil has been classified as a Cambisol with a sandy loam texture (Leitner and Michalzik, unpublished data). The top 75 cm of soil has a relatively homogeneous texture, a stone content of 15–25% and a bulk density of 1.31 ± 0.06 g cm^{-3}. Below 75 cm the sub-soil is heterogeneous, made up of saprolite, irregular granitic rock fragments embedded in a quartz-feldspar rich loam. The bulk density of the subsoil is 1.56 ± 0.08 g cm^{-3}.

While the majority of cacao fine roots (diameter <2 mm) are predominantly concentrated at the soil surface (0–0.40 m depth), the *Gliricidia* fine roots penetrate to greater depths (Moser et al., 2009. Fine roots of both tree species extended to a depth of 2.4 m.

2.2 Experimental design

We established the experiment in a stratified random design using six plots in a one hectare area. Each plot was 40×35 m in dimension. Three plots were left undisturbed (control) while three treatment plots, hereafter called "roof plots", were used to simulate drought conditions. In the simulated drought plots we built a transparent roof below the plantation canopy to divert throughfall away from the plot. The roof was built at a height of approximately 1.2 m and consisted of approximately 1500 individual bamboo panels (0.5×4.6 m) which were covered by polyethylene plastic sheets. The roof was initially 60% closed, where small gaps were located around the tree stems and between some panels. In January 2008 the roof closure was further increased to approximately 80%, by building smaller panels to close some of the bigger gaps. Runoff was diverted into a series of wooden, plastic lined gutters and channeled down-slope of the plot. Every two weeks leaf litter that accumulated on the roof panels was transferred back to the soil surface. Temperature, humidity and incident radiation under the panels were unaffected by the establishment of the roof. Along the perimeter of each plot we dug a 0.4 m trench and lined it with plastic so as to prevent lateral and surface water flows from entering the plots.

All measurements were made within a "core zone" (30×25 m) in the plot, leaving a 5 m buffer zone along the inside of the plot boundary to avoid edge effects. Per plot one central soil pit (0.8 m width×1.6 m length×3.0 m depth) was dug and equipped with gas samplers, thermocouples and soil moisture probes. Three parallel transects per plot were set up within the "core zone" for soil CO_2 flux measurements.

The experiment began on 27 January 2007 with a one month (33 d) baseline evaluation phase (pretreatment) during which conditions prior to roof closure were evaluated. The roof was closed on 1 March 2007 and remained closed for 13 months (404 d). After the roof opening on 10 April 2008 measurements continued for an additional five months to 27 August 2008 (141 d) to monitor the recovery of the ecosystem.

2.3 Soil surface CO_2 efflux measurements

We determined the soil surface CO_2 efflux (soil respiration) using dynamic closed chambers (Norman et al., 1992; Parkinson, 1981). At each plot, two circular polyvinyl chloride (PVC) chamber bases (0.045 m^2 area, 0.15 m height) were deployed in each of three parallel transects. In total six chambers were established per plot. Chamber bases were embedded 1–2 cm into the soil surface. At each chamber base we removed all emergent vegetation prior to measurement, and fanned the air above the chamber for at least one minute in order to bring the soil surface CO_2 concentrations to near atmospheric concentrations. We also measured the chamber height at three places around the chamber base to get a good estimate of air volume within the chamber headspace. Measurements entailed attaching a chamber hood (12 cm height) tightly to the chamber base. Air in the headspace was subsequently circulated by a small battery-operated pump at a rate of 0.8 L min^{-1} between the chamber and an infrared CO_2 gas analyzer (IRGA) (LI-800; Li-Cor Inc., Lincoln, NE, USA). The chamber was closed for 5 min 30 s. Atmospheric pressure was maintained within the chamber during measurements by using a small metal vent (0.1 cm in diameter and 2.5 cm length) installed on top of the chamber hood. Carbon dioxide concentrations were recorded every 5 s using a datalogger (Campbell CR800). A two point calibration of the infrared CO_2 gas analyzer was done in the laboratory between measurement campaigns. The first point calibration was with a "zero" standard gas, which was created by removing CO_2 from the air by running air in a loop through a scrubber column of soda lime (4–8 mesh). The second point calibration was made using a CO_2 standard gas (700 ppm, Deuste Steininger GmbH, Mühlhausen, Germany), while a third CO_2 standard gas (356 ppm, Deuste Steininger GmbH, Mühlhausen, Germany) was used to test the quality and accuracy of the calibration.

Soil respiration flux was calculated from a 2.5 min time window during which CO_2 concentrations increased linearly; the coefficient of determination (R^2) usually exceeded 0.993. Simultaneous to CO_2 efflux sampling we measured soil and air tem-

perature with a handheld electronic thermometer (Greisinger GMH 3210) with a 12 cm measurement probe, and soil moisture using a portable TDR (Campell Scientific Hydrosense – CS620) unit at 3 points around the chamber base. Measurements were made every two weeks between 8 a.m. and 5 p.m. The sequence in which plots were measured was randomized during each sampling campaign to minimize effects from diurnal fluctuations. In total, 36 soil respiration measurements were made per sampling campaign using the portable infrared CO_2 gas analyzer. During the experimental period we carried out 47 measurement campaigns. Due to an equipment failure with the IRGA we did not measure soil respiration in August 2007.

To study the contribution of leaf litter to CO_2 efflux, we randomly selected six experiment chambers in the control plots. At each of these six sites, two additional chambers were installed directly adjacent to the "main" chamber (<1 m away). We removed litter from one chamber and placed it into the second chamber. The "main" chamber was left undisturbed and used as a control. The difference in CO_2 efflux between the three chambers was compared. Measurements were made during 36 measurement campaigns.

2.4 Soil air CO_2 concentrations and soil moisture depth profiles

Gas samples for CO_2 concentration analyses were collected from one central soil pit per plot. Samples were taken on a bi-weekly basis in tandem with the soil surface respiration measurements. The gas samplers consisted of thin stainless-steel tubes (1 mm inner diameter), where one end was perforated with small holes and the other end was fitted with an airtight septum holder. The samplers were inserted horizontally into the soil profile at 10, 20, 40, 75, 150 and 250 cm depths. Samplers in the top 75 cm were 1 m in length, while the samplers inserted at greater depths (150 and 250 cm) were slightly longer (1.5 m) to take into consideration the diffusion losses near the soil pit wall. Each sampler was equipped with a thermocouple (Type K) at its tip so that temperature could be recorded at the time of sampling with a handheld unit (Greisinger GMH 3210). Before taking a gas sample, 5 mL of air was extracted and

discarded to clear the sampler of any stagnant "dead" air. We took the gas samples by connecting a pre-evacuated, air-tight glass vial (50 mL) to the sampler's septum holder with a syringe needle and short flexible plastic tube and then opened a two-way stop valve on the glass vial to suck in the gas sample. A sample was also taken at the soil surface by sticking a polypropylene syringe (with 5 cm needle) into the ground and drawing a sample.

Samples were analyzed in a laboratory at Tadulako University in Palu, Sulawesi, within 72 h after collection in the field. We measured the CO_2 concentration of each sample using a gas chromatograph (GC) (GC-11, Delsi Instruments, Suresnes, France) with thermal conductivity detector (TCD). Sample CO_2 concentrations were calculated by comparing the integrated peak areas to that of two known standard gas concentrations (0.07% and 3.5%, Deuste Steininger GmbH, Mühlhausen, Germany), to make a two point calibration.

Additional to the CO_2 concentration and temperature measurements, we also measured volumetric soil water content using time domain reflectometry (TDR) sensors (Campbell CS616) in three soil pits per plot. TDR sensors were installed adjacent to each gas sampler, in the central pit, by inserting them into the undisturbed soil at the end of a 30 cm hole dug horizontally into the soil pit wall. Soil moisture was recorded hourly using a datalogger (Campbell CR1000). Due to high rock content we could not install TDR sensors in three plots at 250 cm depth. Using undisturbed soil samples we calibrated the water content measurements using the methodology described by Veldkamp and O'Brien (2000). Soil CO_2 concentration measurements were made during 46 field campaigns, in tandem with the IRGA soil respiration measurements. One additional field campaign was missed due to a large landslide that limited access to the site with the gas sampling equipment.

2.5 CO_2 leaching losses

To determine whether the downward flux from leaching accounted for an important CO_2 exit pathway we calculated the amount of CO_2 dissolved in water and linked it

with modeled drainage estimates. According to Henry's Law, CO_2 dissolved in water is proportional to the partial pressure of CO_2 above the solution and the CO_2 Bunsen absorption coefficient. When carbon dioxide dissolves into water it can produce two possible reactions (Eqs. 1 and 2). The solubilization of CO_2 gas:

$$CO_2\ (\text{gas}) \rightarrow CO_2\ (\text{aq}) \quad (1)$$

and hydration of CO_2 (aq) to form carbonic acid

$$CO_2\ (\text{aq}) + H_2O \rightarrow H_2CO_3\ (\text{aq}) \quad (2)$$

However, given the low proportion of H_2CO_3 (aq) relative to CO_2 (aq) it is possible to lump their concentrations together with Henry's law. The dissolved CO_2 was calculated as follows:

$$M\text{–}CO_2w = CO_2a \times VWC \times B \quad (3)$$

Where: $M\text{–}CO_2w$ is the CO_2 content dissolved in the liquid phase (g CO_2 m^{-3}), CO_2a is the partial pressure of CO_2 (concentration) in the soil air (g CO_2 m^{-3}) at atmospheric air pressure, VWC is the soil's volumetric water content and B is the Bunsen solubility coefficient for CO_2. The Bunsen coefficient is the volume of gas that can be absorbed by one cubic meter of water at standard atmospheric air pressure, at 24 °C, the CO_2 Bunsen coefficient is 0.7771 g m^{-3}.

Dissolved CO_2 was calculated for the gas samples taken at 250 cm soil depth and interpolated to give daily values of dissolved CO_2 throughout the duration of the experiment period. Subsequently, dissolved CO_2 was multiplied with daily modeled soil water drainage to determine CO_2 leaching losses. Soil drainage from roof and control plots were modeled using HYDRUS 1D (Šimůnek et al., 2008) with measured transpiration rates, net precipitation and soil water contents as input. The method has been described in greater detail in Köhler et al. (in preparation). Leaching losses were calculated only from 10 February 2007 to 5 June 2008 because of the shorter time frame in which soil water drainage was modeled.

2.6 Isotope analysis

To identify the origin of the high CO_2 concentrations in deep soil, $^{13}CO_2$ isotope signatures were measured. One soil air sample was taken from each plot at 250 cm depth, stored in airtight, stainless steel vials and transported to the Center for Stable Isotope Research and Analysis (KOSI, Georg-August-University Göttingen, Germany) for analysis using a Isotope Ratio Mass Spectrometer (Finnigan MAT Delta Plus, Bremen, Germany). The isotopic signature can indicate whether the CO_2 was produced either biologically or from geological origins.

2.7 Data analysis

We divided the experiment into three time periods: pre-treatment, treatment and post-treatment. Throughout the experiment, roof plot measurements were compared to adjacent control plots to decipher roof plot ecosystem drought response from normal fluctuations. Individual soil CO_2 efflux chamber measurements were averaged for each plot at each measurement date and logarithmically transformed to normalize data distributions. The significance of the drought effect difference was tested using mixed linear effects models for the three time periods mentioned above, the overall experiment period (from start to finish) and an extra time interval during the last three months of the treatment period during which drought effects were most pronounced. In the model, the desiccation treatment was considered a fixed effect while the measurement day (from day 1 to day 579) and plot were considered as random effects. Differences were considered significant if $P \leq 0.05$. Additionally, temporal autocorrelation in this time series CO_2 flux dataset was corrected for by using a first order autoregressive model.

The relationship between soil CO_2 efflux and soil surface temperature, *Gliricidia* and cacao sap flux densities, and chamber distance from tree stem were tested with linear regressions. The relationship between soil CO_2 efflux and soil moisture (at 10 cm) was tested using a non-linear inverse parabolic function. The reported coefficient of

determination (R^2) in the non-linear model was calculated in the same way as the linear model. All statistical analyses were done using the statistical package R version 2.8.1 (R Development Core Team, 2008).

3 Results

3.1 Volumetric soil water content and soil temperature

During the pre-treatment phase, volumetric soil water content of all six experiment plots were in the same range for each respective sampling depth (Fig. 1c). Approximately ten days after roof closure, soil water contents began to diverge between the control and roof plots. Soil moisture contents in the plots under the roof decreased simultaneously at all depths, apart from the depth of 250 cm depth which began drying out only after a period of two and a half months. Although gaps in the roof did permit some throughfall to enter, the water recharge was limited to the upper soil layers and was never enough to recharge the soil under roof to control plot levels. A natural drought in January–February 2008 reduced soil water contents in both roof and control plots. The drying effect was recorded down to 250 cm depth in the control plots. Minimum soil water contents in the roof plots were experienced during this dry spell. Upon roof opening in April 2008, soil water contents in the roof plots quickly rose to near control plot levels.

Soil surface temperature exhibited little fluctuation throughout the duration of the experimental period, ranging from a minimum temperature of 21.8 °C to a maximum temperature of 24.8 °C. The average soil temperature at 5 cm depth was unaffected by the roof installation, measuring 23.2±0.8 °C and 23.0±0.7 °C (mean±SD) for the roof and control plots, respectively. At 250 cm depth, soil temperatures were slightly higher than at the surface and averaged 24.0±0.4 °C (mean±SD).

3.2 Soil surface CO_2 efflux

Soil surface CO_2 efflux was highly variable in both space and time. Spatially, the average coefficient of variation of the 18 roof plot and 18 control plot chambers was 52% and 46% respectively over the period of the experiment. The temporal coefficient of variation for individual chamber measurements was slightly lower in the control plots (40%) in comparison to the treatment plots (53%).

During the pre-treatment phase, soil CO_2 efflux measurements were slightly higher in the roof plots as compared to the control, though not statistically significant (p=0.13) (Fig. 1a and Table 2). Following roof closure in March 2007, soil respiration rates in the roof plots began a slow decline that lasted until late October 2007. From early November until mid December 2007, roof plot respiration rates experienced a short lived peak followed by a second decline during a two month natural drought. Respiration rates reached a minimum level in late February 2008 and thereafter remained low until roof opening in April 2008. During the treatment period the control plots did not exhibit any distinct temporal trend although soil CO_2 efflux variability was highest during the first half year and less so thereafter.

The overall differences in average soil CO_2 efflux between the control and the roof plots were relatively minor. Soil CO_2 efflux declined only slightly in the control plots in comparison to the roof plots. On average, roof plots respired 13% less than the control plots, although this difference was not statistically significant (p=0.16). In the last three months of the simulated drought the onset of a natural dry spell in combination with improved roof closure resulted in a further decline in the soil CO_2 efflux. During this time the roof plots averaged 75% of the control soil respiration, a decline of 25% (p=0.03). Immediately upon roof opening, in April 2008, we measured a flush of soil CO_2. Within three days, soil CO_2 efflux exceeded the control plots by more than 15%. Over the next five months the average roof plot CO_2 efflux remained consistently above control plot efflux levels, although the treatment means were not significantly different (p=0.22). One roof plot chamber was removed from the analysis shortly after roof opening as it

suddenly began producing very high CO_2 fluxes.

The cumulative CO_2 respired from control and roof plots was not significantly different, indicating the drought had a CO_2 neutral effect (p=0.64). The cumulative CO_2 flux from the 579-day experiment was 17.5±0.75 Mg C ha^{-1} and 16.6±0.74 Mg C ha^{-1} for the control and roof plots, respectively. Annually this equates to 11.1±0.5 Mg C ha^{-1} yr^{-1} for the control plot and 10.5±0.5 Mg C ha^{-1} yr^{-1} for the roof plot.

Although the overall drought response in the roof plots was relatively moderate, 11 of the 18 efflux chambers in the roof plots exhibited stronger drought effects than the others (Fig. 3). Drought effects were most pronounced at chamber sites already producing high CO_2 before the roof closure. We used the coefficient of determination (R^2) of a linear regression between CO_2 efflux and the soil moisture as an index of drought response (hereafter called the "drought response index") and plotted it spatially (Fig. 2). The drought response appeared to be localized, as some chamber sites measured strong relationships to soil water content changes (up to R^2=0.70), while other chambers often located nearby measured little to no response to decreasing soil water contents.

Over the course of the 19-month measurement period, no distinguishable seasonal patterns in either precipitation (Fig. 1d) or in air temperature were measured (data not shown).

3.3 Controls regulating CO_2 efflux

Soil CO_2 efflux exhibited an inverse parabolic relationship with soil moisture (R^2=0.32, p=0.00) (Fig. 4). When conditions were either dry or extremely wet (saturated) soil respiration rates were low. Respiration rates peaked at intermediate soil water contents (0.37–0.41 m^3 m^{-3}) which coincided with field capacity (0.36–0.38 m^3 m^{-3}, from water retention curve measurements (van Straaten, unpublished data)). Soil temperature had little effect on soil CO_2 efflux. Only in the control plots did we find a significant,

but weak, positive relationship with soil temperature (R^2=0.16, p=0.01). There was no relationship found between soil moisture and soil temperature.

A weak diurnal pattern was detected in soil respiration, whereby CO_2 efflux was lowest early in the early morning before 8 a.m. and rose steadily throughout the day reaching a maximum in the late afternoon between 4 and 6 p.m. (Table 3). No nighttime measurements were made.

Soil respiration was found to decrease with distance from cacao tree stems (R^2=0.22, p=0.00), but showed not relationship with distance from *Gliricidia* trees. CO_2 efflux measurement chambers were established between 1.1 and 2.1 m from the nearest tree. In the roof plots, the CO_2 drought response index declined with distance from cacao tree stems (R^2=0.23, p=0.053), but showed no relationship with distance to *Gliricidia* tree stems.

3.4 Leaf litter respiration

The leaf litter layer contributed on average 16.8% of the total respired CO_2 efflux. Although we did not measure the moisture of the litter layer directly there is a strong indication that respiration rates were positively related to the moisture regime of the leaf litter. Soil moisture probes located at 10 cm soil depth showed a positive linear relationship (R^2=0.20, p=0.01) between soil moisture and the leaf litter CO_2 efflux contribution. In other words, when conditions were dry CO_2 efflux from the litter was low and did not contribute much to the overall soil flux (~3–4% of the total flux). However, when conditions were wet, leaf litter CO_2 efflux increased and became an important CO_2 production source contributing up to 40% of the overall CO_2 efflux. The leaf litter CO_2 contribution to the overall flux over the duration of experiment is shown in Fig. 5.

3.5 Soil profile CO_2 concentrations

Soil CO_2 concentrations increased with soil depth, displaying an exponential shape in concentration rise (Table 2), where concentrations near the soil surface (0–10 cm)

were relatively low and increased rapidly with depth (between 20–75 cm depth) and finally approached an asymptote at deeper soil depths (150–250 cm). Average CO_2 concentrations in the control plots over duration of the experiment period at 250 cm were 11.8% – this is more than 300 times higher than atmospheric CO_2. The highest recorded CO_2 concentration was 15.3% in October 2007 in one of the control plots.

During the pre-treatment period soil CO_2 concentrations in the control and treatment plots were similar for each respective soil depth (Fig. 6). Upon roof closure, CO_2 concentrations in the roof plots began to decline in tandem with the drying out of the soil profile. CO_2 concentrations declined steadily over the 13-month treatment period and reached a minimum level in the last month of the induced drought. CO_2 concentrations reached lows of between 17% (at 10 cm depth) and 52% (at 250 cm depth) of the control plot levels. During the driest period of the simulated drought the soil CO_2 concentration depth profile was nearly linear in shape, supposedly saturating at a deeper depth than from which we sampled. Although CO_2 concentrations in the control plots remained relatively constant throughout the treatment period, a sharp drop was measured at all soil depths in January–February 2008, during a phase of natural drought. When we opened the roof in April 2008, CO_2 concentrations rose quickly; within a one month period CO_2 concentrations at all depths rose to near control plot levels whereby CO_2 concentrations at shallower depths rebounded faster than in the subsoil. Thereafter, CO_2 concentrations leveled off, and remained lower than the control plot until the end of the experiment in August 2008.

The δC^{13} isotope signature of the six CO_2 gas samples was −23.63±0.19‰ (mean±SD) indicating that the CO_2 present in the soil profile is biologically produced and most likely produced by C_3 plants – e.g. cacao and *Gliricidia*.

3.6 CO_2 leaching losses

The control plots on average stored 93% of the total carbon dioxide in soil water as aqueous CO_2, while the remaining 7% was present in the gaseous phase. In the roof plots, on average 65% of the total CO_2 was dissolved in soil water.

Dissolved CO_2 drainage losses during the experiment period are shown in Fig. 1b. In the control plots CO_2 leaching losses spiked during periods of high drainage. They reached as high as 36.5 mg C m^{-2} h^{-1} (15% of the total CO_2 flux), on a single day. However, on average the CO_2 drainage in the control plots remained low at 3.5 mg C m^{-2} h^{-1}, which is 2.6% of the overall surface flux. In the roof plots, CO_2 leaching was even lower given the drier soil profile and reduced drainage discharge. During the treatment period soil water drainage approached zero. In these plots the CO_2 leaching losses were on average 0.82 mg C m^{-2} h^{-1}.

4 Discussion

4.1 CO_2 fluxes in a cacao agroforestry system

As far as we are aware this study represents the first in situ measurements of soil CO_2 dynamics of a cacao agroforestry ecosystem. Measured CO_2 efflux rates indicate that the ecosystem is very productive as respiration rates were within or slightly below the range measured in tropical forest ecosystems in Asia (Adachi et al., 2006; Ohashi et al., 2008), and in Latin America (Davidson et al., 2000, 2008; Schwendenmann et al., 2003; Sotta et al., 2006). Like most of these studies, soil CO_2 efflux was highly variable across the study sites. The cacao plantation exhibited a mild diurnal pattern (Table 3) in the CO_2 respiration, peaking in the mid afternoon between 14:00 and 16:00.

Prior to roof closure, three pretreatment one-day field campaigns showed no difference in the average soil respiration rates between the control and roof plots. Roof plot respiration averages were slightly higher than the control and are attributed to the higher bulk densities in the control plots.

The main controlling variable driving soil CO_2 efflux in this ecosystem was soil moisture. Soil respiration exhibited an inverse parabolic relationship with soil moisture, where respiration peaked at intermediate soil water contents and declined under both wetter and drier conditions (Fig. 4). Unlike the gradual decline observed in soil respira-

tion when conditions got drier, as was observed in the roof plots and will be discussed later, soil respiration rates in the control plots often plummeted when moist soil became slightly wetter. As a result, the CO_2 flux in the control plots exhibited strong efflux fluctuations with minor changes in soil moisture. The reduction in soil CO_2 efflux under the saturated conditions may be a result of a diffusion block that prevented CO_2 from exiting the soil through the saturated pore space, and/or prevented oxygen from diffusing into the soil – subsequently creating anaerobic conditions (Luo and Zhou, 2006).

CO_2 production from the leaf litter was sensitive to moisture conditions. When external conditions were wet, the litter layer could contributed as much as 40% of the total CO_2 efflux, however when conditions were dry, the CO_2 contributions from the litter layer was nearly zero percent.

Soil temperature displayed a slightly positive relationship with soil CO_2 efflux (data not shown). The temperature influence was however not very predominant given the small temperature variation (in total 3 °C) experienced during the 19 month experimental period. In contrast to studies conducted in rainforests in the Amazon basin (Wofsy et al., 1988) and in Costa Rica (Schwendenmann et al., 2003) the influence of solar radiation on plant photosynthesis was not measured in our soil respiration measurements for this site.

Dissolved CO_2 leaching beyond 250 cm soil depth proved to be only a minor CO_2 exit flux (Fig. 1b). Considering the high proportion of CO_2 stored in the liquid phase, the overall CO_2 leaching flux from below 250 cm was relatively low (3.5 and 0.8 mg C m^{-2} h^{-1} for control and roof plots, respectively). This is in line or slightly higher than CO_2 leaching fluxes reported by Schwendenmann and Veldkamp (2006) and Johnson et al. (2008). The diffusion of carbon dioxide through soil water along the CO_2 concentration gradient is considered negligible since liquid phase diffusion (in free water) is more than 8000 times slower than CO_2 transport through free air (Moldrup et al., 2000).

4.2 Drought effects on soil CO_2 efflux

In contrast to our initial hypotheses, the cacao agroforestry system did not exhibit a strong CO_2 efflux response to the induced drought. Instead, the average CO_2 efflux declined moderately (13%) in the roof plots in comparison to the adjacent control plots even though soil matrix potentials approached permanent wilting point (measured in the laboratory) in the roof plots. The overall muted CO_2 efflux response may be attributed to a number of reasons:

First, the nature in which CO_2 efflux responds to soil moisture may have obscured effect differences between control and roof plots. As has been observed in earlier studies (Davidson et al., 2000; Schwendenmann et al., 2003; Sotta et al., 2006), a pronounced peak of soil CO_2 emission was measured at intermediate soil water contents and declined under both drier and wetter conditions (Fig. 4). Therefore, when we compare average soil respiration rates between roof plots and control plots during a time when the roof plots were dry and when the control plots were saturated, not only would the measured respiration rates in the roof plots be depressed because of the induced drought, but respiration rates in control plots would also be lower because of the high soil water content.

Second, we suspect that different CO_2 production sources reacted differently to the drought stress; while some sources may have suppressed CO_2 production, other sources may have become more active – thereby producing confounding results. We have several indirect indications that different CO_2 sources reacted differently to drought stress. The first indirect indication comes from the spatial variability of soil respiration across the project area. While eleven efflux chamber sites in the roof plots showed relatively strong declines in soil CO_2 efflux as the soil dried out, the other seven efflux chambers, often just a few meters away, exhibited little to no reaction (Figs. 2 and 3). This localized drought response is indicative of the contrasting processes taking place directly below the respective chambers. The second indirect indication was that soil CO_2 efflux from chambers that exhibited strong drought re-

sponse correlated closely to the sap flux ratios of both cacao (R=0.61, p=0.00) and *Gliricidia* trees (R=0.65, p=0.00) as reported by Schwendenmann et al. (2009). In contrast, those chambers that did not exhibit a drought sensitive CO_2 efflux did not correlate significantly with sap flux density. Although this does not necessarily establish a causal relationship between soil CO_2 efflux and tree sap flux, it does however show that when tree metabolisms slowed down, we correspondingly measured lower CO_2 effluxes from the drought responsive efflux chambers. Our interpretation is that these drought responsive chambers, which had higher than average respiration rates even during the pre-treatment measurements, were situated above active roots and the onset of drought conditions induced tree drought stress which resulted in root respiration decreases. This is substantiated by the strong correlation between the average soil respiration prior to roof closure (pre-treatment) and the drought response index (R^2=0.76, p=0.00, n=18). This means that the high flux chambers were situated above already active CO_2 production sources, very likely active roots, which were susceptible to drought stress.

Furthermore, the drought effect on autotrophic respiration was again detected when examining the relationship between soil CO_2 efflux and the distance to tree stems. We found that the drought response index declined with distance from cacao tree stems suggesting that cacao rooting activity near the stem declined during the induced drought, while further away the effect was not as pronounced. We also found that average soil CO_2 respiration rates declined with distance from cacao tree stems in both control and roof plots. Soil compaction was excluded as a potential explanatory variable for these decreases, as bulk density cores taken at 0.25 m distance intervals outward from the tree stem to a maximum distance of 1.75 m, failed to show any systematic increases with distance (p=0.26, n=6 cacao trees). Stem flow and the potentially wetter conditions around the tree base was also excluded as an explanatory variable as we did not find an evident relationship between the average soil moisture and the respective distance to the tree.

Unlike the cacao trees, we did not observe similar tree distance relationships with

Gliricidia trees. This is thought to be primarily due to the deeper and more diffuse root architecture and rooting behavior exhibited by *Gliricidia* fine roots (Moser et al., 2009), which may have masked measurable effects with distance. A Deuterium (δD) study by Schwendenmann et al. (2009) found that tree water uptake was partitioned vertically in the soil horizon, where cacao accessed water from the upper horizons while *Gliricidia* explored for water in deeper soil layers.

Additionally, a root excavation exercise done by Moser et al. (2009) at the site, found that coarse roots of both cacao and *Gliricidia* were primarily concentrated around the tree stems while fine root (diameter <2 mm) distributions extended well into the agroforestry plantation. Other studies by Harteveld et al. (2008) and Kummerow et al. (1982) confirm that cacao fine roots extend well beyond the stem and are primarily concentrated in the uppermost 30 cm. Although overall autotrophic respiration rates appeared to decline, Moser et al. (2009) reported that cacao and *Gliricidia* fine root biomass remained unchanged at all soil depths to 250 cm, over the duration of the 13-month induced drought. These findings suggest that regardless of the drought stress, the trees still continued to maintain and build new fine roots required to search for available water resources.

The litter layer, as was previously mentioned, is sensitive to changes in moisture regimes. Therefore, given that the litter layer would have dried out relatively quickly, the effect on soil respiration would have also been correspondingly fast. By the end of the roof experiment, in April 2008, considerable amounts of leaf litter had accumulated on the ground of the roof plots, although leaf litter fall was unaffected by the induced drought (Schwendenmann et al., 2009). This is an additional indication that decomposition rates decreased under the drier conditions.

Although we have little data to substantiate how heterotrophic CO_2 respiration from soil microorganisms in the bulk soil reacted to the drought, the results from the leaf litter study clearly show that heterotrophic respiration is sensitive to droughts.

4.3 Belowground CO_2 dynamics

Baseline carbon dioxide concentrations in deep soil air were among the highest ever reported for soils. The average CO_2 concentration at 250 cm soil depth in the control plots was 11.8%, and peaked at 15.3%, during the 19-month experiment. As far as we are aware of no other study has found CO_2 concentrations of this magnitude so close to the soil surface. The δC^{13} isotope signature (−23.63‰) confirmed that the CO_2 was produced by biological sources and most likely originated from plants having a C_3 photosynthetic pathway – such as cacao or *Gliricidia*.

The high CO_2 concentrations in soils of the cacao agroforestry ecosystem are thought to be caused by a diffusion block that prevented CO_2 molecules from traveling upward along the concentration gradient to the atmosphere. Gaseous CO_2 diffusion was slowed down by the soil medium's high bulk density (low porosity), high concentration of coarse rock fragments as well as soil water. Each of these components would have increased the tortuousness of the gas pathway to the soil surface. During wet conditions CO_2 concentrations were high in the soil air, as the pore-space would have been saturated with water and resulted in slow diffusion. However, as soon as the soil dried out the CO_2 concentrations began to decline, as there were more open air filled pore-spaces available for CO_2 diffusion. This trend is apparent in both the roof plots (where we artificially manipulated the soil moisture) and in the control plots during a natural drought in January–February 2008 (Fig. 6). In and of itself, the soil air CO_2 concentrations do not say very much about the soil carbon allocation dynamics, but highlight the CO_2 storage capacity of the soil.

Attempts to determine CO_2 production shifts with time vertically within the soil profile by modeling CO_2 production from soil air CO_2 concentrations with a one dimensional gas transport model were not successful. We believe that due to the high rock fragment content and the heterogeneous composition of the sub-soil various assumptions required by the gas transport model were not met.

4.4 Rewetting phases

In November 2007, approximately halfway through the simulated drought period, soil respiration rates in the roof plots (at both drought responsive and non-responsive chamber sites) experienced a short lived rebound that lasted for approximately two months. The rebound coincided with two small rewetting peaks measured in the uppermost 40 cm of the soil, during an extended period of intense rain showers. During this time it is speculated that the CO_2 flush resulted from a sudden burst in root activity and a pulse of microbial activity which mineralized built up organic compounds.

The second and planned rewetting phase took place after the first rain showers following the roof opening in April 2008, at which time we measured a flush of CO_2 from the soil surface that lasted for approximately two weeks. During this time the labile carbon stocks that had accumulated during the induced drought (including dead roots, accumulated litter and other organic compounds) probably mineralized. Additionally, tree roots may have responded to the favorable soil moisture conditions and at minimum resumed normal activity, or extended their root network. Schwendenmann et al. (2009) reported that sap flux densities of both cacao and *Gliricidia* trees recovered quickly.

Beyond the initial two week flush, average soil CO_2 fluxes remained slightly but not significantly above control plot averages until the end of the measurement period in late August 2008. This is likely due to two reasons: 1) the time the ecosystem required to return to equilibrium – for trees to extend their root systems and for microorganisms to decompose built up carbon stocks, or 2) it may reflect the effect of slightly higher bulk densities in the control plots.

5 Conclusions

Although, there were evidently some carbon reallocation responses to drought periods in the cacao agroforestry ecosystem, the net effect on soil CO_2 production and emis-

sion over the duration of the experiment was neutral. During the 13-month treatment phase, we observed slight decreases in soil respiration in the roof plots likely due to localized changes in root activity, and declines in decomposition rates both above and below ground. The decline in soil respiration in the treatment period were however compensated for during the post-treatment phase (after roof opening), when accumulated labile carbon stocks, both above and below ground mineralized, and when trees recovered from their drought stress.

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Table 1. Bulk density, soil texture, carbon and nitrogen content, cation exchange capacity and pH (H_2O) of the upper 75 cm at the desiccation experiment site, Marena, Central Sulawesi. The values are means ±SE, n=3.

Depth	Bulk density ($g\,cm^{-3}$)	Soil texture Sand (%)	Silt (%)	Clay (%)	Carbon ($g\,kg^{-1}$)	Nitrogen ($g\,kg^{-1}$)	ECEC ($cmol\,kg^{-1}$)	Soil pH (H_2O)
Control plots								
−5	1.27±0.02	60.7±1.7	25.7±0.2	13.6±1.6	16.6±1.4	1.5±0.1	7.7±1.3	5.8±0.3
−10	1.31±0.01	54.1±1.8	31.1±2.4	14.8±1.3	10.7±1.3	1.0±0.1	6.6±0.6	5.6±0.1
−20	1.33±0.02	55.1±1.0	28.3±0.9	16.5±0.5	6.4±0.1	0.6±0.0	7.3±1.3	5.9±0.3
−40	1.31±0.02	53.9±0.0	25.5±1.2	20.6±1.2	4.2±0.3	0.4±0.0	5.3±0.8	5.7±0.0
−75	1.36±0.08	58.6±2.8	22.2±2.6	19.2±1.8	3.4±0.3	0.4±0.0	7.5±1.9	5.9±0.0
Roof plots								
−5	1.23±0.02	59.6±0.9	28.4±1.8	12.1±2.7	16.3±2.4	1.6±0.2	9.9±1.2	6.0±0.1
−10	1.26±0.02	55.9±1.1	28.2±1.8	16.0±1.1	14.5±2.9	1.3±0.2	9.0±0.3	6.4±0.1
−20	1.30±0.0	56.2±3.0	28.1±2.6	15.6±0.4	7.7±1.1	0.7±0.1	7.9±0.1	6.3±0.0
−40	1.32±0.04	56.1±1.7	27.4±2.6	16.6±1.6	4.6±0.1	0.4±0.0	5.6±0.2	6.0±0.1
−75	1.37±0.01	57.3±1.2	23.4±1.5	19.3±0.9	3.3±0.2	0.4±0.0	7.9±2.5	5.8±0.3

Table 2. Soil surface CO_2 efflux (mg C m^{-2} h^{-1}), soil air CO_2 concentrations (%) for different soil depth for the pre-treatment, treatment, post-treatment. Mean value±1 SE.

	Pretreatment			Treatment			Post-treatment			Entire experiment period		
	n	Control	Roof	*n*	Control	Roof	*n*	Control	Roof	*n*	Control	Roof
CO_2 efflux (mg C m^{-2} h^{-1})	3	118.0±15.6	142.5±31.8	28	131.8±7.6	114.7±6.8	16	112.0±6.4	129.4±8.5	47	126.2±5.4	119.5±5.4
Soil CO_2 concentrations (%)												
−5 cm	3	0.4±0.2	0.5±0.3	28	1.3±0.2	0.6±0.0	15	1.3±0.2	1.2±0.1	46	1.2±0.1	0.8±0.1
−10 cm		3.7±0.9	5.1±0.6		2.4±0.2	1.2±0.1		2.8±0.2	2.7±0.1		2.6±0.2	1.8±0.1
−20 cm		5.7±0.4	6.0±0.5		4.0±0.2	1.7±0.2		5.0±0.2	3.8±0.1		4.4±0.1	2.4±0.1
−40 cm		6.1±0.5	7.8±0.4		4.9±0.2	2.4±0.2		5.5±0.3	4.5±0.1		5.1±0.2	3.2±0.2
−75 cm		7.1±0.5	8.5±0.4		6.3±0.2	3.2±0.2		7.4±0.3	5.5±0.1		6.6±0.2	4.0±0.2
−150 cm		9.9±0.3	10.3±0.4		9.2±0.2	5.7±0.3		10.1±0.2	7.6±0.2		9.5±0.1	6.3±0.2
−250 cm		12.4±0.2	12.3±0.7		11.6±0.2	8.7±0.3		12.2±0.1	10.6±0.1		11.8±0.1	9.3±0.2

Table 3. Diurnal soil CO_2 efflux, soil temperature and air temperature. The mean values are ±SE.

	Time	*n*	Roof plot Soil CO_2 flux (mg C m^{-2} h^{-1})	*n*	Control plot Soil CO_2 flux (mg C m^{-2} h^{-1})	Soil temperature (°C)	Air temperature (°C)
Early morning	06:00–08:00	19	95.0±12.5	9	107.6±12.6	23.1±0.2	22.7±0.5
Mid morning	08:00–10:00	238	110.0±3.8	267	109.3±3.3	22.9±0.0	24.3±0.1
Late morning	10:00–12:00	318	124.0±4.0	292	118.6±3.6	23.0±0.0	26.6±0.1
Early afternoon	12:00–14:00	149	127.9±6.0	141	125.3±6.0	23.3±0.0	27.6±0.1
Mid afternoon	14:00–16:00	71	132.8±9.6	85	142.0±8.6	23.8±0.1	26.6±0.2
Late afternoon	16:00–18:00	36	131.9±12.8	36	138.3±12.8	24.2±0.1	25.4±0.1

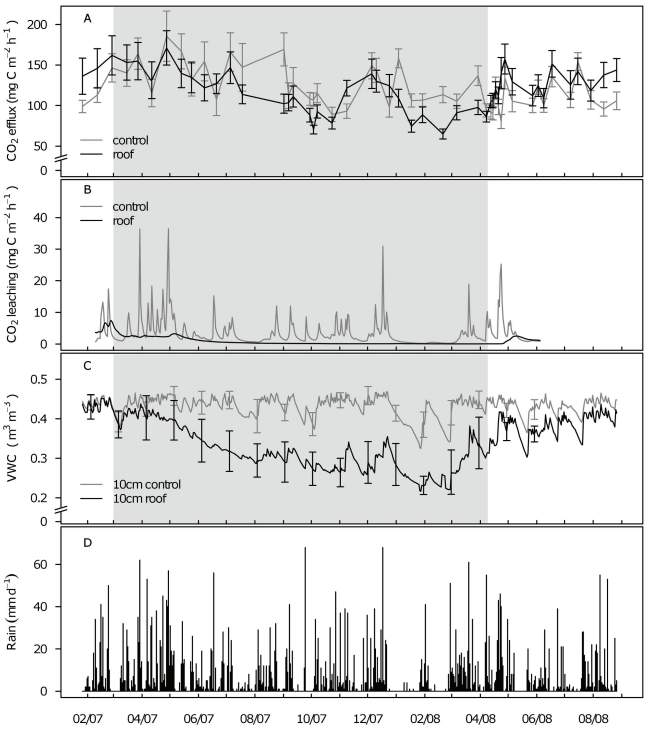

Fig. 1. (a) Average soil surface CO_2 efflux in control and roof plots, **(b)** average CO_2 leaching losses in control and roof plots, **(c)** average volumetric water content at 10 cm soil depth in control and roof plots and **(d)** daily precipitation. Error bars indicate ±1 SE. The shaded area indicates the period of roof closure.

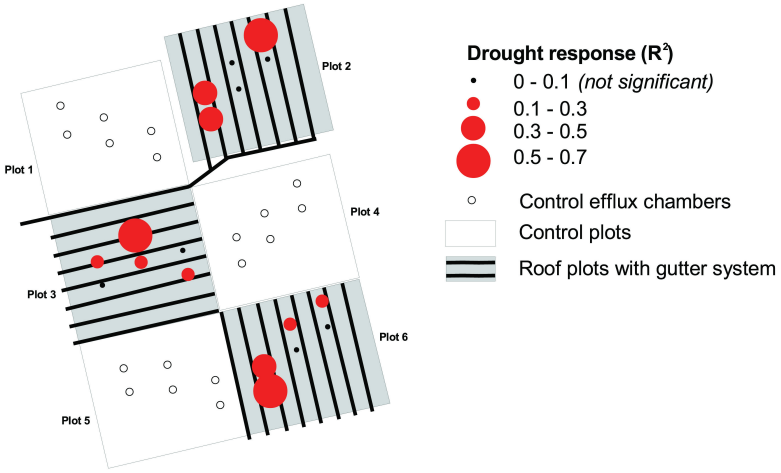

Fig. 2. Schematic of cacao agroforestry plot layout and response of CO_2 flux chambers to soil water content changes. The coefficient of determination (R^2) for the CO_2 efflux to volumetric water content was used as index of how strong a chamber reacted to changes in soil moisture.

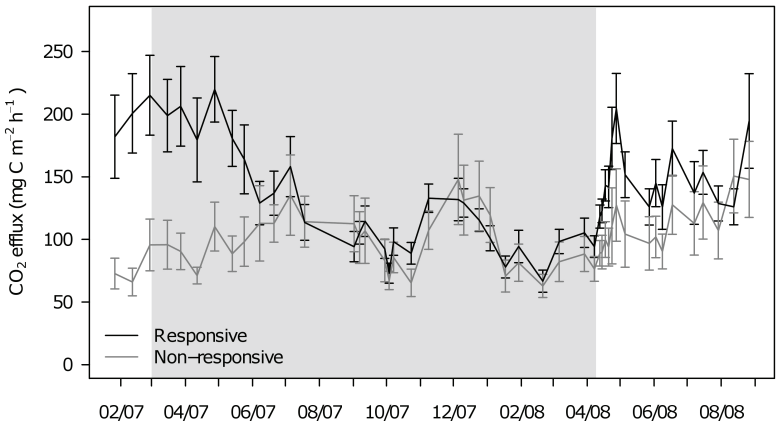

Fig. 3. Soil CO_2 efflux from drought responsive efflux chambers and non-responsive efflux chambers in the roof plots. Error bars indicate ±1 SE. The shaded area indicates the period of roof closure.

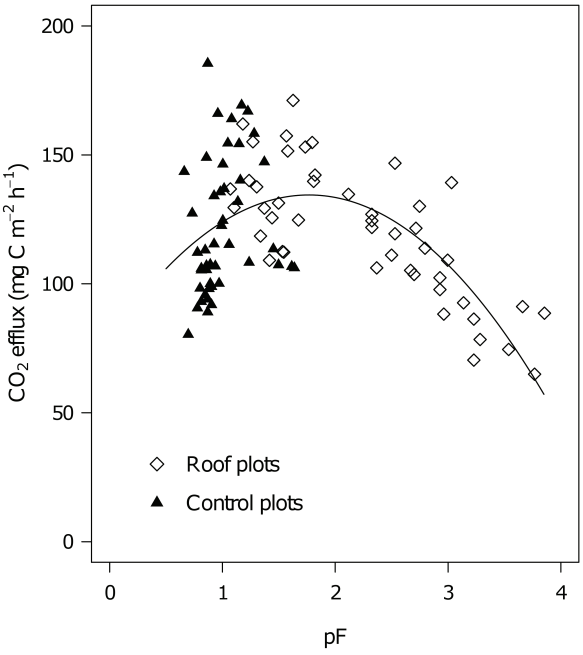

Fig. 4. Relationship between soil CO_2 efflux and soil water potential (pF) from TDRs. CO_2 efflux$=-17.819\,pF^2+62.974\,pF+78.835$ ($R^2=0.32$, $p=0.00$, $n=94$). Average soil CO_2 efflux measurements for roof and control plots for each measurement campaign are shown here. Each point represents the average of 18 CO_2 efflux measurements. Volumetric water content was measured using TDR sensors in three soil pits per plot embedded horizontally at 10 cm soil depth.

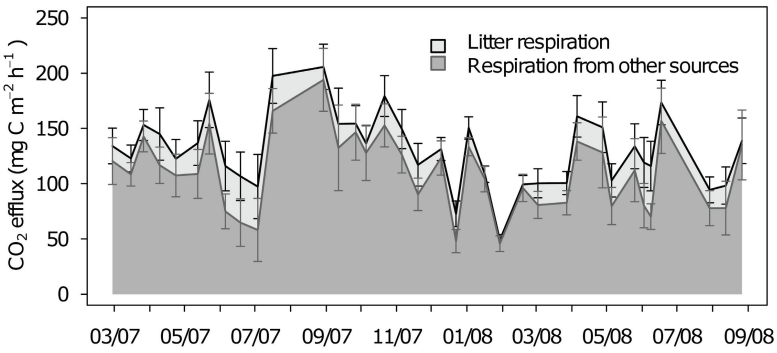

Fig. 5. CO_2 efflux from leaf litter contribution study in the control plots. The dark grey indicates the proportion of each measurement that is derived from the leaf litter, while the light grey is produced within the soil profile from other sources.

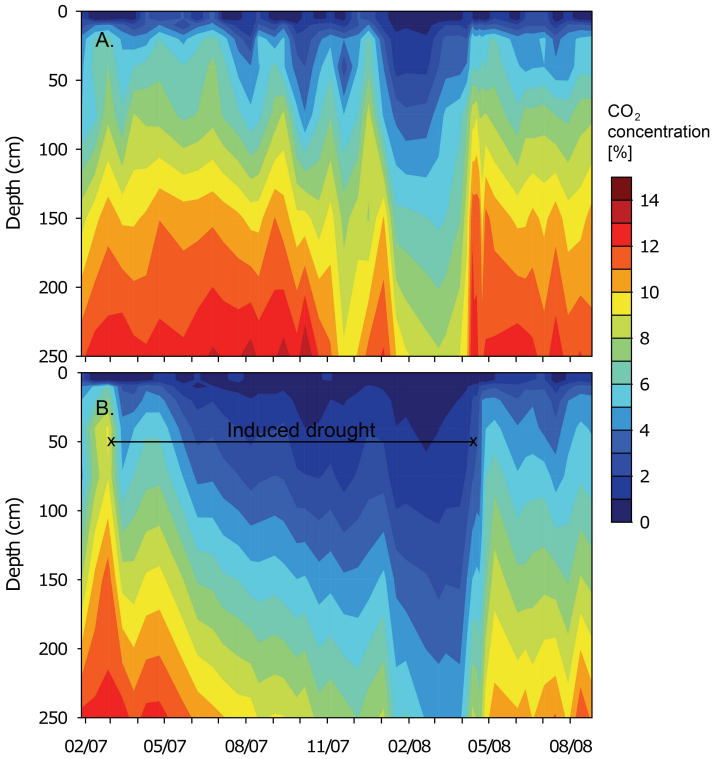

Fig. 6. Isopleths of average soil CO_2 concentrations (percent) in the soil profile of **(a)** control plots and **(b)** roof plots in soil air throughout the experiment period.