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The use of soil respiration as an ecological indicator in arid ecosystems of the SE of Spain: Spatial variability and controlling factors

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ABSTRACT

In the context of an ongoing monitoring study of the Cabo de Gata-Níjar Natural Park (SE of Spain), we explored the use of soil respiration as an indicator of ecosystem functioning reflecting changes in ecological processes in semiarid environments. With this purpose, we measured soil CO_2 efflux in six different and representative ecosystems of the Natural Park, with different land uses (forest and agricultural sites) and under different soil covers (under plant and bare soil) in two distinctive periods of the year: summer (dry period) and spring (growing season). We also measured the main soil properties and environmental variables. Soil CO_2 efflux ranged from 0.40 μmol m^{-2} s^{-1} in the dry period to 1.93 μmol m^{-2} s^{-1} in the growing season. Soil CO_2 efflux showed a large spatial variability, with different behaviour between the measured periods. Whereas in the dry period differences among ecosystems were larger (CVs 75–80%) than within them (CVs 40–55%), in the growing season the CVs were smaller (40–50%) and no differences were observed between or within ecosystem. The factors controlling soil CO_2 efflux also differed in the two measurement occasions. Whereas in the dry period soil CO_2 efflux was mainly the result of transport processes in the soil and therefore related to local factors (OC content, CN ratio, clay, rock outcrop, etc.) assigned to ecosystem conditions, in the growing season soil CO_2 efflux was dominated by soil CO_2 production and thus related only to organic carbon content and plant cover. In the growing season environmental variables explained ca. 10% of the variation in soil CO_2 efflux. In order to capture these different processes in different times of the year, i.e., diffusion versus production processes we calculated a new index, *normalised seasonal difference in soil respiration* (SDSR), which is proposed as a good indicator of the state and functioning of the ecosystem.

1. Introduction

Monitoring actions require precise indicators to obtain accurate information about ecosystems conditions. Meanwhile ecosystem indicators must be sensible to different spatial-temporal scales. The term "*vital monitoring signs*" has been proposed for a group of elements or processes (physical, chemical or biological) that can be used universally to determine the overall health of an ecosystem (Davis, 2005), as well as to provide an effective alert system (Fancy et al., 2009). Herrick et al. (2002) proposed some basic guidelines for the selection of such indicators: (a) to identify indicators consistently related to the functional state of critical ecosystem processes, (b) to consider intrinsic site characteristics, (c) to make use of the spatial variability in the development and assessment of the indicator to ensure representativeness of ecological processes and (d) to apply the indicator in the context of the non-linear dynamic knowledge of a process. Understanding the process, the factors that control it, its natural variability and its sensitivity to change, are crucial to evaluate the usefulness of a variable as an indicator, which must demonstrate sufficient sensitivity to spatial-temporal change under the specific ecosystem conditions (Andreasen et al., 2001).

Soil respiration is a biogeochemical process involving several processes that act at different scales and which, in turn, are influenced by a wide number of biotic and abiotic factors observed at different hierarchical levels (Luo and Zhou, 2006). Part of the CO_2 production in soils is related to the metabolic activity of plant roots and associated mycorrhizas (autotrophic respiration) (Hanson et al., 2000; Hörberg et al., 2001), while another important fraction is associated with the heterotrophic respiration of microbial communities (Giardina et al., 2004). The proportion of these components varies from one ecosystem to another (Raich and Schlesinger, 1992). This suggests that soil respiration has great potential as an indicator of ecosystem metabolism, by linking below and aboveground processes that respond to a large number of factors controlling metabolic processes (Ryan and Law, 2005).

Despite extensive research on soil respiration over the last decade (Hibbard et al., 2005; Luo and Zhou, 2006; Reichstein et al., 2003), knowledge of the drivers that control soil respiration in

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Table 1
Ecosystem type site data and description.

COD	Landscape	Lithology	Soils (WRB, 2006)	Vegetation/Land use
AT_CAL	Plateaux. Large, flat, relatively elevated land portion which is limited on escarpment	Coral reef limestones	Calcaric and Rendzic Leptosols	Alfa steppes (*Stipa tenaccisima*)
MT_SCH	Mountain. Elevated land portion characterised by important relative height in relation to lower-lying and important internal dissection	Schists	Calcaric Leptosols and Calcaric Regosols	Shrubland. Alfa steppes (*Stipa tenaccisima*) with *Genista sp*
MT_VOL	Mountain	Andesites	Leptic Cambisols and Luvic Phaeozems	Palmeto Brush. *Stipa tenaccisima* and *Chamaerops humilis*
PD_CAL	Piedemont. Sloping land portion lying at foot of more elevated landscape units	Colluvio_Alluvium with petrocalcic horizon	Calcaric and Rendzic Leptosols	Alfa steppes (*Stipa tenaccisima*)
PD_VOL(a)	Piedemont.	Colluvio_Alluvium with volcanic materials	Eutric Regosols and Eutric Cambisols	Field crops. Pseudo steppes with grasses and annuals
PD_CAL(a)	Piedemont.	Colluvio_Alluvium with calcareous materials	Calcaric Regosols and Haplic Calcisols	Field crops. Pseudo steppes with grasses and annuals

arid ecosystems is still rather poor. Furthermore, only few studies have considered the spatial heterogeneity that characterised these ecosystems, with the majority reporting measurements at plot scale (≈100 m^2) (Bond-Lamberty and Thomson, 2010a; Herbst et al., 2009a; Martin and Bolstad, 2009; Tang and Baldocchi, 2005; Webster et al., 2009), even though the physical and biogeochemical processes that lead to CO_2 production and efflux in soils depend on the complex interaction between environmental variables, soil physical-chemical properties, amount and quality of substrate, etc. (Kang et al., 2006; Scott-Denton et al., 2006). Studies at landscape scales have been carried out in watersheds (ten to thousands of hectares), mainly with the aim of analysing the influence of topographic factors on water redistribution or changes in temperature (e.g. Martin and Bolstad, 2009; Pacific et al., 2008; Riveros-Iregui and McGlynn, 2009; Sponseller and Fisher, 2008; Webster et al., 2008) and very few have considered aspects such as C amount or substrate quality (Webster et al., 2009). Studies comparing soil CO_2 efflux from the mosaic of ecosystems integrated in a landscape, have only been done very recently (Chen et al., 2010) with special attention to intra and inter site variability (Martin and Bolstad, 2009).

In the context of a proposal for monitoring a protected area in the most arid region in Europe, the Cabo de Gata-Nijar Natural Park (SE Spain), we consider soil respiration as an ecosystem attribute that reflects early changes in ecological processes and indicates that a more significant change is likely to occur. Therefore, as a "vital sign", it could be an ideal indicator (Davis, 2005) of the ecosystem that can be used universally and at very different scales, although its use would have to be adjusted to specific ecosystem conditions.

The overall aim of this study was to examine the use of soil respiration as an ecosystem indicator, according the Heink and Kowarik (2010) definition: an attribute with the capacity to describe the state of an ecosystem or to analyse interannual environmental changes. Our specific objectives were: (1) to characterise soil CO_2 efflux in the various ecosystems present in the Cabo de Gata-Níjar NP, (2) to analyse its spatial variability, (3) to examine which factors control soil CO_2 efflux in arid ecosystems, and (4) to evaluate its usefulness as an indicator of ecosystems changes conditions.

2. Material and methods

2.1. Site description

The study sites are located in the Cabo de Gata-Níjar Natural Park, (hereafter CGNNP) in the SE of Spain, one of the few protected semi-deserts in the European continent. Mean annual precipitation is 220 mm and mean annual temperature is around 18.1 °C, with a minimum of 14.6 °C and a maximum of 21.7 °C (30-year averages). The distribution of temperatures and precipitation is typically Mediterranean, characterised by strong interannual variation and random precipitation patterns typical of arid climates. Annual potential evapotranspiration is around 1390 mm, with an aridity index (I_a) below 0.2, which classifies this area as an arid zone.

Most of the Park is mountaneous with heterogeneous relief and lithology. Landscape characteristics are derived from Tertiary tectonic episodes and most of the area is of volcanic origin with an upper platform of detritic carbonate lithology (Fernández Soler, 1996). Along with this variety of geological substrates and diversity of relief, alternating climatic regimes resulting from paleoenvironmental variations are responsible for the wide diversity of soils and justify the complex spatial pattern of soil properties, such as texture, iron oxides and carbonates (Oyonarte, 2004).

2.2. Experimental design

The experimental design was intented to capture variability in diagnostic criteria such as relief, lithology and vegetation. In order to capture a broad variability in the biophysical conditions, six types of ecosystems with distinguished features were selected: four of them with shrubland vegetation at different relief height (mountaneous to flat sites) and lithologies (limestones, schists, andesites, etc.), and the other two correspond to extensive agricultural sites. These ecosystems were selected as the most representative in the CGNNP. The main characteristics of each type are summarised in Table 1.

A stratified random design was used because of its effectiveness for reliable estimation of the variability of soil CO_2 efflux (Rodeghiero and Cescatti, 2008). Four permanent plots (10 m × 10 m) per ecosystem type, in which the distribution of vegetation was mainly in patches, were selected. In order to estimate the fractions of heterotrophic and autotrophic respiration we selected random areas and placed four replicated soil collars under the plant cover (UP), and another four collars on bare soil (BS) in each plot. It is assumed that the soil is the same for both types of ground cover, and thus, that the main differences in soil CO_2 efflux between them were the result of the autotrophic component under UP (Tang and Baldocchi, 2005). In the agricultural ecosystems, soil collars were only placed on bare soil. The PVC collars were 7 cm height and 11 cm in diameter and were inserted 3 cm into the soil.

To examine the controlling factors of soil respiration (R_S), soil CO_2 efflux was measured at two different periods reflecting contrasting physiological states of the ecosystems: September