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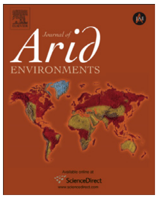

# Seasonality of net carbon exchanges of Mediterranean ecosystems across an altitudinal gradient

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## ABSTRACT

In the present climate change context it is important to understand the carbon balance seasonality of Mediterranean areas, that will suffer important changes in precipitation according to the last climate change predictions. This work analyzed the seasonality of carbon exchanges of three Mediterranean ecosystems according to a variety of water and temperature regimes due to differences in altitude (alpine, subalpine and lowland). Results show that the timing and duration of the growing season depended on temperature at the alpine site, while the dependence on water availability increased as altitude decreased. Thus, maximum values of net carbon uptake occurred in late spring for the alpine and subalpine sites (up to 60 and 30 gC $m^{-2}$ $month^{-1}$ respectively) whereas the lowland site absorbed carbon throughout winter (up to 30 gC $m^{-2}$ $month^{-1}$). Similarly increases in aridity conditions resulted in monthly increases in carbon emissions during dry periods. Thus from May to October, the lowland emitted up to $60^{\circ}gC^{\circ}m^{-2\circ}month^{-1}$, the subalpine emitted half that with a delay of two months, whereas the alpine site continued with slight uptake sequestration. Finally, the EVI could be used to provide reasonably accurate estimates of photosynthesis ($R^2$ around 0.6) but this relation varies depending on the site.

## 1. Introduction

The Mediterranean climate is distinctly characterized by mild temperatures (*T*) and asynchronous patterns of precipitation, versus light and *T*. The dry summer characteristic of this climate makes Mediterranean ecosystems very sensitive to climate change via land degradation, which can decrease the potential for plant carbon (C) assimilation (Mouat and Lancaster, 2006). In addition, the C and water balances are tightly linked as precipitation pulses (Inglima et al., 2009), soil water content (Rey et al., 2005), and the timing of precipitation (Xu and Baldocchi, 2004) have been shown to exert strong controls on the C balance. As predictions for climate change in this region indicate a decrease in water availability (via decreases in rain events and total precipitation (IPCC, 2007)), the link between the C and water cycles is expected to be tighter as the growing period is shortened due to drought (Janssens et al., 2005; Baldocchi, 2008). Therefore, monitoring and understanding the seasonality of net C exchanges in Mediterranean ecosystems and how they are linked to the water balance is essential to be able to understand the effects that future climate change will exert on the behavior of these ecosystems as sources or sinks of $CO_2$.

Grasslands and shrublands, representing the first stages of colonization in Mediterranean ecosystems, are the main vegetation types due to years of human intervention, deforestation and desertification (Dato et al., 2010). Moreover, in recent decades, 18.3 million ha of European agricultural areas (globally, 235 million ha) were abandoned (Rounsevell et al., 2003, 2006; FAO, 2004). This

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phenomenon is particularly relevant in the Mediterranean area (Correia, 1993), leading to shrubland encroachment (Maestre et al., 2009), changing former agricultural and grasslands to shrublands. However, most research on C and water balances in Mediterranean ecosystems has been focused on forest or semiarid grassland ecosystems (Janssens et al., 2005), paying less attention to shrublands with different water and $T$ regimes.

The eddy covariance technique provides direct and continuous measurements of C and water exchanges between terrestrial ecosystems and the atmosphere, and has been applied to examine the potential of different ecosystems as C sinks (Dabberdt et al., 1993; Baldocchi, 2003). Such studies define net $CO_2$ fluxes (NEE) as the sum of photosynthetic, gross primary production (GPP) and ecosystem respiration ($R_{eco}$; Falge et al., 2002; Reichstein et al., 2005), neglecting non biological processes. However, recent studies reveal a contribution of abiotic fluxes to net C exchange (Kowalski et al., 2008; Stone, 2008; Xie et al., 2008; Ferlan et al., 2011). Such abiotic processes – mainly subsoil ventilation (Serrano-Ortiz et al., 2010) – provoke $CO_2$ releases during dry periods (Serrano-Ortiz et al., 2009; Rey et al., 2012) that are strongly related to wind speed (Pérez-Priego et al., 2013) and have relevant magnitudes at least on short time scales (Kowalski et al., 2008). In this context, such ventilation processes can be particularly important in Mediterranean ecosystems characterized by dry and warm summers.

To estimate $CO_2$ exchange over wide areas, the measured NEE from distributed points must be scaled up to spatially continuous estimates. Satellite vegetation indices, such as the Enhanced (EVI) or Normalized Difference (NDVI) Vegetation Index, were developed to optimize the area-averaged canopy photosynthetic capacity and are highly correlated with processes that depend on absorbed light, such as GPP (Potter et al., 2007). Several studies have shown that both vegetation indices have a linear relationship with GPP in various vegetation types (Xiao et al., 2004; Rahman et al., 2005; Huete et al., 2006; Sims et al., 2006; Nagai et al., 2010). Since the EVI and NDVI are structural indices, for evergreen Mediterranean ecosystems they may not provide good estimates of GPP because they should be largely insensitive to short-term leaf physiological changes that are independent of structure, such us reductions in GPP caused by water stress (Zarco-Tejada et al., 2013); however, a recent study reveals good agreement between annual values of EVI and annual stem diametric increment for Mediterranean forest (Garlbusky et al., 2012). Thus, further modeling efforts should be concentrated on sites with summer drought (Sims et al., 2006).

The main objective of this work is to characterize the seasonality of carbon fluxes in non-forested Mediterranean ecosystems, characterized by hot and dry summers, over a gradient of altitude, precipitation and temperature. Monitoring and understanding this seasonality will enable assessment of the effect that future climate change conditions will have on Mediterranean ecosystems in a more specific way. For this purpose, we have compared the net ecosystem carbon exchange measured by eddy covariance systems in three grassland and shrubland ecosystems at different altitudes, analyzing the seasonality and main variables controlling these fluxes as well as the main processes responsible for them in the three ecosystems studied. Finally, EVI and NDVI values are compared with GPP to test the use of this product for estimation of GPP in Mediterranean ecosystems.

## 2. Material and methods

### 2.1. Sites description

Measurements of $CO_2$ and water fluxes along with environmental variables were made during 2007 and 2008 at three Mediterranean sites located in the Southeast of Spain: an alpine meadow, Laguna Seca in the Sierra Nevada range (ALP); a subalpine plateau (SUB), el Llano de los Juanes in the Sierra de Gádor range; and a lowland alpha-grass steppe, Balsa Blanca in Cabo de Gata-Níjar natural park (LOW). Table 1 summarizes the main environmental values characterizing the three sites, separated by less than 90 km along an East–West transect.

### 2.2. Micrometeorological and eddy covariance measurements

During 2007, 2008 measurements of air temperature ($T$) and relative humidity (RH), incident and reflected photosynthetic photon flux densities (PPFD), net radiation ($R_n$), rainfall, volumetric soil water content (SWC), and soil heat flux ($G$) were carried out at the three study sites, and stored and averaged every 30 min in data loggers. Table 2 indicates the instruments used at each site and their deployment.

Densities of $CO_2$ and water vapor, the three components of the wind velocity vector and the sonic $T$ were measured at 10 Hz, and means, variances and covariances were stored in data-loggers and converted to 30 min means following Reynolds rules. To obtain NEE and evapotranspiration (ET) a 2-D coordinate rotation (McMillen, 1988; Kowalski et al., 1997) and density corrections (Webb et al., 1980) were applied in post-processing.

Several filtering procedures were applied to the flux data to obtain reliable 30 min NEE and ET values following Reverter et al. (2010) and Serrano-Ortiz et al. (2009) such as half hourly values excluded when <75% of 18,000 possible data sets during each averaging period are available or data rejected due to rain or

**Table 1**
Characteristic climatic, vegetative and soil features of each site.

| Features | Alpine (ALP) | Subalpine (SUB) | Lowland (LOW) |
|---|---|---|---|
| Location in Spain | Sierra Nevada (Granada) | Sierra de Gádor (Almería) | Cabo de Gata-Níjar (Almería) |
| Site code[a] | ES-LgS (Laguna Seca) | ES-LJu (Llano de los Juanes) | ES-Agu (Balsa Blanca) |
| Elevation [m a.s.l.] | 2300 | 1600 | 195 |
| Climate type | Med.-alpine | Med.-subhumid | Med.- semiarid |
| Mean annual $T$ [°C] | 5.5 | 12 | 18.1 |
| Annual rainfall [mm] | 800 | 538 | 271 |
| $P/ET_P$[b] | 1.3 | 0.8 | 0.3 |
| Mean annual $SWC_n$[c] | 0.21 | 0.39 | 0.44 |
| Ecosystem type | Alpine shrubland | Shrubland plateau | Shrubland steppe |
| Dominant species[d] | *F. indigesta*, *Cytisus purgans* | *F. scariosa*, *G. pumila pumila*, *H. spinosa* | *S. tenacissima* |
| Mean vegetation height [m] | 0.2 | 0.5 | 0.8 |
| Maximum LAI $[m^2 \circ m^{-2}]$ | 2.9 | 2.1 | 1 |
| Soil type | Alluvial silicates | Clay over carbonate bedrock | Alluvial with carbonate deposition |
| References | Reverter et al. (2010) | Serrano-Ortiz et al. (2007) | Rey et al. (2011) |

[a] According to European Fluxes Database Cluster (http://www.europe-fluxdata.eu/home/sites-list).

[b] $P$ – mean annual precipitation; $ET_P$ – averaged potential annual evapotranspiration (measured during the studied period and calculating following Hargreaves and Samani (1982)).

[c] Species representing more than 10% of the vegetation cover of the site.

[d] $SWC_n$ – mean annual normalized soil water content calculated following Equation (3).