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Changes in soil moisture predict soil carbon losses upon rewetting in a perennial semiarid steppe in SE Spain

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ABSTRACT

Our understanding of the spatial and temporal dynamics of soil CO_2 pulses after rainfall events is still limited and thus, our capacity to predict the consequences of future changes in precipitation patterns for dryland soils. In this study we examined the response of soil CO_2 pulses to rainfall size and pre-rain soil moisture conditions in a semiarid grassland. In a first experiment, we manipulated the amount of rainfall in a factorial combination that included three levels of rainfall size (1, 5 and 15 mm), three soil covers: vegetated areas (VEG), biological soil crusts (BSC) and bare soil (BS) and two nearby sites: a natural grassland and a degraded grassland. We measured soil CO_2 efflux over 24 h to capture rainfall pulses. In a second experiment conducted at the natural grassland, we measured soil CO_2 efflux after manipulating soil moisture to its full range in the area by wetting the soil to: 0–10%, 10–15%, 20–25%, 30–35% water content levels. All soil covers responded to the rainfall treatments within minutes, reaching up to 120 times baseline values and shortly returning to background rates. Rainfall size had a larger impact on the response than pre-rain soil moisture conditions. Whereas in most cases rainfall amount increased soil CO_2 pulses, initial moisture conditions did not affect total carbon losses despite much larger CO_2 peaks in very dry soils. Interestingly, even extremely low rainfall events (1 mm) caused significant carbon losses. The amount of carbon lost after rainfall events ranged from 0.45 in bare soils to 1.18 g C m^{-2} day^{-1} in vegetated areas. Overall, rainfall had a larger impact in vegetated areas at the degraded site implying that larger carbon losses can be expected as a result of land degradation. Sudden changes in soil moisture caused by rainfall predicted 65% of total carbon losses in BS, 70% in BSC and 80% in VEG at both sites. However, the slope was significantly lower in bare soils suggesting substrate limitation. Since most of the carbon resides belowground in these grasslands, carbon losses as a result of larger rainfall events and longer dry periods in this area could have important consequences for soil carbon stocks.

1. Introduction

Semiarid and arid ecosystems are characterised by irregular rainfall events that often produce what is known as rainfall pulses (Birch, 1958). These rainfall pulses wet the soil surface, where labile carbon and microbial biomass accumulate over dry periods, and become available for microbial decomposition leading to large soil CO_2 effluxes (e.g. Harper et al., 2005; Rey et al., 2005; Sponseller, 2007; Borken and Matzner, 2009; Williams et al., 2009; Munson et al., 2010). Abiotic processes, including carbonate dissolution (Schlesinger, 1985; Roland et al., 2013; Rey, 2015) and water physical CO_2 displacement from soil pore spaces (Huxman et al., 2004; Lupascu et al., 2014) may also contribute to the observed soil CO_2 pulses upon rewetting.

In semiarid and arid ecosystems most of the carbon resides belowground (Burke et al., 2008) so soil CO_2 pulses caused by episodic precipitation events have potential important consequences for soil carbon stocks. Thus, accurately quantifying soil CO_2 pulses after rainfall events is essential to understand carbon balance dynamics in these belowground dominated ecosystems. Since precipitation frequency and intensity are predicted to increase (IPCC, 2013), rainfall pulses may become even more important in the near future. Furthermore, it has recently been shown that semiarid ecosystems are much more important in the global terrestrial carbon balance than previously thought, determining the interannual variation in the terrestrial carbon sink (Ahlström et al., 2015).

Several studies have tried to quantify and describe rainfall pulses (e.g. Yang et al., 2008; Munson et al., 2010; Xu and Luo, 2012). The

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Table 1
Three-way ANOVA results to tests differences between rainfall size treatment, soil covers in environmental conditions: initial temperature, initial soil water content, change in SWC in Experiment I ($n = 4$).

Factors		T_0 (°C)			SWC_0 (%)			ΔSWC (%)		
Three-way MANOVA		F	df	*P*	F	df	*P*	F	df	*P*
Exp. I	Site	13.635	1	**0.0005**	35.297	1	**0.0001**	21.69	1	**0.0001**
	Rainfall size	0.7894	2	0.4597	0.3958	2	0.8522	173.64	2	**0.0001**
	Soil cover	22.008	2	**0.0001**	7.4033	2	0.2582	1.258	2	0.2924
	Site x Treat	0.6185	2	0.5425	2.4438	2	0.3782	9.378	2	**0.0003**
	Site x SC	0.0003	2	0.9969	3.6977	2	0.2327	5.003	2	**0.0102**
	Treat x SC	0.0727	4	0.9901	2.1230	4	0.7882	3.3995	4	**0.0102**
	Site x Treat x SC	0.3321	4	0.8552	0.6458	4	0.9705	1.4971	4	0.2160

Bold numbers are statistically significant ($P < 0.05$).

magnitude of soil carbon loss is positively correlated to rainfall event size (Cable and Huxman, 2004; Chen et al., 2008), pre-rain soil water conditions (Sponseller, 2007), plant activity (Harper et al., 2005) and soil organic matter content (Ma et al., 2012). Despite the increasing number of studies and recent advances in our understanding of rainfall pulses, several aspects need urgent attention. For instance, the spatial variability that characterises these ecosystems is rarely taken into account and the effect of soil degradation on carbon losses after rainfall events is poorly understood.

Semiarid ecosystems are characterised by highly heterogeneous sparse vegetation with patches of bare soil and presence of biological soil crusts, which are widespread across arid regions (Belnap and Lange, 2003). These communities are dominated by lichens, mosses and cyanobacteria and play an important role in water, carbon and nutrient cycles (Castillo-Monroy et al., 2011; Berdugo et al., 2014). Plants regulate soil moisture dynamics by minimising evaporative losses, intercepting rainfall water and taking up water through roots. Plants also modify soil physicochemical characteristics by providing labile carbon substrates as root exudates for heterotrophic microorganisms and litter as organic matter input (Cardon and Gage, 2006). Moreover, growth and maintenance of plant roots (autotrophic respiration) directly contribute to soil respiration, reaching up to 50% of annual soil CO_2 efflux in some cases (Rey et al., 2002). Microbes and biological soil crusts that live in the topsoil are capable of responding to sudden soil moisture availability much faster than roots, and are capable of withstanding extended periods of drought (Schimel et al., 1999). Given that different biotic components contribute to soil CO_2 efflux in different soil covers, the response to rainfall events of these highly patchy soils may differ. Despite the large spatial variability of these ecosystems, few field studies have taken into account soil cover when quantifying the dynamics of soil CO_2 efflux after rainfall events. Such information would be very valuable when assessing carbon losses in semi-arid ecosystems at large spatial scales.

Another important factor affecting semiarid ecosystems is land degradation. More than 20 of semiarid lands are degraded or prone to desertification, and this area is expected to increase, potentially affecting soil carbon dynamics (Reed et al., 2012; Feng and Fu, 2013). Thus, understanding how changes in vegetation cover and soil impoverishment as a result of land degradation will affect ecosystem and soil carbon fluxes is important for the prediction of ecosystem carbon dynamics to global change. Loss of vegetation cover, and shallow soils, as a result of land degradation, alter soil hydrological conditions (Rey et al., 2011) and in turn, may affect soil CO_2 pulses upon rewetting.

Although the importance of rainfall pulses for the ecosystem carbon balance in this biome is widely recognised (e.g. Jarvis et al., 2007; Collins et al., 2008; Jenerette et al., 2008; Yan et al., 2010), a proper understanding of the response of soil CO_2 efflux to rainfall events is still lacking. Despite much research on soil CO_2 pulses (e.g. Jenerette and Chatterjee, 2012; Collins et al., 2014), it is not yet clear which factors control the pulse effect of a single rainfall event and its implications for semiarid ecosystem functioning (Nielsen and Ball, 2015).

The overall aim of this study was to characterise how soil CO_2 efflux responds to rainfall pulses, and how rainfall size and soil moisture conditions affect the response of different characteristic soil covers: bare soil (mostly heterotrophic respiration), biological soil crusts and vegetated areas (that includes autotrophic respiration). Moreover, we aimed to understand whether land degradation affects rainfall pulses in different soil covers beyond changes in plant cover and soil depth, by comparing two nearby grassland sites with similar characteristics but different land use history.

We hypothesised that: (1) the response of soil CO_2 efflux to rainfall events and thus, the amount of carbon loss upon rewetting, will increase with both, soil dryness prior to rainfall event (that favours the accumulation of labile carbon) and the size of the event (that will increase moisture activating microbial activity) (2) the response will differ between soil covers with greater response under plant patches, given the large accumulation of labile carbon compared to bare soils, (3) land degradation will induce larger CO_2 pulses given that the degraded soils are subject to longer dry periods (with an altered hydrological cycle as a result of significantly lower vegetation cover and shallower soils) favouring the accumulation of labile carbon that becomes available upon rewetting.

2. Material and methods

To address these hypotheses we carried out a multifactorial field experiment in two nearby grassland sites differing in land use history, where we manipulated the amount of rainfall and followed rainfall pulses over 24 h in three soil covers. In another experiment carried out at the natural grassland site we manipulated the initial soil moisture conditions.

Table 2
Four-way ANOVA with repeated measures (time) results of Experiment I to test differences in the response of soil respiration to different rainfall size treatments in different sites and soil covers over 24 h ($n = 4$).

EXP. I		SR (g m^{-2} day^{-1})		
Four-way ANOVA		F	df	*P*
Factor	Site	1.0845	1	0.3071
	Rainfall size	42,965	2	**0.0001**
	SC	18.754	2	**0.0001**
	Site × Rainfall size	1.5808	2	0.2157
	Site × SC	4.9855	2	**0.0108**
	Rain × SC	4.0638	4	**0.0002**
	Site × Rainfall size × SC	1.4212	4	0.2403
	Time	20.749	10	**0.0001**
	Time × Site	3.2822	5	**0.0127**
	Time × SC	10.971	10	**0.0001**
	Time × SC × Site	3.9080	20	**0.0002**
	Time × Site × Rainfall size	4.3398	10	**0.0001**
	Time × SC × Rainfall size	3.0953	20	**0.0001**
	Time × SC × Rainfall size × Site	1.3812	20	0.1390

Bold numbers are statistically significant ($P < 0.05$).