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Carbon and water exchange in semiarid ecosystems in SE Spain

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ABSTRACT

The changing climate is affecting biological and physical processes occurring in the biosphere, including the biogeochemical cycles of water and carbon. The response of ecosystem carbon exchange to changes in temperature and the water balance is still very uncertain, a fact that highlights the need for research in order to understand the role of the biosphere in the future global carbon budget. South east Spain is on the borderline between the tropical and mid-latitude climate zones, with climates ranging from sub-humid to arid, and the majority representing the driest area in Europe. Initial predictions on climate change for this region point to decreases in total precipitation and the number of precipitation events, meaning a decrease in water availability underlining the vulnerability of the region to desertification. This region, due to these special climatic conditions, has been the subject of experimental carbon and water field research in recent years. This paper defines the state of the art of carbon and water balance measurement and modelling studies in this region, analyses the different processes involved in aggregate exchanges (vegetation and soil; net ecosystem carbon balance–evapotranspiration, photosynthesis–transpiration, soil respiration–evaporation), and identifies needs for future research.

1. Introduction

The response of the ecosystem carbon balance to changes in temperature and the water balance is still very uncertain, and yet essential to understanding the role of the biosphere in the future global carbon budget (Moore et al., 2008). Because carbon and water cycles are strongly linked, mainly through photosynthesis and respiration, changes in the water balance will produce changes in the carbon cycle determining the CO_2 source/sink behaviour of ecosystems. Initial climate forecasts for the Mediterranean point to a decrease in net precipitation and number of events, and an increase in intensity (Christensen et al., 2007). This would diminish water availability in already water-limited Mediterranean ecosystems sensitive to desertification, especially semiarid regions such as SE Spain. In these semiarid ecosystems, the link between the carbon and water cycles is expected to tighten as the growing period shortens due to drought (Baldocchi, 2008; Janssens et al., 2005).

SE Spain is on the borderline between tropical and mid-latitude climate zones, with climates ranging from sub-humid to arid, and the majority representing the driest area in Europe. Due to the scarce precipitation, socio-economic activities must rely strongly on ground water resources (Pulido-Bosch et al., 2000). In-depth knowledge of the water balance is thus critical for sustainable water management in this region. The water balance can be summarised as the difference between water inputs, mainly precipitation (P) but also dew and atmospheric water adsorption by soil, and water loss processes such as runoff (R_{off}), infiltration (I) and

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evapotranspiration (ET), which affect the aquifer recharge rate (R). Moreover, this equilibrium between water gains and losses determines the soil water content (SWC), a crucial resource in water-limited ecosystems responsible for vegetation scarcity which in turn determines the SWC heterogeneous spatial distribution characteristic of these ecosystems (Rodriguez-Iturbe et al., 1999). As precipitation, runoff, infiltration and recharge are analysed elsewhere in this special issue, our attention in relation to the water balance will be on ET, dew and atmospheric water adsorption by soil in SE Spain.

Water and carbon exchanges between ecosystems and the atmosphere are interrelated, each regulated by processes occurring in both soil and vegetation. To understand how the carbon flux in semiarid ecosystems changes with varying water availability, the relationship between the net ecosystem exchange and ET must be analysed in different seasons. According to studies done in different ecosystems (Law et al., 2002; Luyssaert et al., 2007), this relationship is expected to be important in water-limited ecosystems with highly seasonal precipitation. Therefore, the relationship between transpiration and photosynthesis according to SWC has also been studied in semiarid SE Spain, in order to understand how vegetation growth and resilience will be affected by changes in water availability.

Advances in micrometeorological theory and technology (Aubinet et al., 2000) provide appropriate means of measuring ecosystem-scale fluxes over a spectrum of time-scales ranging from hours to years (Baldocchi et al., 2001). The eddy covariance (EC) technique (Swinbank, 1951) provides a direct measurement of energy and mass (such as CO_2 and water vapour) exchange across the biosphere–atmosphere interface (Baldocchi, 2003; Dabberdt et al., 1993; Valentini et al., 2000) and makes long-term integration possible (Wofsy et al., 1993). Combined with inverse modelling, remote sensing and meteorological information, the information acquired by this technique can be used to estimate reliable regional (and ultimately global) carbon and water cycling (Dolman et al., 2006; Mahadevan et al., 2008). The EC technique has proliferated (Aubinet et al., 2000; Baldocchi et al., 2001), with hundreds of towers/nodes for annual ecosystem CO_2 exchange estimation. In this research, terrestrial CO_2 flux is usually interpreted as a biological flux (Houghton, 2002; Valentini et al., 2000). Net ecosystem exchange (NEE, the difference between gross primary production and heterotrophic ecosystem respiration) determinations are combined with meteorological information in semiempirical hyperbolic models to determine the contribution of uptake (gross photosynthesis) and loss (ecosystem respiration) (e.g. Kowalski et al., 2004; Lasslop et al., 2010; Reichstein et al., 2005). In the last decade, several micrometeorological towers using the EC technique have been installed in semiarid SE Spain.

Hence, in SE Spain, due to its special climate conditions and substrate, carbon and water in all of these mentioned related processes have been the subject of experimental field research in recent years. The aims of this paper are to: i) define the state of the art of carbon and water balance measurement and modelling studies in this region, ii) analyse the different strata (vegetation and soil) and processes involved at different levels (NEE-ET, photosynthesis-transpiration, soil respiration-evaporation), and iii) identify needs for future research.

2. Ecosystem carbon dioxide and water exchange

Although the "flux community" has widened knowledge of the carbon cycle, nascent research has focused mainly on forest and cropland ecosystems, and continental-scale integrations have thus far neglected the functional behaviour of sparse shrubland ecosystems in Mediterranean climates (Schulze et al., 2009). However, currently this community is expanding to examine the relevance of semiarid lands in the carbon cycle, as highlighted by a recent special issue of the Fluxnet newsletter (FluxLetter Vol. 2 No. 4 - January, 2010).

The micrometeorological towers using the eddy covariance (EC) technique installed to measure NEE and ET in shrubland ecosystems in SE Spain have provided relevant data about CO_2 exchange in such ecosystems. They are characterised by asynchronous annual patterns of sunlight and precipitation, and particularly strong summer droughts (Serrano-Ortiz et al., 2007). Recent measurements from the "El Llano de los Juanes" flux site carbonate ecosystem reveal a possible contribution of abiotic processes to the NEE related to subsurface storage and later release of CO_2 via ventilation processes (Serrano-Ortiz et al., 2010a). "El Llano de los Juanes" is a Mediterranean shrubland plateau at 1600 m altitude located in the Sierra de Gádor (Almería, south east Spain; 36°55′41.7′N 2°45′1.7′W) characterised by a sub-humid montane Mediterranean climate. Such abiotic exchanges can temporarily (during summer drought) dominate the ecosystem CO_2 exchange (Kowalski et al., 2008). Empirical, hyperbolic models based on biological processes fail to describe such CO_2 exchange, and require alternative means of filling data gaps for long-term integration. Despite such difficulties, the mean annual NEE from May 2004 to December 2007 was estimated to vary from −63 (uptake) to 29 g C m^{-2} (release), averaging -2 ± 23 g C m^{-2} (a nearly neutral carbon sink) (Serrano-Ortiz et al., 2009). However, a recent study shows that heterogeneity of the subterranean pore space (preferential ventilation zones) could violate the micrometeorological "fetch" criterion, such that the measured NEE may not be representative of a wider area (Were et al., 2010). The origin of stored subsurface CO_2, which can exceed concentrations of 50,000 ppm in Mediterranean areas (Vadillo et al., 2007) and the drivers of its exchange with the surface are still unknown.

Additional micrometeorological towers using the EC technique have been installed in semiarid SE Spain at different altitudes and in different land-use types, and preliminary results show differing behaviour. Fig. 1 presents an example of the differing CO_2 exchange patterns for ecosystems in this region during an early summer week in 2008, and a synopsis of more general results from these ecosystems follows.

An alpine Mediterranean shrubland site located in the Sierra Nevada mountain range (2300 m a.s.l; 37°05′N 2°57′W) was found to be a carbon source of ca. 50 g C m^{-2} $year^{-1}$ during both 2007 and 2008 (Reverter et al., 2010). In addition, two semiarid carbonate shrubland sites near sea level and within a few km of the coast in Cabo de Gata Natural Park (Almería; 36°56′26′N 2°1′58.8′W) showed sizeable CO_2 emissions reaching ca. 8 μmol m^{-2} s^{-1} during dry periods (Serrano-Ortiz et al., 2010b). Preliminary analyses suggest contribution of subsurface ventilation. Finally, an average of more than 100 000 ha of Spanish forest burn annually (MIMAM, 2007), converting ecosystems into carbon sources for months to even years (Amiro et al., 2003; Bond-Lamberty et al., 2007); therefore, there is great interest in quantifying fire's contribution to global CO_2 emissions (Beringer et al., 2003; Conard and Ivanova, 1997) and the effect of different post-fire wood managements. In this context, two towers operating in a Mediterranean pine forest that burned in a wildfire in 2005, with different post-fire management of the burnt trees are shown in Fig. 1 as preliminary results (Sierra Nevada Natural park; Castro et al., 2011). During the displayed period, daytime CO_2 emissions of ca. 1 μmol m^{-2} s^{-1} were measured where all trees had been cut down and the trunks and branches removed (salvage logging, common post-fire silvicultural management; Castro et al., 2011), while the non-intervention treatment (dead forest left standing) showed a daytime CO_2 uptake of ca. 3 μmol m^{-2} s^{-1} (Fig. 1d). However, to assess the

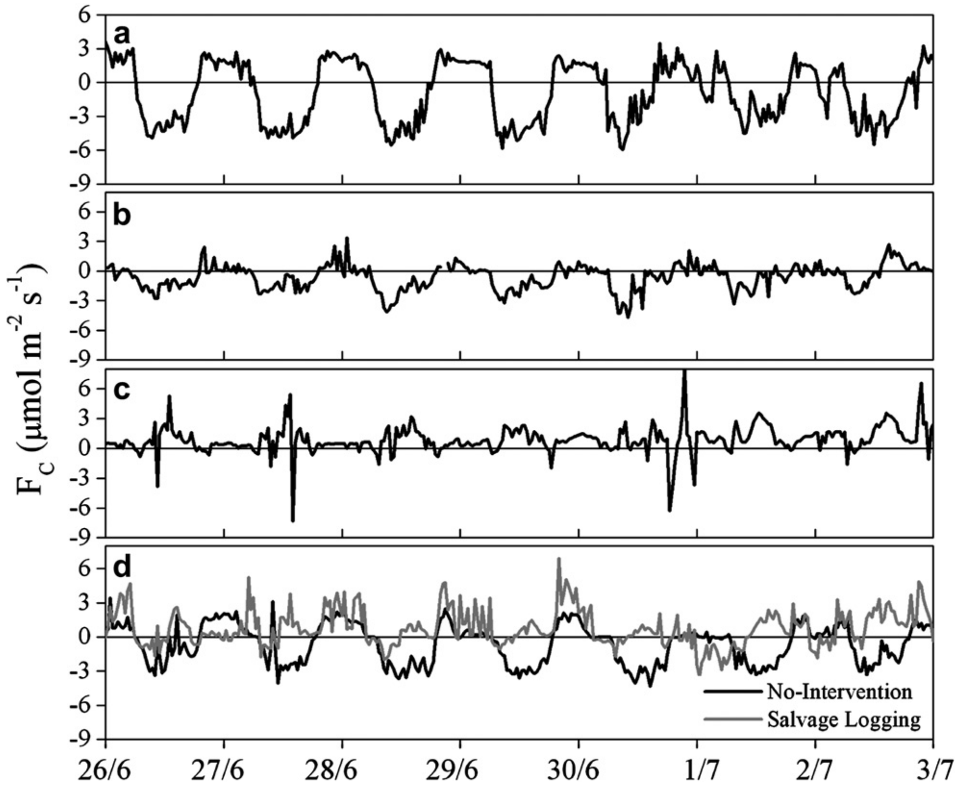

Fig. 1. Patterns of CO_2 exchange (Fc) from 26th June to 3rd July 2008 in different ecosystems located in Southeast Spain. a) Laguna Seca (Sierra Nevada), b) Llano de los Juanes (Sierra de Gádor), c) Balsa Blanca (Cabo de Gata) and d) two ecosystems with different post-fire management of burnt trees.

impact of salvage logging management on the carbon cycle, several years of CO_2 exchange estimations are needed.

The micrometeorological towers using the EC technique have also been used in SE Spain to measure and model the water balance through measurements of ET. In arid and semiarid environments, where ET is critical to the water balance, it can represent up to 90% of annual P. However, some areas can act as soil water sources when $P > ET$, or as sinks when $P < ET$ (Domingo et al., 2001). Environmental characterisation of these areas as either source or sink is fundamental for determining adequate management policies (Cantón et al., 2010). Evapotranspiration models enable ecosystem-scale estimation, and have been used widely in semiarid SE Spain (Brenner and Incoll, 1997; Domingo et al., 1999, 2001; Ramírez et al., 2007a; Villagarcia et al., 2007, 2010; Were et al., 2007, 2008). Brenner and Incoll (1997) developed a physically-based evapotranspiration model (Clumped Model-CM) for sparse vegetation. This model has been successfully applied in stands of three species typical of SE Spain (*Retama sphaerocarpa* L. (Boiss), *Anthyllis cytisoides* L., and *Stipa tenacissima* L.) and compared to Bowen ratio measurements, eddy covariance, and (sapflow) heat balance methods (Domingo et al., 1999; Villagarcía et al., 2010; Were et al., 2008).

Domingo et al. (2001) demonstrated that by combining CM with data for I and R_{off}, sites may be classified as sources or sinks. For example, they found that the valley floor of the Rambla Honda experimental site (Tabernas, Almería 37°8′N, 2°22′W, 630 m a.s.l.), where the roots of the predominant shrub *R. sphaerocarpa* L. (Boiss) can reach ground water 30 m deep (Haase et al., 1996), acts as a long-term soil water sink ($ET >> P$). Neither run-on from surrounding slopes, nor infiltration of local rainfall appear to be sufficient to explain the water deficit observed, and they concluded that infiltration of channel flow coming from the top of the catchment during flash floods replenishes the water deficit. Supporting this idea, Archer et al. (2002) and Domingo et al. (1998) demonstrated that, on the surrounding hill slopes, the typical funnel shape of some plant species (such as *A. cytisoides*) (García, 2006) facilitated preferential flow towards the shallow root system of the shrub, but afterwards, in summer, all this water that did not reach the water table was locally transpired and evaporated. The role of transpiration is also highlighted in wetland areas of SE Spain, where water managers must take the high transpiration rates of riparian zones into account (Moro et al., 2004).

South east Spain exhibits a wide variety of ecosystems from alpine Mediterranean to semiarid coastal ecosystems that should be analysed from these perspectives and major efforts are ongoing to characterise ET and associated processes in aquifer recharge areas (Sierra de Gádor-Almería; Ventós catchment-Alicante) and coastal carbonate areas (Cabo de Gata, Almería).

As already indicated in the Introduction, in order to project the effects of climate change on the functioning of ecosystems it is important to understand the interrelationship of the carbon and water cycles (e.g., Janssens et al., 2005; Law et al., 2002). In the SE of Spain, where climate change is predicted to have strong effects, with higher temperatures and lower precipitations, this issue is of high importance. Although, some first steps have been taken to study water use efficiency in steppe ecosystems (Ramírez et al., 2008b), several ongoing projects are monitoring the carbon and water balances over a range of ecosystems, from mountainous areas to coastal steppes. These projects will generate results that will help to better understand how the water balance affects the carbon balance of these ecosystems, and, therefore, how the expected reduction in water availability will affect the vegetation growth and resilience in these ecosystems.

3. Component water and CO_2 processes and scaling

3.1. Soil respiration

In semiarid ecosystems, SWC is the fundamental driver of biological activity and soil respiration (Almagro et al., 2009; Conant et al., 2000; Jia et al., 2006; Liu et al., 2009). The dry and warm climate of SE Spain determines that the seasonal dynamics of soil respiration are mainly controlled by water availability, and only occasionally by temperature. Results from Rey et al. (2011) (Fig. 2) show such dynamics in Cabo de Gata Natural Park where precipitation is hardly 200 mm.

Although SWC has been recognised as an important factor incorporated in respiration models (Rey et al., 2002), its role as a determinant in semiarid ecosystems may be more complicated (Schwinning et al., 2004). Drylands are characterised by erratic, random rainfall events that interact with the functioning of autotrophic and heterotrophic soil respiration processes, and cause pulses of CO_2 to the atmosphere (Jarvis et al., 2007; Rey et al., 2002, 2005) that contribute significantly to the total amount of carbon respired (Huxman et al., 2004). Two major processes may contribute to the rapid increase in soil emissions following rainfall. First, the large amounts of CO_2 accumulated in pore spaces during dry periods are physically displaced and released (Emmerich, 2003; Huxman et al., 2004; Inglima et al., 2009; Serrano-Ortiz et al., 2010a), and second, decomposition of readily available carbon accumulated during the previous dry period are rapidly activated (Kieft et al., 1997).

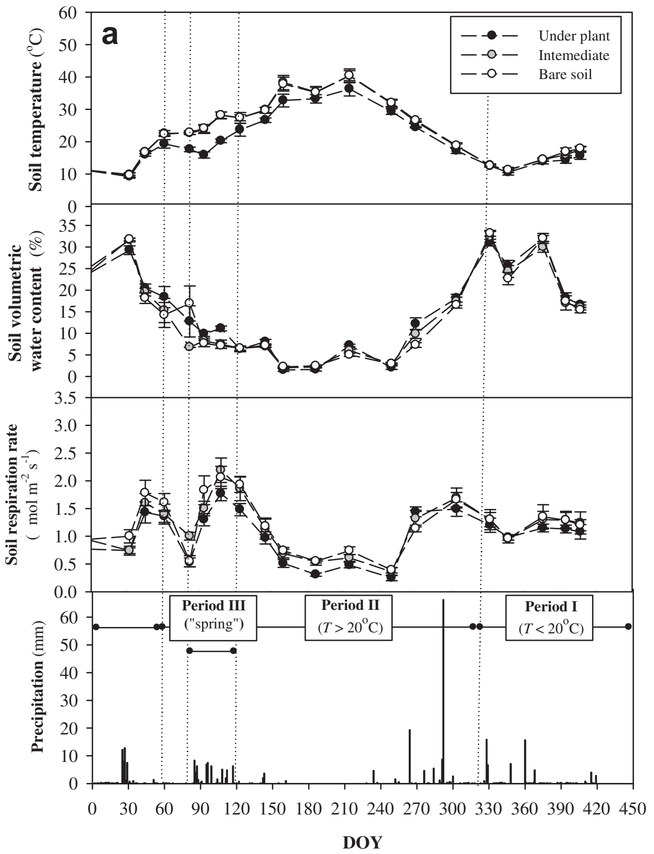

Fig. 2. Precipitation and soil respiration dynamics, soil water content and soil temperature in three surface positions in a semiarid steppe (*Stipa tenacissima L.*) ecosystem in Balsa Blanca (Cabo de Gata) (Rey et al., 2011).

Another distinctive characteristic of arid and semiarid ecosystems such as those in SE Spain is the high spatial variability and patchy distribution of resources (Schlesinger and Pilmanis, 1998), which must be reflected in fluxes via soil respiration. Small rainfall events and dew may potentially trigger microbial respiration in canopy interspaces, whereas larger rainfall events are required to stimulate root and microbial activity under plants (Luo and Zhou, 2006). Rey et al. (2011) found no significant differences in soil respiration between canopy and intercanopy spaces during one year in a semiarid steppe in SE Spain (Cabo de Gata, Almería) (Fig. 2), although significant differences were observed in soil properties and soil carbon content. Therefore, the interaction between water availability and ecosystem structure is another critical aspect that needs to be considered. In semiarid ecosystems, inorganic carbon can exceed organic carbon by up to tenfold (Schlesinger, 1982). Current estimates of inorganic accumulation rates in arid and semiarid soils range from 0.5 to 5 g C m^{-2} yr^{-1} (Marion et al., 2008). Diaz-Hernandez et al. (2003) estimated that in an intramontane sedimentary basin in SE Spain (an important landscape for the evaluation of soil carbon stored in semiarid regions) the organic carbon content was 7.8 kg m^{-2} (down to 2–3.5 m depending on soil depth), whereas inorganic carbon was as high as 134.4 kg m^{-2}. Recent studies have indicated that the turnover time of inorganic carbon may be much shorter than previously thought (Monger and Gallegos, 2000), and thus, this fraction may play an important role in the ecosystem carbon balance (Kowalski et al., 2008). Part of soil CO_2 emissions may be the result of the weathering of soil inorganic carbon in the form of carbonates, whereas CO_2 accumulation occurs as a result of carbonate precipitation (Serrano-Ortiz et al., 2010a). Furthermore, arid and semiarid ecosystems are prone to soil degradation, which may be aggravated by land use and climate change (UNEP, 1997). The impact of land degradation on soil respiration is therefore likely to lead to considerable changes in the carbon balance of semiarid ecosystems (Rey et al., 2011).

Some studies on soil respiration carried out in SE Spain illustrate some of these processes. Almagro et al. (2009) investigated the dynamics of soil respiration under different land uses in Murcia Province where mean annual precipitation is around 400 mm and mean annual temperature around 15 °C. Mean annual soil respiration rates beneath canopies were 2.35, 1.87 and 2.18 μmol CO_2 m^{-2} s^{-1} in forest, abandoned agricultural and rainfed olive orchards, respectively. Whereas temperature was the main driving variable of soil respiration during the autumn and winter, SWC was the limiting factor for late spring and summer. In a drier area (200 mm and 18 °C) Rey et al. (2011) found that SWC was the main driver of soil respiration for most of the year, particularly below a threshold of 13% (volumetric SWC), and even during those few winter months with soil moisture above this, the effect of temperature was mediated by soil moisture. Annual mean soil respiration was 1.01 and 0.77 μmol CO_2 m^{-2} s^{-1} for natural and degraded sites, respectively. Both studies analysed the spatial variability of soil respiration, measuring rates under plants versus canopy interspaces, and found somewhat contrasting results. Whereas Rey et al. (2011), as mentioned above, did not find any significant differences between ground cover types in either ecosystem (natural and degraded sites), Almagro et al. (2009) found significant differences in the olive grove and forest sites, but no differences in the abandoned field. Similarly, Maestre and Cortina (2003) in a nearby area in the Province of Alicante (380 mm y^{-1}, and 16 °C), found that SWC was the main factor controlling temporal dynamics of soil respiration. In contrast, they reported significant differences between rates measured under alpha grass tussocks and in bare ground. However, they reported results only during the growing season (spring), and differences were pronounced mostly after rainfall events, which is in agreement with the results reported by Rey et al. (2011).

3.2. Leaf and plant gas exchange

Numerous ecological studies have focused on leaf-scale gas exchange measurements employing chambers (Kruijt et al., 1997). In semiarid SE Spain, leaf measurements of net photosynthesis, transpiration, and stomatal conductance have been widely used for assessing water stress avoidance strategies (*sensu* Levitt, 1980) for some prominent species (Balaguer et al., 2002; Domingo et al., 2003, 2002; Haase et al., 1999; Pugnaire and Haase, 1996; Pugnaire et al., 1996; Ramírez and Bellot, 2009), ontogenetic comparison (Ramírez et al., 2008b), assessing the results of restoration activities (Vilagrosa et al., 2005), among other things.

More recently, the sub-leaf scale has gained importance for examining intrinsic water use efficiency and competition by making use of the isotopic composition of carbon (Ramírez et al., 2009) and landscape function analysis (Maestre and Cortina, 2006).

Leaf-scale results have also been extrapolated to individual-canopy scale in semiarid SE Spain. In a *S. tenacissima* 'alpha' grassland, Haase et al. (1999) calculated daily canopy net photosynthesis by integrating the hourly carbon assimilation measured by an IRGA chamber, and scaling by the foliar area of the assessed tillers. On the other hand, the combination of crown architecture/geometry (e.g., YPlant, Pearcy and Yang, 1996) and canopy photosynthesis (Beyschlag and Ryel, 2007) models has allowed individual-canopy net photosynthesis to be calculated by taking the heterogeneity of canopy characteristics such as age, physiology, foliar arrangement and microclimatic conditions of the branches using summation and averaging schemes to scale-up (*sensu* Jarvis, 1995). Neglect of the internal heterogeneity of the individual might lead to overestimation of the individual net photosynthesis. For example, extrapolation of daily net photosynthesis in *S. tenacissima* in the wet season by Haase et al. (1999) ranged from 508 to 893 mmol CO_2 m^{-2} day^{-1}, whereas the maximum daily net photosynthesis at individual scale calculated by an architectural model (YPlant) was 292 mmol CO_2 m^{-2} day^{-1} (Valladares and Pugnaire, 1999). These authors highlighted the fact that self-shading of leaves limited carbon assimilation to only 40% of potential.

Regarding water fluxes, calculation of the individual-canopy stomatal conductance and transpiration rates at leaf–branch scale has been carried out for the implementation of the above mentioned evapotranspiration models (Clumped Model-CM) in stands of *S. tenacissima*, *R. sphaerocarpa* and *A. cytisoides*. The goal was to estimate transpiration by combining direct sap flow measurements in some branches (Domingo et al., 1999) with empirical modelling of stomatal conductance in terms of photosynthetic photon flux density and vapour pressure deficit (Villagarcía et al., 2010) and leaf temperature measurements to calculate the vapour saturation density (Brenner and Incoll, 1997). Once transpiration and stomatal conductance are estimated, these are extrapolated to the stand level, scaling by the fraction of vegetation cover and leaf area index. On the other hand, using a crown architectural model and following a sequential scaling process (Baldocchi et al., 1991), Ramírez et al. (2006, 2008a) found that leaf senescence and self-shading are crucial to scaling transpiration from leaf to individual in *S. tenacissima*. Ramírez et al. (2008a) assessed the individual transpiration of three tussock size classes in different soil water conditions (from <5 to >25% of volumetric SWC), by calculating empirical functions for each size class that allowed correcting the overestimation from extrapolated leaf measurements. Ramírez et al. (2007a) used these functions to scale transpiration in *S. tenacissima* from individual to stand with satisfactory results compared to stand transpiration calculated by CM.

3.3. Scaling water and CO_2 fluxes: the role of remote sensing

As mentioned above, eddy covariance (EC) is one of the most successful techniques for ecosystem characterisation of water and carbon fluxes. However, EC measurements limit spatial coverage to a footprint of around 1 km^2 (Kljun et al., 2004), and the only data source providing frequent simultaneous and spatially explicit information correlated with the biophysical properties of the surface and its water and energy status is remote sensing (RS) (Kustas and Norman, 1996).

The particularities of drylands make remote sensing modelling of carbon and water fluxes more challenging than other biomes. For instance, the mosaics of vegetation, dry matter and bright, and dry soils (Okin, 2002) cause nonlinear effects in pixel reflectance that can mask vegetation signals (Asner, 1998; Huete and Jackson, 1987). This patchiness also results in strong soil–vegetation interaction among surface fluxes (Chehbouni et al., 2000; Moran et al., 1994). Dryland ET and photosynthetic rates are generally low, with peak activity following rainfall pulses (D'Odorico and Porporato, 2006). In semiarid SE Spain, with asynchronous wet and warm seasons (Serrano-Ortiz et al., 2007), water fluxes on many days do not exceed the average error of most RS ET models ($\sim$0.8 mm day^{-1}, Seguin et al., 1999), and are even lower than fluxes at other semi-arid sites where rainy and warm seasons coincide (Gillies et al., 1997). Additionally, capturing pulse activity requires daily overpasses, guaranteed only by sensors such as MODIS or SEVIRI that have coarse spatial resolution (1–3 km).

To improve comparability and scaling of coarse spectral measurements to EC measurements, Gamon et al. (2006) created SpecNet (Spectral Network) which adds standardised field spectral samplings to existing FLUXNET sites. SpecNet currently includes six desert and semiarid sites. In semiarid SE Spain, the EEZA (CSIC) Desertification and Geoecology Group has been working on four nested scale-up levels for monitoring ecosystem fluxes with remote sensing using both permanent and portable field sensors (Morillas et al., 2009), Unmanned Aerial Vehicles (UAVs; Berni et al., 2009) in thermal (40 cm) and VNIR (15 cm) ranges, hyperspectral images (Hymap and DAIS) at 4 m and 10 m, and ASTER (30–90 m) and MODIS data (250 m–1 km) (García et al., 2007; García et al., 2008b, 2009).

Scaling carbon fluxes from stand to patch and landscape can be done using a bottom-up approach, but this requires a high degree of parameterisation and complicates regional applications. In addition, feedback processes might cause bulk stomatal response and CO_2 assimilation to be unscalable from leaf to canopy and region (Houborg et al., 2009). Top-down approaches use simple scaling rules, but require some degree of empiricism at some point (Houborg et al., 2009). The Light Use Efficiency (LUE) model (Monteith, 1972) is widely used to estimate Gross Primary Productivity (GPP) in process-based models such as NASA–CASA (Potter et al., 2003) and also in other remote sensing applications (Hilker et al., 2008). Vegetation Indices (VI) are used to estimate fPAR (fraction of absorbed PAR). Since in drylands, water availability is the main constraint for maximum biological efficiency (Brogaard et al., 2005), remote sensing water-deficit indicators would be useful in improving current LUE estimates (Carlson et al., 1995; Sandholt et al., 2002). These indicators have been tested in semiarid SE Spain using ASTER (García et al., 2007) and MODIS data (García et al., 2008a, 2009), and can be directly incorporated into LUE modelling.

In semiarid SE Spain, Morillas et al. (2009) showed the relationship of the locally field measured PRI (Photochemical Reflectance Index) and thermal stress indices with leaf conductance and transpiration for *S. tenacissima* in Cabo de Gata Natural Park. We used the same dataset to explore correlations with carbon flux (F_c) and LUE (Table 1), and found that pigment content indices (chlorophyll and carotenoids) and canopy water content indices estimated F_c better than PRI or NDVI. Water stress indicators showed negative correlations with F_c at midday when water stress tends to be maximum, and LUE was significantly correlated with those indices highly correlated with F_c. These results emphasise the importance of using different spectral regions, including thermal and narrow-band to characterise the functioning of semiarid vegetation (Ustin et al., 2009). It remains to be seen whether the performance of these indices is similar at the ecosystem level using imagery and EC measurements.

Regarding the scaling of water fluxes there are some comprehensive reviews describing models ranging from empirical to semiempirical and using physical or numerical approaches (see Courault et al., 2005; Kustas and Norman, 1996). The most popular RS algorithms for estimating water fluxes in semiarid areas calculate ET as a residual of the surface energy balance equation. In semiarid SE Spain, the Simplified Relationship (Seguin and Itier, 1983), that estimates daily sensible heat flux using a classic surface-resistance approach using midday measurements of surface and air temperatures, provided better results despite of considering an homogeneous aerodynamic resistance across the shrublands than the Carlson et al. (1995) approach, where aerodynamic resistances were modelled spatially as a function of vegetation greenness, and which seems to be better suited to dense vegetation cover areas (García et al., 2007). In other semiarid areas, such as Arizona, dual source models explicitly modelling vegetation and soil fluxes separately and also their interactions, showed better results than single source models treating the mixture of soil and vegetation as a whole (Norman et al., 1995). However dual source modelling requires disaggregation of pixel temperature into vegetation and soil which is solved by iterations or else requires measurements of surface temperature from different view angles.

One of the first contextual models estimating ET in semiarid natural vegetation was the WDI (Water Deficit Index) by Moran et al. (1994). Later versions of the WDI such as the TVDI (Temperature Vegetation Dryness Index; Sandholt et al., 2002) or the Jiang and Islam (2001) model have been successfully applied in semiarid regions such as Senegal (Stisen et al., 2008) and semiarid SE Spain (García et al., 2008b). RS data has also been incorporated in the Penman–Monteith equation to characterise surface conductance (Cleugh et al., 2005; Leuning et al., 2008). However, in SE Spain, their performance has been found to be poor, requiring modelling of SWC temporal dynamics (Morillas et al., 2011).

One outstanding issue in the use of sun-synchronous satellites is scaling instantaneous estimates of the energy balance components: net radiation (Rn), soil heat flux (G), sensible heat flux (H) and ET to daily estimates (Bisht et al., 2005). A sinusoidal model for semiarid SE Spain scaling Rn from instantaneous to daily estimates based on the daily solar trend performed better than assuming constant scaling factors (Morillas et al., 2008).

In some approaches, the role of RS is just to estimate vegetation cover and incorporate it into water balance modelling. For instance, Boer and Puigdefábregas (2005) developed a spatial ET model working at annual time-scales in the Guadalentín Basin (SE Spain). Their model was run by Contreras et al. (2008) in the dry Mediterranean mountains of Sierra de Gádor for an average rainfall year. As it relies in the hydrological equilibrium hypothesis, stating that vegetation adjusts to maximise its growth while minimising water stress (Nemani and Running, 1989), this approach is strictly limited to long time-scales (annual averages) and perennial vegetation.

3.4. Non-rainfall water inputs

Non-rainfall water inputs include fog, dew formation and atmospheric water adsorption by soil (AWAS). In the absence of fog, dew and AWAS are outstandingly relevant processes that improve the water balance in semiarid and arid ecosystems. Research on dew and AWAS is underway in semiarid SE Spain.

Few studies have assessed the contribution of dew to the water balance in semiarid environments. The direct use of dew by plants or biological soil crusts has also been poorly studied in these areas. Moro et al. (2007, 2009) have explored the suitability of the EC technique, combined with qualitative methods such as wetness sensors, as a tool to measure actual dewfall in semiarid conditions, both in a dry river bed (Rambla Honda, Tabernas, Almería) (Moro et al., 2007), and in a coastal steppe dominated by *S. tenaccisima* with bare soil and biological soil crusts (Balsa Blanca, Cabo de Gata, Almería) (Moro et al., 2009). In Rambla Honda, dewfall was calculated as 12% of rainfall for 2003, averaging 0.08 mm day^{-1}. Dewfall was higher in late winter and early spring, when vegetation starts active growth. Dew episodes were recorded on over 50% of the nights throughout the study period, averaging 6.5 h per night. Sparse *R. sphaerocarpa* canopies significantly influenced condensation on the soil surface. The gradient of dew occurrence increased from the centre of the canopy outward to the open, bare soil. Dew duration (hours per night) decreased from the inner position under the *R. sphaerocarpa* canopy (4.1) outward to the open spaces (7.7), with 7.3 at the edge. These results need further validation, but seem to be due to a combination of aerodynamic and longwave radiative characteristics that differ for plants and soil, and can change the energy balances of the individual components in the system (Domingo et al., 2000).

In a preliminary study in Balsa Blanca, dewfall was recorded on 98% of nights during one whole year (2007). This percentage, although surprisingly high, is being confirmed by ongoing dew measurements in the area (Uclés et al., personal communication). Dewfall length varied from 1 to 16 h per day with an average of 6.3 h per day. The average dewfall rate was 0.016 mm h^{-1}, with relatively little variability over the year (Moro et al., 2009). Dewfall episodes were longer in late autumn and winter and decreased in

Table 1
Pearson's correlation coefficient (R) between carbon assimilation variables: F_c in μmol CO_2 m^{-2} s^{-1} and light use efficiency (LUE) (Licor6400) vs. spectral (GER2400) and thermal indices (Raytek). Measurements were made at midday on *Stipa tenacissima* in Cabo de Gata (Almeria, Spain) between June 2008 and February 2009. * and ** indicate significant correlations at $p < 0.05$ and $p < 0.01$ respectively.

Indicator of	Name/formula	Reference	F_c	LUE
Green vegetation cover	Normalized Difference Vegetation Index: NDVI = $(R_{800} - R_{670})/(R_{800} + R_{670})$	Tucker and Sellers, 1986	0.65	0.56
Canopy water content	Normalized Difference Water Index NDWI = $(R_{860} - R_{1240})/(R_{860} - R_{1240})$	Gao, 1996	0.86*	0.66
Xanthophyll cycle	Photochemical Reflectance Index PRI = $(R_{570} - R_{531})/(R_{570} + R_{531})$	Gamon et al., 1992	0.12	0.28
Chlorophyll content	R_{750}/R_{710}	Zarco-Tejada et al., 2003	0.95**	0.88*
Carotenoids content	R_{800}/R_{470}	Blackburn, 1998	0.96**	0.84*
Water stress	$T_{canopy} - T_{air}$	Sepulcre-Cantó et al., 2007	−0.9*	−0.83
Water stress	$T_{soil} - T_{canopy}$		−0.93*	−0.83

spring. Comparing the contribution of dewfall to the local water balance in Balsa Blanca during a wet (January–May 2007, total P of 120 mm) and a dry period (January–May 2008, total P of 15 mm), Moro et al. (2009) found dewfall totalled 15% of rainfall in 2007 and more than 100% in 2008. Long-term average rainfall in the area is 200 mm. Overall, these results stress the relevance of dewfall as a relatively small but constant source of water for some arid ecosystems, as well as its significant contribution to the local water balance, mainly during dry periods.

Regarding AWAS, Agam and Berliner (2004, 2006) highlighted that it can be even more common than dew formation in some areas. In semiarid Mediterranean environments, Kosmas et al. (1998) calculated that water gain from AWAS was 26.3% of the precipitation during February–August of 1996 in Athens, Greece. Such water gains via AWAS can supply 55.7%–70.7% of the soil evaporative demand (Kosmas et al., 2001). Verhoef et al. (2006) reported and characterised AWAS occurrence in Mediterranean SW Spain (Seville Province) by implementing a mechanistic model. In semiarid environments like in Almería Province, soil water fluctuation (Villagarcía et al., 2004) has been related to AWAS, and in Alicante Province, Ramírez et al. (2007b) found that the AWAS covers the ET demands of a *S. tenacissima* grassland during the water-deficit season. Some studies (Ramírez and Bellot, 2009; Ramírez et al., 2007b, 2008b) have suggested that *S. tenacissima* could make use of water gains from AWAS in interspaces among tussocks. The main evidence (all gathered during summer) to support this hypothesis was that (1) the total AWAS water gain was very similar to the evaporation of soil under tussocks and bare soil calculated by CM, (2) the stomatal conductance of these tussocks was higher (from 21.8 to 43.1 mmol H_2O m^{-2} s^{-1}, Ramírez et al., 2007a) in summer than found in other studies (from 0 to 0.08 mmol H_2O m^{-2} s^{-1}, Balaguer et al., 2002; Pugnaire and Haase, 1996), and (3) *S. tenacissima* stands decoupled from the surrounding soil, located in places with high rock outcrops, showed greater stress symptoms (lower gas exchange rates and lower maximum photochemical efficiency of photosystem II) than stands in deep soil well connected with the tussocks. This evidence contradicts the paradigm that *S. tenacissima* is not able to make use of water gains from bare soil among tussocks (Puigdefábregas and Sánchez, 1996; Puigdefabregas et al., 1999).

Based on the above, supporting the hypothesis of water consumption from non-rainfall water gains in bare soil surrounding the tussock, Ramírez, Querejeta and Bellot (personal communication) designed a preliminary experiment with *S. tenacissima* using water enriched with a high concentration of Deuterium (it was mixed 20 ml of D_2O solution with 99.9% of D per litter of distilled water) as a tracer in the "El Ventós" experimental area (38°29′N; 0°37′W), Alicante Province, SE Spain. They detected significant isotopical composition of Deuterium (δD) enrichment in leaves (sampled from 9:00 to 10:00 h local time) after a water pulse in bare soil (Table 2), and also slight δD enrichment in leaves in the tussock upslope in water pulses applied 0.5 m downslope from the tussock. This result confirms the aforementioned hypothesis and also a possible physiological integration mechanism among tillers in the tussock.

Table 2
Average Deuterium isotope composition (δD, ‰) ± standard error ($n = 10$) in water in *Stipa tenacisima* leaves located on the growing front (downslope, GF) and in the terracette (upslope, T) of the tussock before (11th December, 2007) and after (14th December, 2007) an enriched water pulse from 0.1 to 0.5 m downslope from the individuals assessed. The water pulse was simulated by filling 5 holes (0.02 m diameter and 0.1 m deep) with water enriched with δD (2%). The repeated measures 2-way ANOVA with time as a factor only detected significant differences in Time ($F = 9.32$, $p = 0.01$).

	GF	T	0.1m	0.5m
Before	3.1 ± 1.9	5.0 ± 1.2	3.9 ± 1.9	4.3 ± 1.3
After	11.4 ± 2.4	6.7 ± 0.8	7.2 ± 1.1	12.3 ± 2.6

4. Needs for future research

Although several experimental field sites are monitored for net ecosystem carbon and water balance, further research is needed to characterise underlying processes and predict the impact of climate change on such balances on the ecosystems in dry and semiarid Mediterranean SE Spain. For such an extensive area, a high proportion of land use is agricultural (e.g., olive groves) in which gas exchange with atmosphere has yet to be measured. Thus, for understanding and monitoring regional carbon and water flows relating to land-use types, observations are needed in such agricultural systems. In addition, many years of continuous water and CO_2 measurements are required in order to characterise the response of different land-use types to desertification processes, post-fire management practices and climate variability. Regarding interpretation of carbon cycling over carbonate sites, it is imperative to supplement micrometeorological studies with other methodologies in order to discriminate between biological and abiotic components of the CO_2 fluxes. Such information could further be used to achieve reliable regional models based on inverse modelling and remote sensing.

Soil respiration is one of the main sources of carbon loss in arid and semiarid ecosystems. Despite the large amount of research in soil respiration over the last decade, semiarid ecosystems are much less studied than other ecosystems (Subke et al., 2006). Consequently, little is known about the temporal and spatial dynamics of soil respiration in these regions. Although some insights and major directions of research are starting to emerge from recent studies, more work on this subject is needed.

Soil water content is a crucial variable controlling both the carbon and water balances at ecosystem scale, especially in arid and semiarid climates. Since SWC is a key variable in the functioning of semiarid ecosystems and due to its high spatial heterogeneity, more research is needed to be able to characterise the soil water balance of more ecosystems in semiarid SE Spain, and to estimate this variable accurately. Important research efforts have been done to calculate SWC from satellite observations of microwave radiation (Dolman and de Jeu, 2010) that in the future could be key to improve the estimation of this variable in semiarid SE Spain.

In view of the importance of non-rainfall water gains in semiarid environments, this phenomenon should be studied in depth, testing different substrates (e.g. soil mixed with stone, gravel or mulch) on water gains from AWAS or dew in Mediterranean semiarid areas. This would also provide an additional source of water for vegetation in the dry summers, thus improving ecological restoration activities in these environments.

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