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The influence of precipitation pulses on soil respiration – Assessing the “Birch effect” by stable carbon isotopes

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ABSTRACT

Sudden pulse-like events of rapidly increasing CO_2-efflux occur in soils under seasonally dry climates in response to rewetting after drought. These occurrences, termed “Birch effect”, can have a marked influence on the ecosystem carbon balance. Current hypotheses indicate that the “Birch” pulse is caused by rapidly increased respiration and mineralization rates in response to changing moisture conditions but the underlying mechanisms are still unclear. Here, we present data from an experimental field study using straight-forward stable isotope methodology to gather new insights into the processes induced by rewetting of dried soils and evaluate current hypotheses for the “Birch“-CO_2-pulse. Two irrigation experiments were conducted on bare soil, root-free soil and intact vegetation during May and August 2005 in a semi-arid Mediterranean holm oak forest in southern Portugal. We continuously monitored CO_2-fluxes along with their isotopic compositions before, during and after the irrigation. $\delta^{13}C$ signatures of the first CO_2-efflux burst, occurring immediately after rewetting, fit the hypothesis that the “Birch” pulse is caused by the rapid mineralization of either dead microbial biomass or osmoregulatory substances released by soil microorganisms in response to hypo-osmotic stress in order to avoid cell lyses. The response of soil CO_2-efflux to rewetting was smaller under mild (May) than under severe drought (August) and isotopic compositions indicated a larger contribution of anaplerotic carbon uptake with increasing soil desiccation. Both length and severity of drought periods probably play a key role for the microbial response to the rewetting of soils and thus for ecosystem carbon sequestration.

1. Introduction

The annual carbon balance of terrestrial ecosystems is controlled by two major processes, respiratory carbon loss and photosynthetic carbon gain. Seasonal changes in climatic conditions can have large influence on both processes thus altering the source/sink behavior of the system (e.g. Ciais et al., 2005; Granier et al., 2007; Pereira et al., 2007). Drought is the main limiting growth factor in most ecosystems with seasonal rainfall such as the Mediterranean (e.g. Joffre et al., 1999). In the Mediterranean, the onset and length of summer drought strongly influence annual net carbon gain and determine whether the system will be a source or a sink for carbon and thus decrease or enhance atmospheric CO_2-concentrations (e.g. Pereira et al., 2007; Unger et al., 2009). Furthermore, the Mediterranean climate is highly variable with an irregular seasonal distribution of rain events (Luterbacher et al., 2006).

Eddy covariance measurements in drought adapted evergreen holm oak (*Quercus ilex*) forests, the typical land use form of the south-western Iberian Peninsula (Joffre et al., 1999), revealed that a phenomenon, first characterized by Birch (1964) and henceforth termed the “Birch effect”, can have a significant influence on the sink capacity of the system (Pereira et al., 2004, 2007; Jarvis et al., 2007): Birch (1964) showed that cycles of drying and wetting of soils stimulated the mineralization of soil organic matter carbon (SOM-C), leading to the rapid release of mineral nitrogen and carbon dioxide.

This transient effect was observed in several studies at the ecosystem (e.g. Austin et al., 2004; Xu et al., 2004; Tang and Baldocchi, 2005; Jarvis et al., 2007; Inglima et al., 2009) and soil (e.g. Birch, 1964; Bottner, 1985; Denef et al., 2001; Fierer and Schimel, 2002, 2003; Inglima et al., 2009) scales (for a review see

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Borken and Matzner, 2009). Furthermore, rewetting dried soils did not significantly enhance CO_2-fluxes from inorganic carbon pools but rather induced rapid increases in mineralization rates (Inglima et al., 2009).

Four main hypotheses have been proposed to explain the "Birch" pulse: (i) a spontaneous increase in fungal and microbial biomass in response to water availability (Griffiths and Birch, 1961; Jager and Bruins, 1974; Orchard and Cook, 1983; Scheu and Parkinson, 1994); (ii) drying and rewetting of soils shatters soil aggregates exposing previously unavailable organic substrates for decomposition (e.g. Denef et al., 2001); (iii) drying causes an increase in dead microbial biomass, which is rapidly decomposed by new microorganisms and fungi after rewetting (e.g. Bottner, 1985); (iv) nutrient and carbon pulses are due to a hypo-osmotic stress response of the soil microbial community after sudden changes in soil water status (Kieft et al., 1987; Fierer and Schimel, 2002, 2003; Jarvis et al., 2007). However, a complete understanding of the processes underlying the "Birch effect" has not yet been achieved (Jarvis et al., 2007).

Irregular rain events during summer drought are of little use for the vegetation (Nahal, 1981) and thus do not markedly increase carbon gain of the systems. Under Mediterranean climate the herbaceous understory vanishes at the beginning of June (Unger et al., 2009) and deep rooted trees do not have immediate access to water and subsequently released nutrients from the first fall rains. Therefore, the loss of carbon and nitrogen from the soil pools caused by the "Birch effect" may actually have a negative effect on plant productivity (Pereira et al., 2004).

The cycles of drying and rewetting of soils, combine inhibition of plant carbon uptake and at the same time stimulation of carbon losses by the "Birch effect". The length of summer drought and the frequency of irregular summer rain events might become more influential, since climate models for Mediterranean ecosystems predict an increase in both, temperature and irregularity of precipitation (Miranda et al., 2002). It has been proposed that increased variability in soil water content may decrease long-term carbon sequestration due to the "Birch effect" (Fierer and Schimel, 2002). Therefore, identifying the mechanisms underlying the "Birch effect" will add to our understanding of the impacts of increasing drought and rainfall variability, which are expected from global climate change, on ecosystem carbon balance.

Through the imprint of photosynthetic and post-photosynthetic fractionation processes on assimilated atmospheric carbon, the isotopic signature of respired CO_2 can give insights into origin, source and age of carbon released from soil pools (Dawson et al., 2002; Bowling et al., 2008). Specifically, the rapid short-term dynamics in isotopic composition of respired CO_2 have been shown to be important tracers of the environmental drivers of carbon metabolism at the plant (Hymus et al., 2005; Mortazavi et al., 2005; Priault et al., 2009; Werner et al., 2007a, 2009; Wegener et al., 2010), soil (McDowell et al., 2004; Ekblad et al., 2005) and ecosystem (Ekblad and Högberg, 2001; Mortazavi et al., 2005; Werner et al., 2006, 2007b) scales. Thus, the application of stable isotope techniques has the potential to reveal new insights into the origin of the "Birch effect" (Inglima et al., 2009).

In this study we report the results from two irrigation experiments at the beginning and at the end of the dry season in an open Mediterranean evergreen oak forest. Here, the "Birch Effect" in response to a single rain event after summer drought (October 10, 2005) can release as much as 11 g C m^{-2} with increases in ecosystem respiration (R_{eco}) of 6–12 $\mu mol\ m^{-2}\ s^{-1}$ as compared to annual net ecosystem exchange ranging between −28 and −140 g C m^{-2} (Pereira et al., 2007).

We continuously monitored soil CO_2-fluxes along with their isotopic composition before, during and after the irrigation treatments on plots with (i) natural soil and vegetation, (ii) bare soil and (iii) root-free soil. These data were used to evaluate the current theories on the origin of the "Birch effect".

2. Materials and methods

2.1. Field site and climatic conditions

The site is located in the centre of the Portuguese Alentejo at Herdade da Mitra a rural district 12 km south of Évora, Portugal (38°32′26.549″N, 8°00′01.424″W, 264 m a.s.l.). The stand is a characteristic Mediterranean savannah-type evergreen oak woodland ("montado", with tree density of 30 ha^{-1}, 21% tree crown cover, leaf area index of 0.55; Carreiras et al., 2006) in a very homogeneous, slightly undulated landscape, which shows the signs of a typical silvo-pastoral system (Werner and Correia, 1996). The plant community is composed of sparse canopy forming *Quercus ilex* ssp. *ballota* L. (syn. *Q. rotundifolia* Lam.) in mixture with *Quercus suber* L. and a grass layer dominated by herbaceous annuals (e.g. *Tuberaria guttata* (L.) Fourr.), some drought deciduous gamines and a few shrubs (e.g. *Cistus salvifolius* L.). Soils are incipient, derived from granitic rock. The climate is Mediterranean with a precipitation/potential evapotranspiration ratio (P/PET) of 0.3–0.5, with hot dry summers and mild wet winters. Mean annual temperature is 15.5 °C and mean annual precipitation is 669 mm. Weather conditions were continuously recorded by a solar-powered meteorological station (datalogger CR10X, Campbell Scientific, Logan, UT, USA), with a Q7 REBS net radiometer (Campbell Scientific), aspirated psychrometer H301 (Vector Instruments, Rhyl, Denbighshire, UK) and a rainfall recorder (tipping-bucket rain gauge Casella, Bedford, UK). Air temperatures (T_{air}), wind speed (anemometer A100R, Vector Instruments), net radiation (RN) and precipitation were measured in 10s intervals and were automatically stored as half-hourly and daily means or totals. Vapor pressure deficit (VPD) was calculated from dry and wet bulb temperatures of the aspirated psychrometer.

2.2. Net ecosystem exchange measurements

Continuous records of CO_2- and H_2O-fluxes and climate variables were taken on top of a 28-m-high metal tower (at the Mitra site of the CARBOEUROPE-IP consortium) equipped with sonic anemometer (Gill R3, Gill Instruments, Lymington, Hampshire, England) and gas analyzer (LI-7000, LI-COR, Lincoln, NE, USA).

The raw data from the eddy covariance measurements were processed off-line using the software Eddyflux (Meteotools, Jena, Germany). Following the Carboeurope-IP recommendations a planar fit coordinate rotation (Wilczak et al., 2001) for wind components was performed. The CO_2-fluxes were determined, on a half-hourly basis (block averaging). A time-lag for each averaging period was determined in order to maximize the covariance between vertical wind velocity and carbon dioxide signal from the gas analyzer. The fluxes were corrected for the damping loss of the closed-path analyzer at high frequencies, according to Eugster and Senn (1995). In general, the correction factors varied between 1.05 and 1.30. A CO_2-storage term, calculated for one point measurement as in Greco and Baldocchi (1996), was added to the estimated carbon flux.

The quality of all primary data was guaranteed by a routine of equipment calibration and, for meteorological data, a comparison with data from stations close-by. To exclude non-representative 30 min measurements of carbon dioxide flux, the following screening criteria were applied: fluxes were removed if the mean vertical velocity deviation to zero was higher than what would be considered as normal for the site, following the same principle as in Rebmann et al. (2005); fluxes were excluded if the high frequency