Agriculture, Ecosystems and Environment 233 (2016) 147–157

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Rainfall regimes control C-exchange of Mediterranean olive orchard

L. Brilli[a,d,*], B. Gioli[a], P. Toscano[a], M. Moriondo[a], A. Zaldei[a], C. Cantini[c], R. Ferrise[b], M. Bindi[b,e]

[a] IBIMET-CNR, Via Caproni 8, 50145 Firenze, Italy
[b] University of Florence, DiSPAA, Piazzale delle Cascine 18, 50144 Firenze, Italy
[c] IVALSA-CNR, Via Aurelia 49, 58022 Follonica, Italy
[d] University of Sassari – Viale Enrico De Nicola, 9, 07100 Sassari, Italy
[e] Reaserch Unit CLimate chAnge SyStem and Ecosystem (CLASSE), University of Florence, Piazza San Marco 4, 50121, Firenze, Italy

ARTICLE INFO

Article history:
Received 18 April 2016
Received in revised form 8 September 2016
Accepted 9 September 2016
Available online 17 September 2016

Keywords:
Olive grove
C-flux
NEE
Rainfall
Time-lag analysis

ABSTRACT

We investigated the relationship between Net Ecosystem Exchange (NEE), energy partitioning and the main climate variables (rainfall, temperature and solar radiation) in a typical Mediterranean rainfed olive orchard. Eddy covariance measurements covered three contrasting and extreme years, spanning over 90% of the long-term rainfall variability. Across those years, the olive orchard resulted overall a net carbon sink (3.6 Mg ha^{-1} year $^{-1}$) comparable to several Italian forestry systems. Annual and seasonal NEE was found to be mostly driven by rainfall regimes and their seasonal variability. More specifically, higher spring-like rainfall increased both spring and summer NEE. On the contrary, monthly scale NEE was poorly correlated with rainfall ($r = -0.286$; p-value = 0.091), whilst good correlations were observed with air temperature ($r = 0.473$; p-value = 0.003) and solar radiation ($r = 0.541$; p-value = 0.001). These results indicated that temperature and light played an important role in regulating NEE, but rainfall amounts and timing represent the most important drivers of carbon storage of rainfed olive orchard in dry environment as Mediterranean basin. Future expected reduction in rainfall pattern, with less rainy days and longer drought periods especially in the warm season, will decrease the carbon sequestration capacity of this agro-system, requiring the adoption of agronomic practices aimed at enhancing the soil water retention capacity.

1. Introduction

A deep understanding of the factors leading to carbon sequestration in agro-forestry systems is crucial for identifying their contribution in a perspective of climate change mitigation. Eco-physiological characteristics (rates of net primary productivity, stomata mechanisms, below-ground C transfer integrating with soil characteristics) and management (tillages, fertilization, cutting, etc.) can highly affect C-sequestration capacity (Lal, 2004; Seidl et al., 2007; Lindner et al., 2010; Hernandez-Ramirez et al., 2011; Jones et al., 2014; Kane, 2015). However, it is well known that climate conditions represent the main driver of carbon sequestration and biomass growth (Reichstein et al., 2013; Ahlström et al., 2015). Looking at future climate projections, predicted changes in temperature and rainfall trends are expected to lead more extreme climatic conditions compared to present (Lenderink and Van Meijgaard, 2008; Jacob and Podzun, 2010; Kjellström et al., 2011; IPCC, 2013). A joint occurrence of higher temperatures and drought period is expected to amplify the impacts on semi-arid ecosystems and, in turn, changes in C-fluxes dynamics especially over Mediterranean (Vautard et al., 2007; Haylock et al., 2008; Durao et al., 2010; Rodda et al., 2010; Del Río et al., 2011).

In Mediterranean basin, while temperature and radiation are not usually considered as limiting factors for crop growth and development, water availability is widely recognized to be the key variable controlling mass exchange and growth (Noy-Meir, 1973; Chaves et al., 2002; Kwon et al., 2008; Medrano et al., 2009; Jia et al., 2014). Investigations on the relations between these ecosystem processes and water availability, made increasingly clear that temporal variability and extremes in precipitation are more important than mean conditions (Swemmer et al., 2007; Heisler-White et al., 2008, 2009; Smith, 2011; Reyer et al., 2012; Thompson et al., 2013). Both the size and timing of precipitation can influence ecosystem response in terms of floral and plant community composition (Li et al., 2015), thus leading spatial and

* Corresponding author at: IBIMET-CNR, Via Caproni 8, 50145 Firenze, Italy.
E-mail address: l.brilli@ibimet.cnr.it (L. Brilli).

http://dx.doi.org/10.1016/j.agee.2016.09.006
0167-8809/

temporal variability of the major ecosystem C-flux components (Chang et al., 2013; Li et al., 2015). Therefore, changes in rainfall patterns may lead to different ecosystem specific responses in terms of carbon fluxes and stocks, that need to be assessed specifically for the most important ecosystems. Among these, olive orchard is one of the most relevant ecosystems with more than 700 million trees cultivated over 9 Mha. Despite the primary role of olive orchards within Mediterranean basin concerns agriculture and, more in detail, the production of olives and olive oil, this ecosystem can play an important role in climate mitigation due to its recognized long-term carbon storage capacity in soil and woody compartments (Nieto et al., 2010; Brilli et al., 2013).

Understanding and quantifying how rainfall can affect olive orchard C-uptake fills a lack of knowledge, since the majority of studies was carried out on irrigated fruit systems (Dichio et al., 2005; Testi et al., 2008; Villalobos et al., 2012; Nardino et al., 2013). Irrigation, however, is unusual for olive trees. In Italy only 8.7% of olive trees farms are managed with irrigation systems (ISTAT, 2010), and, while therefore, results from studies carried out on irrigated olive orchards may not reflect the actual contribution offered by the large majority of these ecosystems, nor are capable of assessing the ecosystem response to climate extremes.

In this study, we investigated the relation between GPP (Gross Primary Production), Reco (Ecosystem respiration), NEE (Net Ecosystem Exchange) and climate variables in a typical Mediterranean rainfed olive orchard. The study focused on a period of 3 years (2010–2012), that were very contrasting and representative of the long term 30 years climate variability at the study area, allowing the investigation of ecosystem response to mean and extreme rainfall patterns characterized by both positive and negative anomalies. Annual, seasonal and monthly rainfall interaction with C-balance dynamics was investigated to finally assess the capacity of Mediterranean olive orchard to front increasing occurrence of climate extremes and drought.

2. Materials and methods

2.1. Study area

The study area is located in central Italy (Follonica, 42°56′N, 10°46′E). According to Thornthwaite's classification (Thornthwaite, 1948) the area has a mesothermic climate, with high temperatures and prolonged drought periods in summer and mild winters. The coldest month is January with a monthly mean temperature of 7.5 °C, while the warmest is August (30.9 °C). The long-term total annual rainfall average (RAIN-LTA) extrapolated by MARS JRC (JRC/MARS-Meteorological Data Base–EC-JRC: http://mars.jrc.ec.europa.eu/) data set for the period 1981–2009 is 626 mm, with rainfall events mainly concentrated in fall and early spring.

The natural vegetation of the area is typical of the Mediterranean basin. In particular the most common herbaceous species are *Cynodon dactylon*, *Trifolium campestre*, *Medicago polimorfa*, *Picris hieracioides*, and *Bromus* sp., while the major tree species are sclerophyllus holm-oak (*Quercus ilex* L.), cork oak (*Quercus suber* L.) and olive trees (*Olea europaea* L.).

The study site is an adult olive orchard placed at 41 m a.s.l. The orchard covers about 6 ha and morphology is regular with slight slope from north to south, containing more than 1500 plants of 4–5 m in height, while canopy cover is about 25% (Maselli et al., 2012). Olive trees have all the same age (20) and plant density (7 × 5m). Soil chemical analysis showed that the orchard consists of clay-loam textural class (40% silt and 38% clay) with an average pH of 7 whilst, the available water capacity of the study area ranges from 60 to 90 mm/m (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009).

Agricultural practices consist of inter-row superficial tillage and fertilization applied once per year (usually in late winter or early spring) while irrigation is not applied. During the whole study period (i.e. 3 years from 2010 to 2012), the orchard was plowed three times at 10 centimeters deep using disk-harrowing: the first time in early May 2010, the second in February 2011 and the last in late May 2012. Fertilizer was applied once per year, at the end of February (2011) or in May (2010 and 2012). Mechanical harvesting was applied in 2010 and 2012 in November, while in 2011 fruits were left on the trees due to the extremely low production. Weeds beneath the trees, litter and residues due to mechanical harvesting (e.g. leaves, small branches, fruits) were incorporated into the soil during tillage.

2.2. Eddy covariance data and processing

The eddy covariance (EC) micrometeorological technique was used to measure fluxes of carbon dioxide (CO_2), water vapor (H_2O), sensible heat (H) and latent heat (LE) between the biosphere and the atmosphere (Baldocchi et al., 1996).

The EC tower was installed in March 2010 and placed in the central part of the olive orchard. The tower was composed of a mobile carriage equipped with a 7 m mast, hosting a Metek USA 1 triaxial sonic anemometer and a Licor 7500 open path infra-red CO_2-H_2O analyzer. Instruments were installed at 7 m above ground and 2 to 3 m above canopy top. A battery power supply was used, charged by 3 solar panels with 90 A/h capacity placed 30 m south from the tower to maximize solar radiation efficiency. This setup caused some power outages during wintertime.

Ancillary data, including soil temperature profiles from 5 to 20 cm (thermocouples J and T types), global and net radiation (CMP3 and NR LITE Kipp & Zonen), air temperature and humidity (HMP45 Vaisala), and rainfall (rain gauge Davis 7852), were stored on half-hourly basis on a data logger (Campbell CR10X). Fast eddy covariance sensors (i.e. sonic anemometer and CO_2/H_2O IRGA) were acquired at high frequency (20 Hz) and stored on a handheld low consumption computer (Matese et al., 2008).

The extension of the area surrounding the tower from where the observed fluxes originated, was assessed with footprint analysis made using an analytical model (Hsieh et al., 2000), that computed footprint distances as a function of wind speed and direction, atmospheric stability, measurement height and surface roughness. The area containing 90% of the observed flux, was computed at an average of 108 ± 16 m around the observation point, that is almost entirely contained within the olive orchard limits, extending 152 ± 26 m in the various directions.

The raw binary files and meteorological data collected by E.C. tower were processed using Eddy Pro® Software in Express Mode. Processing consisted of several steps such as spectral corrections for flux losses (Moncrieff et al., 1997), despiking procedure for detecting and eliminating short-term outranged values in the time series and control tests according to Foken et al. (2004). Gap-filling and flux partitioning procedures were applied following Reichstein et al. (2005), providing continuous record of NEE, GPP and Reco. During the 3 years of experiment some technical issues (i.e. power supply) did not allow a complete data acquisition. The higher loss of data were concentrated during periods of low vegetation activity (i.e. January and February of 2010, January 2011 and 2012, and at the end of 2012). Such losses did not allow a reliable assessment and gap filling of fluxes during these periods which, therefore, were not considered for the analysis (Table 1).

2.3. Statistical analysis

Half-hourly carbon and energy fluxes were averaged in daily, monthly and annual totals as basis for statistical inference. Uncertainties associated to each average value were computed as 95% confidence intervals assuming Gaussian distribution. The

Table 1
Number of half-hourly data measured by eddy covariance during the period 2010 – 2012. Legend: Num. tot. val. coll. indicates all the collected data; Num. gaps indicates the data re-built by gap-filling process. For these half-hourly data the quality classification scheme is: A: best; B: acceptable; C: dubious.

	2010	2011	2012	2010–2012
	(%)	(%)	(%)	(%)
Num tot. val. coll.	79.54	83.83	60.82	74.73
Num. gaps	20.46	16.17	39.18	25.27
~Category: A	18.87	7.71	18.25	14.94
~Category: B	1.50	3.23	20.62	8.45
~Category: C	0.09	5.23	0.31	1.88

relation between NEE and weather variables (air temperature, rainfall and solar radiation) was examined at monthly scale by computing correlation coefficient (r), coefficient of determination (r^2) and the *p*-value of Student-t test of equal means. Finally, to quantify temporal variation in the patterns of relative dynamics a time lag analysis (TLA) was applied. TLA uses a distance-based approach to study temporal dynamics by regressors over increasing time lags (i.e. one-unit lags, two-unit lags, three-unit lags) (Kampichler et al., 2012). Accordingly, we performed a time lag analysis to examine the relation between NEE and rainfall (Eq. (1)).

$$NEE_{(t)} \sim Rainfall_{(t-i)} \quad t = defined\ intervals \quad i = unit\ lags \tag{1}$$

Eq. (1). *Relation between NEE and rainfall*

On these basis, two TLA (i.e. TLA_1 and TLA_2) were performed to analyse the relationship between rainfall cumulated at various time intervals and NEE. To perform the analysis, we followed 5 steps:

- The whole daily NEE dataset (i.e. 2010, 2011 and 2012) was first smoothed by a 10-day mobile average in order to reduce short term variability;
- NEE was cumulated at different intervals (i.e. daily, weekly, 10-days, monthly, two-months, four-months) and then compared with rainfall aggregated at the same time interval;
- TLA_1: the correlation between NEE and lagged rainfall for the intervals was assessed using the correlation coefficients (r) calculated at each lag;
- The highest value of correlation coefficients was found using the four-months window. Thus, the whole NEE dataset was divided into three intervals highly consistent with the seasonal cycle of olive tree (Gucci, 2012; http://www.stuard.it/allegato.asp?ID=235733): WIN (winter period with low physiological activity, from November to February); SPR (spring period with high physiological activity, from March, to June) and SUF (summer-fall period with high physiological stress and subsequent vegetation recovery from July to October);
- TLA_2: using the four-months interval, the NEE was correlated with synchronous (lag = 0) and anterior rainfall data using the determination coefficients (r^2) by moving back rainfall by 1 day at each step (up to lag = −180).

3. Results

3.1. Climate trend

Annual rainfall over the 1981–2012 period the study area showed a wide inter-annual variability (mean = 626 mm; standard deviation (δ) = 128.4). In particular, the 3 study years can be considered as highly representative of average and extreme rainfall annual pattern. While 2012 is perfectly consistent with

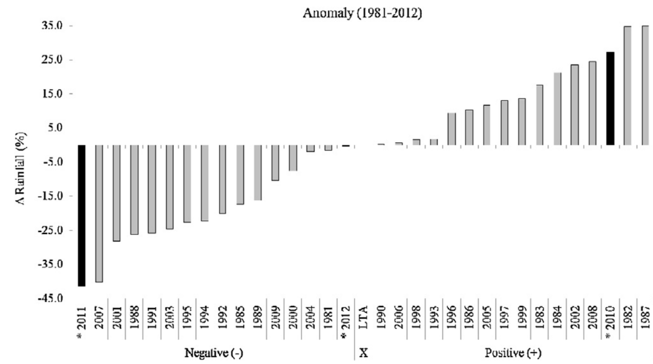

Fig. 1. Rainfall variability range for the period 1981–2012.

the RAIN-LTA (anomaly = −0.3%), 2010 and 2011 well represent both the extremes, with a positive anomaly of −+27.4% and a negative one of −41.3%, respectively (Fig. 1).

The first year (2010) was markedly wetter than the others with a total annual rainfall of 797.2 mm. However, the growing season rainfall was almost consistent with the growing season RAIN-LTA. The annual mean air temperature was only 0.3 °C higher than the 30 years average (14.8 °C) (Table 2). The seasonal rainfall distribution reflected the typical Mediterranean climate, with maximum monthly peaks in springtime (May, 96.4 mm) and autumn (November, 189.4 mm). Maximum monthly mean air temperature occurred in July, associated with maximum VPD (Fig. 2).

Based on the four-months window, the first year (2010) was the wetter during WIN and SPR both compared to 2011 (+176% and +132%) and 2012 (+42% and +63%), than to RAIN-LTA (+74.9% and +45.2%). However, the 2010 experienced dry conditions during SUF with precipitation close to those of 2011 (+10%) but lower than 2012 (+29.5%) and RAIN LTA (-44.4%) (Table 3).

The second year (2011) was the driest of the past 30 years record, both during the growing season (i.e. 205 mm) and along the whole year (i.e. 367.2 mm). Annual mean temperature was consistent with 2010 and 0.4 °C higher than the long-term average (Table 2). The seasonal rainfall distribution indicated a dry springtime (95.4 mm during March, April and May), with low

Table 2
Growing season (March-October) and annual meteorological data (i.e. cumulated rainfall, air mean temperature and mean global radiation) of the study area. Data were reported both as long-term average (LTA, 1981–2010) that specifically for the three years of measurements (2010, 2011 and 2012).

		LTA	2010	2011	2012
Air Temp (°C)	Mar-Oct	17.8	18.1	18	19.1
	Year	14.8	15.1	15.2	15.5
Solar Rad. (Wm^{-2})	Mar-Oct	225.2	210	231.7	224.1
	Year	178.1	162.1	182.8	178.1
Rainfall (mm)	Mar-Oct	371	351.2	205.6	309
	Year	626	797.2	367.2	624

Table 3
Rainfall amount and Δ rainfall aggregated over four-months for the 3 years of study (i.e. 2010, 2011 and 2012) and for LTA. WIN = November, December, January, February; SPR = March, April, May, June; SUF = July, August, September, October.

	Rainfall (mm)			Diff. (%)			
	WIN	SPR	SUF	WIN	SPR	SUF	TOTAL
LTA	255	161.9	209.1	0	0	0	0
2010	446	235	116.2	74.9	45.2	−44.4	25.2
2011	161.6	101.4	104.2	−36.6	−37.4	−50.2	−41.4
2012	315	144	165	23.5	−11.1	−21.1	−2.9

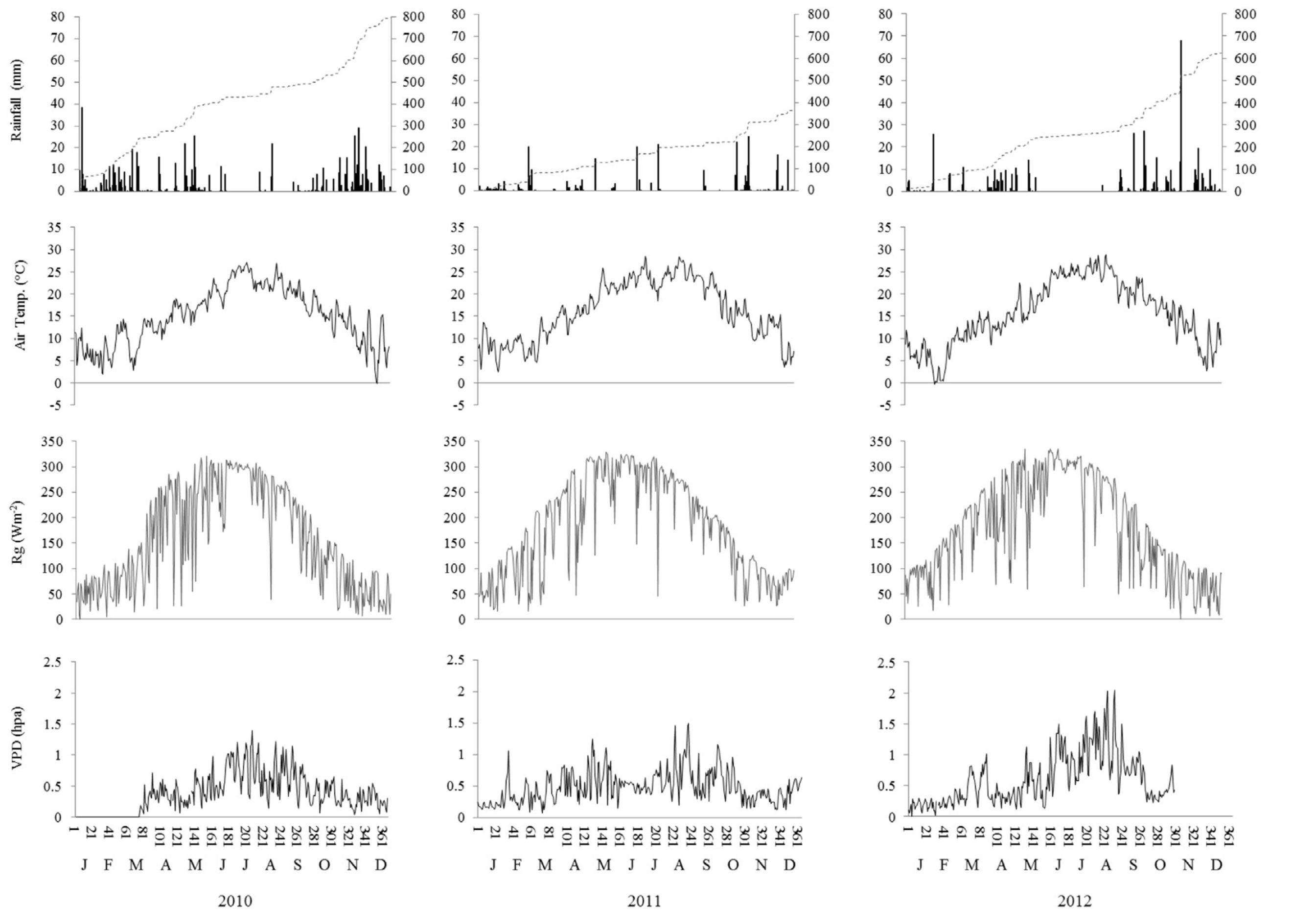

Fig. 2. Daily pattern of meteorological variables (rainfall, cumulated rainfall, mean air temperature, solar radiation and vapor pressure deficit) collected in the study area during 2010, 2011 and 2012.

rainfall both compared to the 30 years average (133.6 mm) and to the previous year (207.2 mm). Despite a general scarcity of rainfall over the year, July was characterized by a high and unusual amount (51 mm). Maximum monthly mean air temperature occurred in August, associated with maximum VPD (Fig. 2). Based on the four-months window, all seasons precipitation in 2011 were lower than 2010 (-64%, −57% and −10%), 2012 (−49%, −29.5% and −26.8%), and RAIN-LTA (−36.6%, −37.4% and −50.2%) (Table 3).

The third year (2012) was perfectly consistent with the RAIN-LTA (624 mm). The annual mean temperature was about 0.7 °C higher than long-term average (Table 2). The seasonal distribution showed highest rainfall in spring (April, 65.8 mm) and autumn (November, 174.2 mm), and a very dry summer: June and July were characterized by total absence of rainfalls, while in August a very low amount was observed (3.2 mm). Based on the four-months window, the 2012 showed the seasonal precipitation closer to RAIN-LTA than 2010 and 2011 (Table 3).

3.2. C-fluxes and energy exchange dynamics

During the first year of study the olive orchard recorded a continuous and robust carbon uptake (Fig. 3). At daily time-scale, NEE was on average $-2.3 \pm 2\,\text{gC}\,\text{m}^{-2}\,\text{d}^{-1}$, with the maximum uptake recorded in early May ($-6.6 \pm 1.1\,\text{gC}\,\text{m}^{-2}\,\text{d}^{-1}$). In 2011 the carbon balance was close to neutral: the average uptake was $-0.4 \pm 1\,\text{gC}\,\text{m}^{-2}\,\text{d}^{-1}$, with the maximum recorded in March ($-4.5 \pm 3\,\text{gC}\,\text{m}^{-2}\,\text{d}^{-1}$). By contrast, the higher C-emissions were observed in July ($2.3 \pm 0.6\,\text{gC}\,\text{m}^{-2}\,\text{d}^{-1}$) and in December ($2.3 \pm 1.1\,\text{gC}\,\text{m}^{-2}\,\text{d}^{-1}$). In 2012 NEE was on average $-1.1 \pm 1\,\text{gC}\,\text{m}^{-2}\,\text{d}^{-1}$.

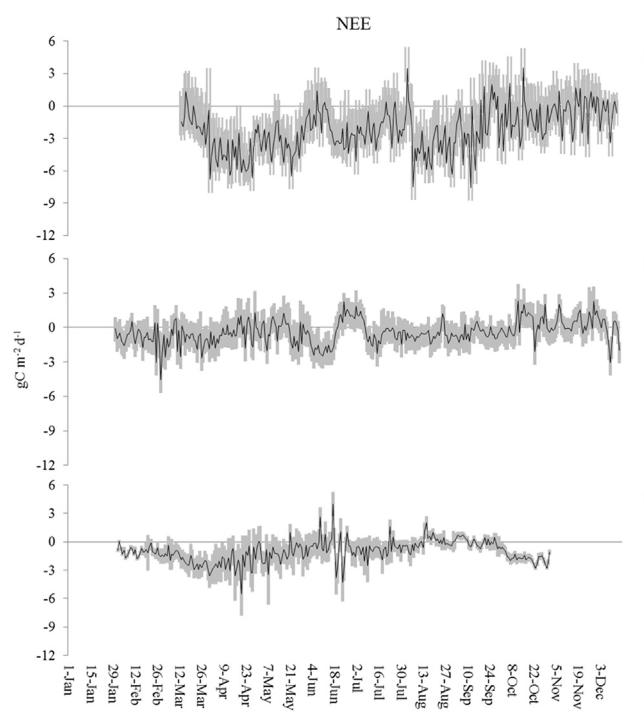

Fig. 3. Daily pattern of NEE for 2010 (a), 2011 (b) and 2012 (c). Grey vertical bars represent 95% confidence interval of the mean.

The maximum uptake was recorded in April (-5.5 ± 2.3 gC m^{-2} d^{-1}) while the highest emission was observed in June (3.9 ± 1.3 gC m^{-2} d^{-1}).

NEE and the other major ecosystem C-flux components partitioned into assimilatory and respiratory processes (i.e. GPP and Reco), and energy fluxes were also cumulated at monthly scale, seasonal and annual scale (Table 4 and Fig. 4).

Monthly NEE showed the typical trend of the Mediterranean woody vegetation, with the maximum physiological activity mainly concentrated in spring and a partial autumnal recovery

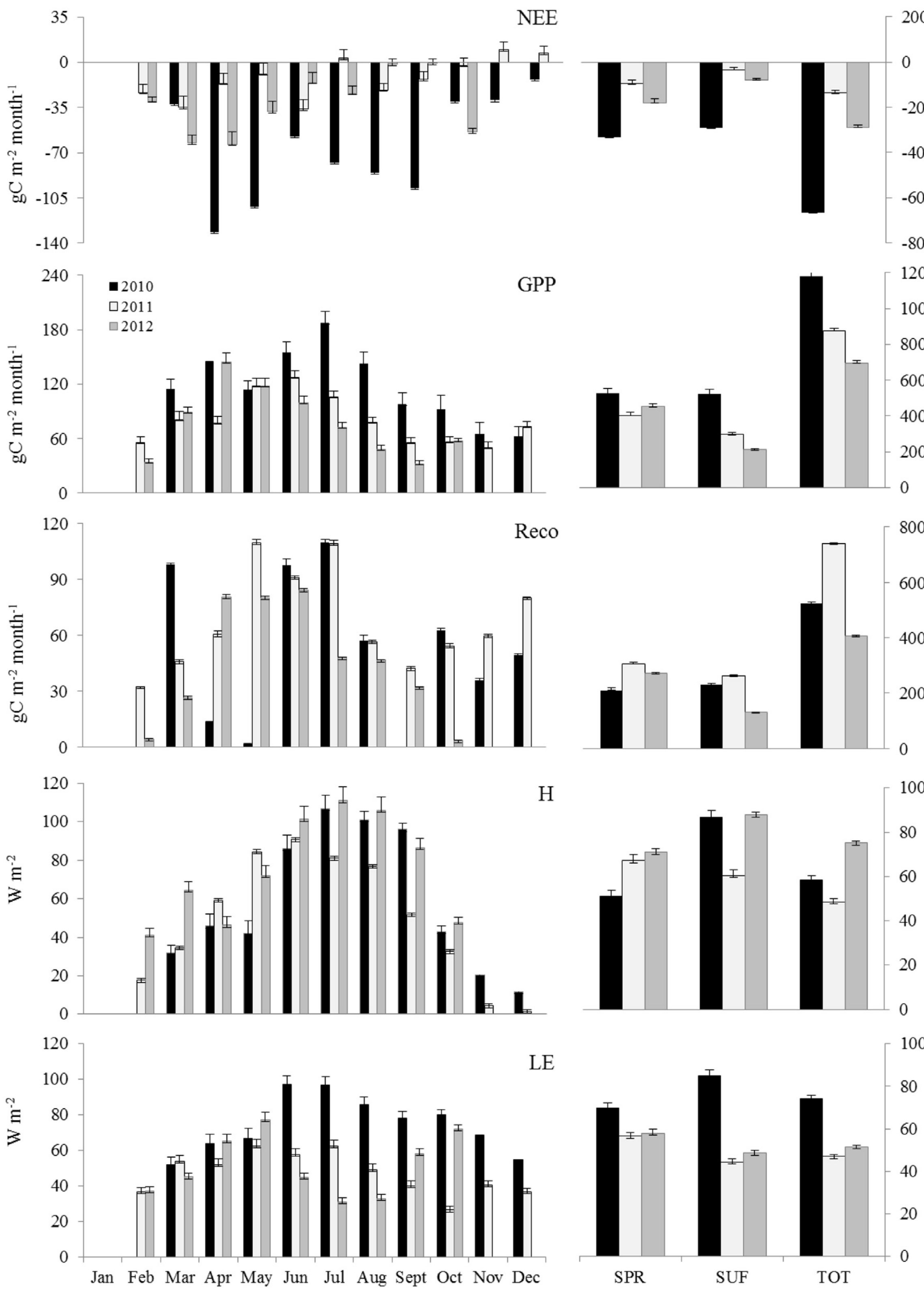

Fig. 4. Monthly, seasonal and annual cumulated NEE, GPP and Reco and LE of the study area for the three years of measurements (2010, 2011 and 2012). Vertical bars represent 95% confidence interval of the mean.

Table 4
Cumulated NEE, GPP, Reco and energy fluxes (LE and H) at seasonal (SPR + SUF) and annual scale for the three years of measurements.

			2010	2011	2012	3yr_av
$gC\ m^{-2}$	NEE	SPR	−333.1 ± 26.9	−96.2 ± 16	−179.6 ± 16.3	−203.0 ± 19.7
		SUF	−290.8 ± 26.8	−33.7 ± 11.6	−79.6 ± 8.3	−134.7 ± 15.5
		Year	−666.8 ± 25.5	−136.7 ± 13.2	−289.1 ± 11.8	−364.2 ± 19.1
	GPP	SPR	527.5 ± 26.9	402.1 ± 16.2	452.0 ± 16.3	460.5 ± 19.8
		SUF	522.9 ± 26.9	295.2 ± 11.6	209.8 ± 8.1	342.6 ± 15.6
		Year	1179 ± 25.7	875.8 ± 12.4	695.7 ± 13.2	916.8 ± 17.1
	Reco	SPR	210.3 ± 8.7	306.0 ± 3.9	270.8 ± 3.2	262.4 ± 5.3
		SUF	228.8 ± 5.5	261.5 ± 3.6	130.1 ± 2.1	206.8 ± 3.7
		Year	523.9 ± 6.1	739.1 ± 3.5	405 ± 3.6	556 ± 4.4
Wm^{-2}	H	SPR	51.3 ± 2.6	86.7 ± 2.7	58.4 ± 2.7	65.5 ± 2.7
		SUF	67.1 ± 3.3	60.5 ± 2.4	48.5 ± 2.9	58.7 ± 2.9
		Total	71 ± 1.8	87.8 ± 1.3	75.1 ± 1.4	78 ± 1.4
	LE	SPR	69.8 ± 2.4	85.1 ± 1.7	74.3 ± 1.7	76.4 ± 1.9
		SUF	56.51 ± 2.5	44.4 ± 1.5	47 ± 1.3	49.3 ± 1.8
		Total	58 ± 1.5	48.5 ± 0.8	51.5 ± 0.8	52.7 ± 1.2

(Fig. 4). April was characterized by the highest NEE in 2010 (−131.5 ± 13.1 $gC\,m^{-2}$) and 2012 (−63.5 ± 9.9 $gC\,m^{-2}$), while in 2011 it was recorded in March (−34.9 ± 8.8 $gC\,m^{-2}$). Summer months were characterized by high uptake in 2010 (−73.4 ± 12.6 $gC\,m^{-2}$ on average), while lower values were recorded in the following years (−18.1 ± 6.5 $gC\,m^{-2}$ and −13.8 ± 5.8 $gC\,m^{-2}$ for 2011 and 2012, respectively). Among the three vegetative seasons (March-September) of this study, only in July 2011 there was a positive NEE (3.2 ± 6.6 $gC\,m^{-2}$). The autumnal physiological recovery was clear in September 2010 (−97.5 ± 13.1 $gC\,m^{-2}$), while it was less evident in 2011 (−13.1 ± 5.7 $gC\,m^{-2}$) and almost absent in 2012 (−0.6 ± 3 $gC\,m^{-2}$).

During the three study years the maximum GPP was observed at different times (Fig. 4). In 2010 the high GPP was observed in spring (124.3 ± 6.9 $gC\ m^{-2}$ on average), with the highest value in April (144.9 ± 2 $gC\,m^{-2}$). Summer months, however, contributed for a total of 484.3 ± 37.9 gC m-2 (161.3 ± 12.6 $gC\,m^{-2}$ on average) whilst July showed the highest GPP (187.2 ± 12.5 $gC\,m^{-2}$). In 2011 the highest GPP was found in June (126. 9 ± 7.4 $gC\,m^{-2}$) and the period between late spring and early summer (i.e. May, June and July) contributed for 351.1 ± 22 $gC\,m^{-2}$ which was about 40% of the yearly total (875.8 ± 13.4 $gC\,m^{-2}$). On the contrary, in 2012 the monthly maximum growth was observed in advance compared to the previous years, with an April GPP of (144.1 ± 10 $gC\,m^{-2}$). April, May and June contributed for 363.2 ± 21.8 $gC\,m^{-2}$, more than 50% of the annual GPP (694.1 ± 12.2 $gC\,m^{-2}$).

Reco showed also the maximum monthly values at different times during the three study years. In 2010, summer was characterized by the highest respiration (88 ± 6.1 $gC\,m^{-2}$ on average), with a peak in July (109.5 ± 1.7 $gC\,m^{-2}$), while spring respiration was about half (37.7 ± 0.2 $gC\,m^{-2}$ on average). In 2011, summer months were similarly characterized by high respiration (85 ± 1.1 $gC\,m^{-2}$ on average) while spring respiration was also sustained and twice larger than the previous year (71.7 ± 1.6 $gC\,m^{-2}$ on average). The highest Reco was recorded in May (109.3 ± 1.7 $gC\,m^{-2}$) and July (109.1 ± 1.5 $gC\,m^{-2}$). By contrast, in 2012 spring was characterized by low respiration (62.3 ± 0.9 $gC\,m^{-2}$ on average), while summer months showed a considerable decrease (59.5 ± 0.6 $gC\,m^{-2}$) compared to the same months of 2010 and 2011 (-32.4% and −30.3%, respectively). The highest Reco was recorded in June (84 ± 1 $gC\,m^{-2}$).

Monthly energy fluxes (i.e. LE and H) showed different patterns. During the three years of study, the latent heat (LE) showed highest values in spring (69.8 ± 2.4 $W\,m^{-2}$, 85.1 ± 1.7 $W\,m^{-2}$ and 74.3 ± 1.7 $W\,m^{-2}$, on average). Maximum peaks were observed in July in 2010 (96.8 ± 5.5 $W\,m^{-2}$) and May 2011 (62.4 ± 3.6 $W\,m^{-2}$) and 2012 (77.2 ± 4 $W\,m^{-2}$). Sensible heat (H) showed the highest value in summer only during 2010 (67.1 ± 3.3 $W\,m^{-2}$, on average), with the maximum peak observed in July (106.8 ± 6.9 $W\,m^{-2}$). On yearly basis, the highest LE was observed in 2010 (58 ± 1.5, $W\,m^{-2}$, on average), whilst the highest H was observed in 2011 (87.8 ± 1.3 $W\,m^{-2}$, on average)

3.3. Relations between NEE and climate conditions

In 2010 and 2011 the correlations between monthly NEE and both air temperature and solar radiation were relatively low, while NEE and rainfall were almost uncorrelated (Table 5). In 2012 the correlations between NEE and air temperature (r = 0.551; p-value = 0.063) and between NEE and solar radiation (r = 0.751; p-value = 0.005) were higher and significant (Table 5), while even if the correlation with rainfall was also higher (r = −0.479) compared to that of two previous years, it did not provide any statistical significance (Table 5).

When based on the entire study period of 3 years, statistically significant correlations were observed between monthly NEE and air temperature (r = 0.473; p-value = 0.003) and NEE and solar radiation (r = 0.541; p-value = 0.001) whilst the correlation between NEE and rainfall was very low (r = −0.286, p-value = 0.091) (Table 5).

Finally, TLA were performed to analyse the relationship between rainfall cumulated at various time intervals and NEE. For each one of the six intervals adopted TLA_1 showed a peak of the correlation coefficient around 120 days before the actual NEE (Fig. 5). The highest value of correlation coefficients was found using the four-months window (r = 0.77). Then, using the four-months interval, the NEE was correlated with synchronous (lag = 0) and anterior rainfall data using the determination coefficients (r^2) by moving back rainfall by 1 day at each step (up to lag = −180) (TLA_2, Fig. 6). Results showed the highest correlation for SPR (R^2 = 0.68) and SUF (R^2 = 0.45) approximately 100 and 160/180 days before the actual NEE, respectively. By contrast, no significant

Table 5
Correlation between monthly NEE and meteorological variables (air temperature, rainfall and solar radiation) over the three years of study. Signif. codes: '***' < 0.001; '**' < 0.01 ' ' < 0.1.

		Year			
Stat.	Label	2010	2011	2012	2010-11-12
r	Air Temp.	0.483	0.383	0.551	0.473**
	Rainfall	−0.109	0.129	−0.479	−0.286
	Rad	0.443	0.404	0.751**	0.541***
p-value	Air Temp.	0.111	0.219	0.063	0.003
	Rainfall	0.735	0.689	0.115	0.091
	Rad	0.149	0.193	0.005	0.001

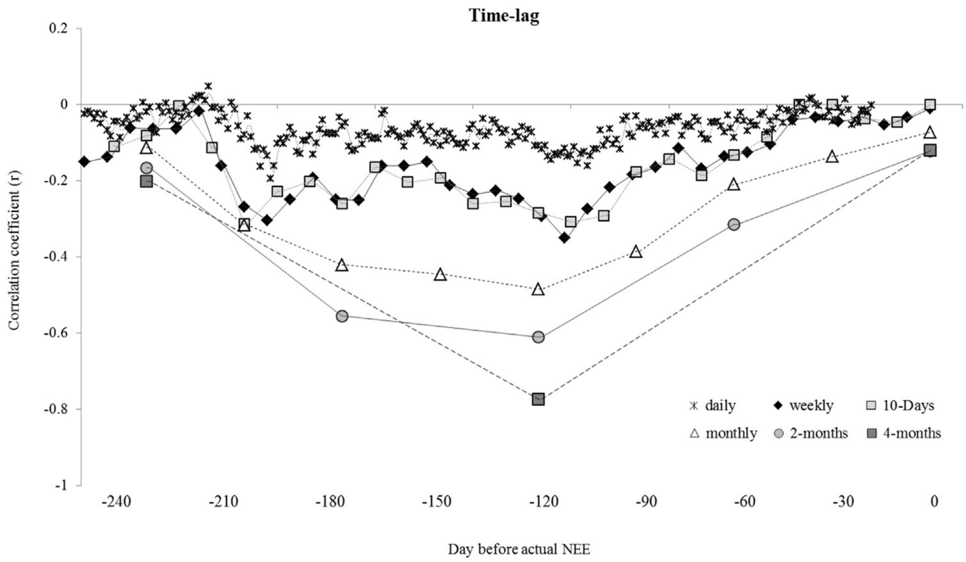

Fig. 5. Time lag analysis between rainfall and NEE at different time step: a) daily; b) weekly; c) 10-days; d) monthly; e) two-months; f) four-months. For each time step analyzed, time-lag analysis showed the higher correlation peaks around 120 days before the actual NEE.

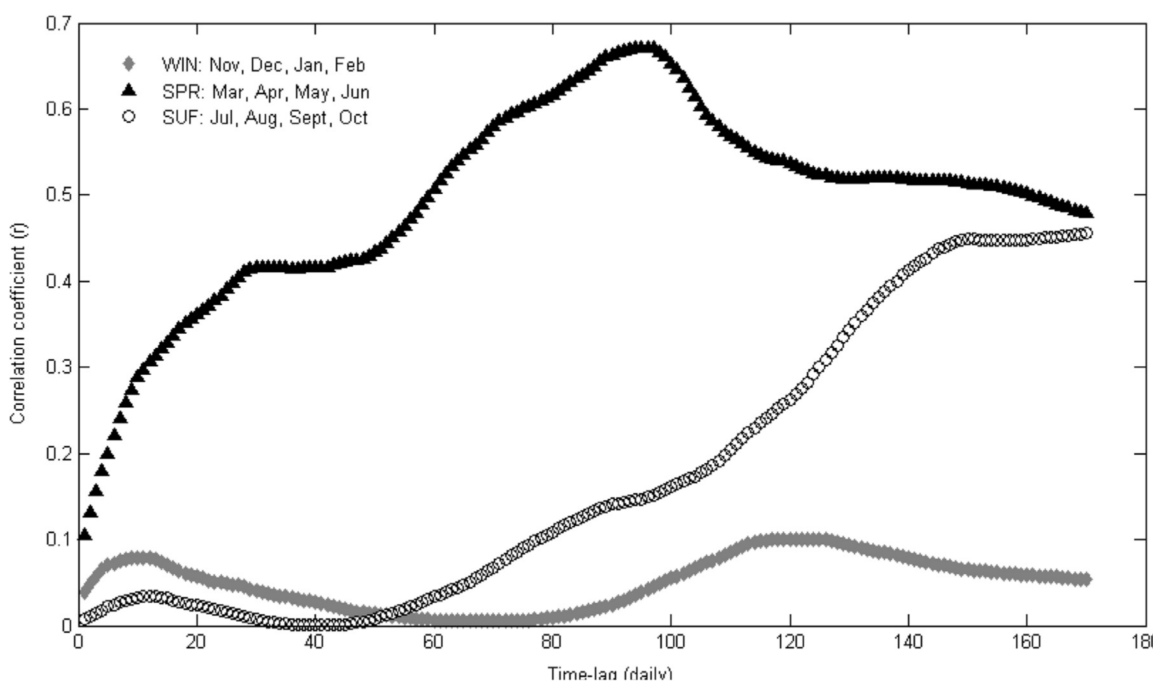

Fig. 6. Determination coefficient (r^2) between smoothed NEE and lagged rainfall calculated for each time-window (i.e. WIN, SPR and SUF) with synchronous (lag = 0) and anterior rainfall data by moving back rainfall daily records by 1 day at each step (up to lag = 170).

correlation was found between winter NEE and anterior cumulated rainfall (Fig. 6).

4. Discussion and conclusions

The experimental period can be considered highly representative of the rainfall variability of the study area (Fig. 1). This peculiar climatic pattern poses great value to the collected dataset, allowing to derive relations between NEE and rainfall that can likely well represent the long-term C dynamics in an adult Mediterranean olive orchard.

Across the whole study period the olive orchard resulted overall a net carbon sink. NEE was on average (i.e. 3.6 Mg ha^{-1} year^{-1}, see Table 4) comparable to several Italian forestry systems. Valentini et al. (2000) observed that at Mediterranean latitude the forest carbon accumulation is less than 6 Mg ha $^{-1}$ year $^{-1}$, whilst Matteucci and Scarascia Mugnozza (2007), reported that the Italian forestry capacity to sequester C is about 4 Mg ha $^{-1}$ year $^{-1}$. Maselli et al. (2008), reported that during the period 1997–2003 the mean annual NEE values from eight Italian forest sites belonging to the FLUXNET network ranged on average from 2 to 6.5 Mg ha $^{-1}$ year $^{-1}$. Similarly, Chiesi et al. (2011), showed that the annual NEE measured by eddy covariance in two Italian forest sites (i.e. a pine wood and an Holm oak forest) were 4.4 and 2.4 Mg ha $^{-1}$ year $^{-1}$, respectively. Our results confirm the findings by Zanotelli et al. (2013), suggesting that C-fluxes from long term agro-ecosystem can be compared to natural forest ecosystems growing in the same biome rank.

Considerable differences were found among the 3 study years (Tables 3 and 4). On yearly basis, NEE exhibited an extremely variability that can be related to the susceptibility of the ecosystem to climatic conditions and particularly to rainfall. Higher sink indeed, was found over years characterized by higher amount of rainfall, consistently with Luo et al. (2007) that found a relationship between yearly rainfall and NEE, and with Xu and Baldocchi (2004), which observed a correlation between total photosynthesis and total annual rainfall. This relation can be attributed to the effect of rainfall at recharging the soil water content. Whilst under non-limiting soil water conditions, the key controlling factors of C-fluxes are widely recognized to be light and air temperature (Hernandez-Ramirez et al., 2011), in dry environments water availability can be considered as the most important factor at driving the NEE-PAR response (Pingintha et al., 2010).

On daily basis, NEE semi-hourly variability (Fig. 3) was larger in the first year (2010, Fig. 3a) with respect 2011 (+49%, on average) and 2012 (+59%, on average), respectively (Fig. 3b and c). The larger variability observed in 2010 was primarily due to the contribution of summer months, in which the NEE semi-hourly values were more than two times greater compared to those of the other two years. The highest NEE semi-hourly values indicated an higher photosynthetic efficiency than the other two years. Since the maximum photosynthetic efficiency is usually reached in absence of limiting factors, the higher water availability during summer of 2010 may have allowed an uninterrupted photosynthetic activity also during the hottest hours of the day. Therefore, in a period (i.e. summer) where temperatures and radiation are not limiting, the availability of water may have allowed the orchard to approach the maximum photosynthetic efficiency and, as a consequence, to exhibit highest C-uptake than observed in 2011 and 2012. This condition was also suggested by the analysis of the mean monthly diurnal courses of GPP, NEE, LE and H of the olive orchard at June, July and August for the three years of measurements (Fig. 7). While in 2010 the daily pattern of NEE, GPP and LE is approximately symmetrical around solar noon, in 2011 and 2012 it showed an asymmetry with a depression in the middle of the day. As indicated by other studies (i.e. Jarosz et al., 2008; Damm et al., 2010), this

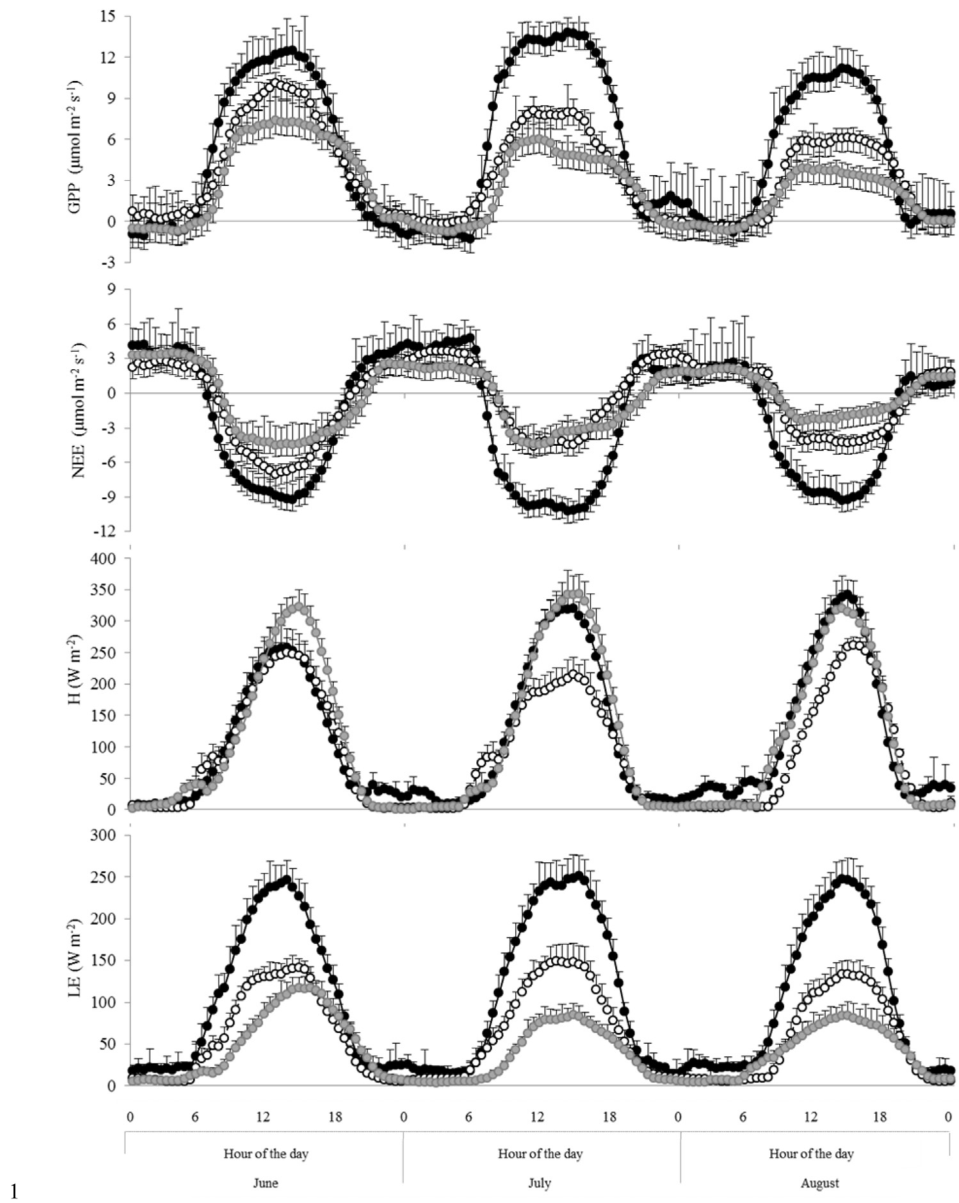

Fig. 7. Comparison of the mean monthly diurnal courses of GPP, NEE, H and LE of the olive orchard at June, July and August for the three years of measurements (2010, 2011 and 2012). Vertical bars represent 95% confidence interval of the mean.

pattern is consistent with water-stressed environments where high temperatures in conjunction with low water availability can cause stomata closure, thus resulting in reduced carbon uptake around the middle of the day.

Despite in Mediterranean rainfed environments precipitation should play a fundamental role in C-fluxes dynamics, no relations were detected using simple statistical correlations. In arid and semiarid regions, and in water-limited ecosystems, complex linkages exist between rainfall and vegetation behaviour, as rain is intermittent, unpredictable, and exhibits lag-effects (Ospina et al., 2012; Li et al., 2015). To quantify temporal variation in the patterns of relative dynamics a time lag analysis (TLA) is usually applied (Angeler et al., 2009). TLA offered a more complete assessment about the control of rainfall on NEE. Results showed that the relation found between rainfall and NEE well reflects the seasonal physiological activity of olive trees in Mediterranean area.

For spring time-window, TLA found the highest correlation between actual NEE and cumulated rainfall approximately 100 days before the end of the same time-window (Fig. 4). This result suggested that the C-uptake recorded during spring is mainly driven by the total amount of rainfall recorded over the same period. Such result is consistent with the photosynthetic process that is highly sensitive to temperature, light and water availability. Indeed, in Mediterranean environment, during spring temperature and light tend to increase while photosynthetic activity is mainly limited by water availability (Scott et al., 2012). Therefore, a decline in rainfall may actually behave as the most limiting condition for plants activity (Schroter et al., 2005; Resco et al., 2007). Our results were consistent with several studies. For instance, Oteros et al. (2013) observed that higher rainfall during spring period increases the rate of phenological development. Similarly, Rapoport et al. (2012) and Moorthy et al. (2011) indicated that limited water availability during the whole floral phenophase (i.e. spring) can affect the olive trees development and, in turn, its photosynthetic efficiency.

For summer-fall time-window, TLA indicated the highest correlation between actual NEE and cumulated rainfall approximately 150–180 days before the end of the same time-window (Fig. 4). This result suggested that also the C-uptake recorded during summer-fall is mainly driven by the spring rainfall and it may be explained by the combined effect of spring rainfall and olive tree physiology. The spring rainfall through the increase of soil water at the beginning of the growing season had a large impact on this rainfed agro-ecosystem in semi-arid region since it contributed to extend the soil water availability also over dry months. This is consistent with Scott et al. (2012), that indicated as in Mediterranean areas water tends to accumulate in soil until energy inputs (radiation and temperature) rise up. Then, the effect of spring rainfall on soil water content was reinforced by the particular physiology of olive tree that, as indicated by Connor (2005), relies on conservative water use in spring with the aim of reducing the extent and intensity of the summer drought. Our results were consistent with literature: in a study carried out in a Mediterranean climate (California), Ma et al. (2007) observed that spring-time rainfall was the predominant factor driving inter-annual differences in NEE over an oak/grass savanna site. Similarly, Kwon et al. (2008) by analyzing a semi-arid climate ecosystem observed different responses of NEE across two growing season characterized by dissimilar spring rainfall. Moreover, they also suggested that the inter-seasonal variability in rainfall can cause clear differences in the patterns and total amount of NEE at different time scale.

The absence of correlation with the rainfall of the same period, was likely related to the prolonged dry and hot periods and the type of precipitation (i.e. size and intensity) that characterize the Mediterranean summers. Olive tree can tolerate prolonged dry periods because of typical adjustments that allow higher resistance to gas diffusion in the leaf such as the reduction of intercellular volume spaces within tissues (Bongi and Long, 1987; Gucci, 1998). However, the combined impacts of high temperatures and lack of precipitation are expected to lead to water stress. When water stress is particularly severe, it leads to photosynthesis and metabolic activity reduction with possible prolonged and permanent damages that, in turn, can delay the photosynthetic activity recovery (Sorrentino, 2001). This condition was clearly observed in September 2012 (Table 4), where rainfall events after a very prolonged dry period did not positively contribute to the recovery of photosynthesis. This evidence is consistent with several studies. For instance, Sorrentino, (2001) indicated that the maximum photosynthetic capacity of olive tree can be completely re-instated only after the complete rebuilding of photosynthetic metabolism. Fereres et al. (1996) in a 22 years old olive orchard observed a stomatal conductance recovery after several weeks from the rehydration of the water potential. Moreover, the type of precipitation recorded during summer-fall may have played an important role in the soil water recharge. In this period rainfall was characterized by sporadic and high intensity episodes: in July 2011 almost all the precipitation was concentrated in two events with more than 20 mm. Similarly, in September 2012 two events characterized by rainfall higher than 25 mm were recorded. They represented about 40% and 65% of the total summer-fall rainfall for 2011 and 2012, respectively. The contribution of these extreme episodes at recharging the soil water capacity cannot be compared to regular rainfall events. Soil infiltration capacity is usually limited, therefore large rainfall events can more easily lead to an increase in surface run-off and evaporation from soil, rather than contributing to recharge the water table (Nitsch et al., 2008). Accordingly, soil water availability for plants may have not increased, thus leading further reduction of photosynthesis and, in turn, C-uptake during summer-fall.

Finally, the effect of moisture storage and carry over between the years (i.e. from a wet to dry year (from 2010 to 2011) or the reverse (from 2011 to 2012)) was not clearly observed. A possible explanation of that is the dry periods are especially concentrated in the spring and summer seasons, therefore autumn and winter rainfall is likely capable of restoring adequate water levels for the following year. Also, since the available soil water capacity at this site is relatively low (i.e. 60–90 mm) it is likely that orchards respond more at relatively short term time scales. This was confirmed by the time lag analysis in which we found that C-flux responds mostly at a 4-months' time scale.

In conclusion, our study provided these evidences: i) a typical managed olive orchards was on average a carbon sink almost comparable with other Italian forestry ecosystems along the three years of study; ii) the magnitude of yearly NEE was found highly correlated with annual rainfall regimes; iii) variability in precipitation may strongly affect inter-seasonal C-fluxes whilst the spring rainfall resulted to be the main driver for spring and summer NEE.

Results from this study also suggest to adopt agronomic practices aimed at increasing soil water content in rainfed orchards. Grass cutting and mulching may reduce the competition for water and nutrients between trees and ground vegetation, also reducing water loss as evapotranspiration (Andersen et al., 2013). When mechanical control of grass cannot be applied, sheep grazing can be a suitable alternative. Inter cropping could improve water-use-efficiency via intensifying vegetation (i.e. full use of cropland water by plant roots, increase the water storage in root zone) (Zhang et al., 2012) and via reducing evapotranspiration (i.e. less inter-row evaporation and control excessive transpiration). The adoption of these agronomic practice may be useful for limiting the impacts of future climate conditions on olive orchard C-sequestration capacity.

Acknowledgements

The authors acknowledge Gianni Bellocchi (French National Institute of Agricultural Research, France) and Luisa Leolini and Gloria Padovan (Department of Agri-Food Production and Environmental Sciences, Italy) for several stimulating discussions on the subject of this paper.

References

Ahlström, A., Raupach, M.R., Schurgers, G., Smith, B., Arneth, A., Jung, M., Reichstein, M., Canadell, J.G., Friedlingstein, P., Jain, A.K., Kato, E., Poulter, B., Sitch, S., Stocker, B.D., Viovy, N., Wang, Y.P., Wiltshire, A., Zaehle, S., Zeng, N., 2015. The dominant role of semi-arid ecosystems in the trend and variability of the land CO2 sink. Science 348 (6237), 895–899.

Andersen, L., Kühn, B.F., Bertelsen, M., Bruus, M., Larsen, S.E., Strandberg, M., 2013. Alternatives to herbicides in an apple orchard, effects on yield, earthworms and plant diversity Agriculture. Ecosyst. Environ. 172, 1–5. doi:http://dx.doi.org/10.1016/j.agee.2013.04.004.

Angeler, D.G., Viedma, O., Moreno, J.M., 2009. Statistical performance and information content of time lag analysis and redundancy analysis in time series modeling. Ecology 90 (11), 3245–3257. doi:http://dx.doi.org/10.1890/07-0391.1.

Baldocchi, D., Valentini, R., Running, S., 1996. Strategies for measuring and modeling carbon dioxide and water vapour fluxes over terrestrial ecosystem. Glob. Change Biol. 2, 159–168. doi:http://dx.doi.org/10.1111/j.1365-2486.1996.tb00069.x.

Bongi, G., Long, S.P., 1987. Light dependent damage to photosynthesis in olive trees during chilling and high temperatures stress. Plant Cell Environ. 14, 127–132. doi:http://dx.doi.org/10.1111/1365-3040.ep11602267.

Brilli, L., Chiesi, M., Maselli, F., Moriondo, M., Gioli, B., Toscano, P., Zaldei, A., Bindi, M., 2013. Simulation of olive grove gross primary production by the combination of ground and multi-sensor satellite data. Int. J. Appl. Earth Obs. Geoinf. 23, 29–36. doi:http://dx.doi.org/10.1016/j.jag.2012.11.006.

Chang, C.T., Wang, H.C., Huang, C., 2013. Impacts of vegetation onset time on the net primary productivity in a mountainous island in Pacific Asia. Environ. Res. Lett. 8 (4) doi:http://dx.doi.org/10.1088/1748-9326/8/4/045030 (article id045030).

Chaves, M.M., Pereira, J.S., Maroco, J., Rodrigues, M.L., Ricardo, C.P.P., Osorio, M.L., Carvalho, I., Faria, T., Pinheiro, C., 2002. How plants cope with water stress in the field. Photosyntesis and growth. Ann. Bot. 89, 907–916. doi:http://dx.doi.org/10.1093/aob/mcf105.

Chiesi, M., Fibbi, L., Genesio, L., Gioli, B., Magno, R., Maselli, F., Moriondo, M., Vaccari, F.P., 2011. Integration of ground and satellite data to model Mediterranean forest processes. Int. J. Appl. Earth Obs. Geoinf. 13 (3), 504–515 (j.jag.2010.10.006).

Connor, J.D., 2005. Adaptation of olive (Olea europaea L:) to water-limited environments. Aust. J. Agric. Res. 56, 1181–1189.

Damm, A., Elbers, J., Erler, A., Gioli, B., Hamdi, K., Hutjes, R., Kosvancova, M., Meroni, M., Miglietta, F., Moersch, A., Moreno, J., Schickling, A., Sonnenschein, R., Udelhoven, T., van der Linden, S., Hostert, P., Rascher, U., 2010. Remote sensing of sun induced fluorescence to improve modelling of diurnal courses of Gross Primary Production (GPP). Global Change Biol. 16, 171–186. doi:http://dx.doi.org/10.1111/j.1365-2486.2009.01908.x.

Del Río, S., Herrero, L., Pinto-Gomes, C., Penas, A., 2011. Spatial analysis of mean temperature trends in Spain over the period 1961–2006. Global Planet. Change 79, 65–75. doi:http://dx.doi.org/10.1016/j.gloplacha.2011.05.012.

Dichio, B., Xiloyannis, C., Sofo, A., Montanaro, G., 2005. Osmotic regulation in leaves and roots of olive trees during a water deficit and rewatering. Tree Physiol. 26, 179–185. doi:http://dx.doi.org/10.1093/treephys/26.2.179.

Durao, R.M., Pereira, M.J., Costa, A., Delgado, J., Del Barrio, G., Soares, A., 2010. Spatial-temporal dynamics of rainfall extremes in southern Portugal: a geostatistical assessment study. Int. J. Climatol. 30, 1526–1537. doi:http://dx.doi.org/10.1002/joc.1999.

FAO/IIASA/ISRIC/ISS-CAS/JRC,, 2009. Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

Fereres, E., Ruz, C., Castro, J., Gómez, J.A., Pastor, M., 1996. Recuperación del olivo después de una sequía extrema. Proceedings of the XIV. Congreso Nacional De Riegos, Aguadulce (Almería), 11–13 June, 1996, pp. 89–93.

Foken, T., Gockede, M., Mauder, M., Mahrt, L., Amiro, B.D., Munger, J.W., 2004. Post-field data quality control. In: Lee, X. (Ed.), Handbook of Micrometeorology: A Guide for Surface Flux Measurements. Kluwer Academic Publishers, Dordrecht, pp. 81–108.

Gucci, R., 1998. Assimilazione e ripartizione del carbonio in foglie di olivo. Fruttico 7-8, 77–82.

Gucci, R., 2012. Morfologyia Fisiologia Del Olivo Master En Olivicoltura. Universidad Politecnica de Madrid, Madrid, 4 Mayo, pp. 2012.

Haylock, M.R., Hofstra, N., Klein Tank, A.M.G., Klok, E.J., Jones, P.D., New, M., 2008. A European daily high-resolution gridded data set of surface temperature and rainfall for 1950–2006. J. Geophys. Res. 113, D20119. doi:http://dx.doi.org/10.1029/2008JD010201.

Heisler-White, J.L., Knapp, A.K., Kelly, E.F., 2008. Increasing precipitation event size increases above-ground net primary productivity in a semi-arid grassland. Oecologia 158, 129–140.

Heisler-White, J.L., Blair, J.M., Kelly, E.F., Harmoney, K., Knapp, A.K., 2009. Contingent productivity responses to more extreme rainfall regimes across a grassland biome. Glob. Change Biol. 15, 2894–2904.

Hernandez-Ramirez, G., Hatfield, J.L., Parkin, T.B., Sauer, T.J., Prueger, J.H., 2011. Carbon dioxide fluxes in corn-soybean rotation in the midwestern U.S.: Inter- and intra-annual variations, and biophysical controls. Agric. For. Meteorol. 151, 1831–1842. doi:http://dx.doi.org/10.1016/j.agrformet.2011.07.017.

Hsieh, C.I., Katul, G.G., Chi, T.W., 2000. An approximate analytical model for footprint estimation of scalar fluxes in thermally stratified atmospheric flows. Adv. Water Resour. 23, 765–772. doi:http://dx.doi.org/10.1016/S0309-1708(99)00042-1.

IPCC,, 2013. Climate Change 2013. Phys. Sci. Basis 2013.

ISTAT, 2010. (Italian National Institute of Statistics) (2010) 6th National Agricultural Census. . http://www.istat.it/en/agricultural-census.

Jacob, D., Podzun, R., 2010. Global Warming Below 2 (C Relative to Pre-industrial Level: How Might Climate Look like in Europe. Nova Acta Leopoldina, NF, pp. 71–76.

Jarosz, N., Brunet, Y., Lamaud, E., Irvine, M., Bonnefond, J.M., Loustau, D., 2008. Carbon dioxide and energy flux partitioning between the understorey and the overstorey of a maritime pine forest during a year with reduced soil water availability. Agric. For. Meteorol. 148 (10), 1508–1523 (j.agrformet.2008.05.001).

Jia, X., Zha, T.S., Wu, B., Zhang, Y.Q., Gong, J.N., Qin, S.G., Chen, G.P., Kellomäki, S., Peltola, H., 2014. Biophysical controls on net ecosystem CO2 exchange over a semiarid shrubland in northwest China. Biogeosci. Discuss. 11, 5089–5122. doi:http://dx.doi.org/10.5194/bgd-11-5089-2014.

Jones, G.A., Sculliona, J., Ostle, N., Levy, P.E., Gwynn-Jones, D., 2014. Completing the FACE of elevated CO2 research. Environ. Int. 73, 252–258. doi:http://dx.doi.org/10.1016/j.envint.2014.07.02.

Kampichler, C., van Turnhout, C.A.M., Devictor, V., van der Jeugd, H.P., 2012. Large-Scale changes in community composition: determining land use and climate change signals. PLoS One 7 (4), e35272. doi:http://dx.doi.org/10.1371/journal.pone.0035272.

Kane, D., 2015. Carbon sequestration potential on agricultural lands: a review of currentscience and available practices. Natl. Sustain. Agric. Coalition (NSAC) . http://sustainableagriculture.net/publications.

Kjellström, E., Nikulin, G., Hansson, U., Strandberg, G., Ullerstig, A., 2011. 21 st century changes in the European climate: uncertainties derived from an ensemble of regional climate model simulations. Special Issue On Regional Climate Studies Using The Smhi-Rossby Centre Models 63, 24–40, 10.1111/j.1600-0870.2010.00475.x.

Kwon, H., Pendall, E., Ewers, B.E., Cleary, M., Naithani, K., 2008. Spring drought regulates summer net ecosystem CO_2 exchange in a sagebrush-steppe ecosystem. Agric. For. Meterol. 148, 381–391. doi:http://dx.doi.org/10.1016/j.agrformet.2007.09.010.

Lal, R., 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123, 1–2. doi:http://dx.doi.org/10.1016/j.geoderma.2004.01.032 1–22.

Lenderink, G., Van Meijgaard, E., 2008. Increase in hourly rainfall extremes beyond expectations from temperature changes. Nat. Geosci. 1, 511–514. doi:http://dx.doi.org/10.1038/ngeo262.

Li, F., Zhao, W., Liu, H., 2015. Productivity responses of desert vegetation to precipitation patterns across a rainfall gradient. J. Plant Res. 128, 283–294.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolstrom, M., Lexer, M.J., Marchetti, M., 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For. Ecol. Manag. 259, 698–709.

Luo, H., Oechel, W.C., Hastings, S.J., Zulueta, R., Qian, Y., Kwon, H., 2007. Mature semiarid chaparral ecosystems can be a significant sink for atmospheric carbon dioxide. Glob. Change Biol. 13, 386–396. doi:http://dx.doi.org/10.1111/j.1365-2486.2006.01299.x.

Ma, S., Baldocchi, D.D., Xu, L., Hehn, T., 2007. Inter-annual variability in carbon dioxide exchange of an oak/grass savanna and open grassland in California. Agric. For. Meterol. 147, 157–171. doi:http://dx.doi.org/10.1016/j.agrformet.2007.07.008.

Maselli, F., Chiesi, M., Fibbi, L., Moriondo, M., 2008. Integration of remote sensing and ecosystem modelling techniques to estimate forest net carbon uptake. Int. J. Remote Sens. 29 (8), 2437–2443. doi:http://dx.doi.org/10.1080/01431160801894857.

Maselli, F., Chiesi, M., Brilli, L., Moriondo, M., 2012. Simulation of olive yield in Tuscany through the integration of remote sensing and ground data. Ecol. Model. 244, 1–12. doi:http://dx.doi.org/10.1016/j.ecolmodel.2012.06.028.

Matese, A., Alberti, G., Gioli, B., Toscano, P., Vaccari, F.P., Zaldei, A., 2008. Compact eddy: a compact, low consumption remotely controlled eddy covariance logging system. Comput. Electron. Agric. 64, 343–346.

Matteucci, G., Scarascia Mugnozza, G., 2007. Ecosistemi forestali e mitigazione dei cambiamenti ambientali: sequestro di carbonio in foreste italiane. In: Carli, B., Cavarretta, G., Colacino, M., Fuzzi, S. (Eds.), Clima e cambiamenti climatici: le attività di ricerca del CNR. ISBN, pp. 709–712 (978 978-88-8080-075-0).

Medrano, H., Flexas, J., Galmés, J., 2009. Variability in water use efficiency at the leaf level among Mediterranean plants with different growth forms. Plant Soil 317, 17–29. doi:http://dx.doi.org/10.1007/s11104-008-9785-z.

Moncrieff, J., Massheder, J.M., de Bruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., Scott, S., Soegaard, H., Verhoef, A., 1997. A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. J. Hydrol. 188–189, 589–611. doi:http://dx.doi.org/10.1016/s0022-1694(96)03194-0.

Moorthy, I., Miller, J.R., Berni, J.A.J., Zarco-Tejada, P., Hu, B., Chen, J., 2011. Field characterization of olive (Olea europaea L.) tree crown architecture using

terrestriallaser scanning data. Agric. For. Meteorol. 151 (2), 204–214. doi:http://dx.doi.org/10.1016/j.agrformet.2010.10.005.
Nardino, M., Pernice, F., Rossi, F., Georgiadis, T., Facini, O., Motisi, A., Drago, A., 2013. Annual and monthly carbon balance in an intensively managed Mediterranean olive orchard. Photosynthetica 51, 63–74.
Nieto, O.M., Castro, J., Fernández, E., Smith, P., 2010. Simulation of soil organic carbon stocks in a Mediterranean olive grove under different soil-management systems using the RothC model. Soil Use Manag. 26 (2), 118–125. doi:http://dx.doi.org/10.1111/j.1475-2743.2010.00265.x.
Nitsch, B., Kemmesies, O., Graeber, P.W., 2008. Groundwater Recharge Balancing Under the Conditions of Climatic Changes, 2013. Available at http://tudresden.de/die_tu_dresden/fakultaeten/fakultaet_forst_geo_und_hydrowissenschaften/fachrichtung_wasserwesen/iaa/systemanalyse/publikationen/Nitsch%20Jaipur08.pdf (accessed 11.12.13).
Noy-Meir, I., 1973. Desert ecosystems: environment and producers. Annu. Rev. Ecol. Syst. 4, 25–51. doi:http://dx.doi.org/10.1146/annurev.es.04.110173.000325.
Ospina, S., Rusch, G.M., Pezo, D., Casanoves, F., Sinclair, F.L., 2012. More stable productivity of semi natural rasslands than sown pastures in a seasonally dry climate. PLoS One 7 (5), e35555. doi:http://dx.doi.org/10.1371/journal.pone.0035555.
Oteros, J., García-Mozoa, H., Vázquez, L., Mestre, A., Domínguez-Vilches, E., Galán, C., 2013. Modelling olive phenological response to weather and topography. Agric. Ecosyst. Environ. 179, 62–68. doi:http://dx.doi.org/10.1016/j.agee.2013.07.008.
Pingintha, N., Leclerc, M.Y., Beasley Jr., J.P., Durden, D., Zhang, G., Senthong, C., Rowland, D., 2010. Hysteresis response of daytime net ecosystem exchange during drought. Biogeosciences 7, 1159–1170. doi:http://dx.doi.org/10.5194/bg-7-1159-2010.
Rapoport, H.F., Hammami, S., Martins, P., Pérez-Priego, O., Orgaz, F., 2012. Influence of water deficits at different times during olive tree inflorescence and flower development. Environ. Exp. Bot. 77, 227–233.
Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grunwald, T., Havrankova, K., Ilvesniemi, H., Dalibor, J., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyer, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M.J., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biol. 11, 1–16. doi:http://dx.doi.org/10.1111/j.1365-2486.2005.001002.x.
Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M.D., Seneviratne, S.I., Zscheischler, J., Beer, C., Buchmann, N., Frank, D.C., Papale, D., Rammig, A., Smith, P., Thonicke, C., van der Velde, M., Vicca, S., Walz, A., Wattenbach, M., 2013. Climate extremes and the carbon cycle. Nature 500, 287–295. doi:http://dx.doi.org/10.1038/nature12350.
Resco, V., Fischer, C., Colinas, C., 2007. Climate change effects on Mediterranean forests and preventive measures. New For. 33, 29–40. doi:http://dx.doi.org/10.1007/s11056-006-9011-x.
Reyer, C., Leuzinger, S., Rammig, A., Wolf, A., Bartholomeus, R.P., Bonfante, A., de Lorenzi, F., Dury, M., Gloning, P., Abou Jaoudé, R., Klein, T., Kuster, T.M., Martins, M., Niedrist, G., Riccardi, M., Wohlfahrt, G., de Angelis, P., de Dato, G., François, L., Menzel, A., Pereira, M., 2012. A plant's perspective of extremes: terrestrial plant responses to changing climatic variability. Glob. Change Biol. 19, 75–89. doi:http://dx.doi.org/10.1111/gcb.12023.
Rodda, J.C., Little, M.A., Harvey, J.E., Mcsharry, P.E., 2010. A comparative study of the magnitude, frequency and distribution of intense rainfall in the United Kingdom. Int. J. Climatol. 30, 1776–1783 (10101/npre.2009.3847.1).
Schroter, D., Cramer, W., Leemans, R., Prentice, I.C., Araujo, M.B., Arnell, N.W., Bondeau, A., Bugmann, H., Carter, T.R., Gracia, C.A., de la Vega-Leinert, A.C., Erhard, M., Ewert, F., Glendining, M., House, J.I., Kankaanpaa, S., Klein, R.J., Lavorel, S., Lindner, M., Metzger, M.J., Meyer, J., Mitchell, T.D., Reginster, I., Rounsevell, M., Sabate, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M.T., Thonicke, K., Thuiller, W., Tuck, G., Zaehle, S., Zierl, B., 2005. Ecosystem service supply and vulnerability to global change in Europe. Science 310, 1333–1337. doi:http://dx.doi.org/10.1126/science.1115233.
Scott, R.L., Serrano-Ortiz, P., Domingo, F., Hamerlynck, E.P., Kowalsky, A.S., 2012. Commonalities of carbon dioxide exchange in semiarid regions with monsoon and Mediterranean climates. J. Arid Environ. 84, 71–79. doi:http://dx.doi.org/10.1016/j.jaridenv.2012.03.017.
Seidl, R., Rammer, W., Jager, D., Currie, S.W., Lexer, J.M., 2007. Assessing trade-offs between carbon sequestration and timber production within a framework of multi-purpose forestry in Austria. For. Ecol. Manag. 248, 64–79.
Smith, M.D., 2011. An ecological perspective on extreme climatic events: a synthetic definition and framework to guide future research. J. Ecol. 99, 656–663.
Sorrentino, G., 2001. Meccanismi fisiologici di recupero dal deficit idrico in Olivo. Gestione dell'acqua e del territorio per un olivicoltura sostenibile, Napoli, 24–28 Settembre 2001.
Swemmer, A.M., Knapp, A.K., Snyman, H.A., 2007. Intra-seasonal precipitation patterns and above-ground productivity in three perennial grasslands. J. Ecol. 95, 780–788.
Testi, L., Orgaz, F., Villalobos, F., 2008. Carbon exchange and water use efficiency of growing irrigated olive orchard. Environ. Exp. Bot. 63, 168–177. doi:http://dx.doi.org/10.1016/j.envexpbot.2007.11.006.
Thompson, R.M., Beardall, J., Beringer, J., Grace, M., Sardina, P., 2013. Means and extremes: building variability into community-level climate change experiments. Ecol. Lett. 16, 799–806.
Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38, 55–94.
Valentini, R., Matteucci, G., Dolman, A.J., Schulze, E.D., Rebmann, C., Moors, E.J., Granier, A., Gross, P., Jensen, N.O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grünwald, T., Aubinet, M., Ceulemans, R., Kowalski, A.S., Vesala, T., Rannik, Ü., Berbigier, P., Loustau, D., Guethmundsson, J., Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrieff, J., Montagnani, L., Minerbi, S., Jarvis, P. G., 2000. Respiration as the main determinant of carbon balance in European forests. Nature 404, 861–865. doi:http://dx.doi.org/10.1038/35009084.
Vautard, R., Yiou, P., D'andrea, F., De Noblet, N., Viovy, N., Cassou, C., Polcher, J., Ciais, P., Kageyama, M., Fan, Y., 2007. Summertime European heat and drought waves induced by wintertime mediterranean rainfall deficit. Geophys. Res. Lett. 34 doi:http://dx.doi.org/10.1029/2006gl028001 (L07711).
Villalobos, F.J., Perez-Priego, O., Testi, L., Morales, A., Orgaz, F., 2012. Effects of water supply on Carbon and water exchange of olive trees. European J. Agron. 40, 1–7. doi:http://dx.doi.org/10.1016/j.eja.2012.02.004.
Xu, L., Baldocchi, D.D., 2004. Seasonal variation in carbon dioxide exchange over a Mediterranean annual grassland in California. Agric. For. Meteorol. 123, 79–96. doi:http://dx.doi.org/10.1016/j.agrformet.2003.10.004.
Zanotelli, D., Montagnani, L., Manca, G., Tagliavini, M., 2013. Net primary productivity, allocation pattern and carbon use efficiency in an apple orchard assessed by integrating eddy covariance, biometric and continuous soil chamber measurements. Biogeosciences 10, 3089–3108. doi:http://dx.doi.org/10.5194/bg-10-3089-2013.
Zhang, F.Y., Wu, P.T., Zhao, X.N., Cheng, X.F., 2012. Water-saving mechanisms of intercropping system in improving cropland water use efficiency. PMID 3 (5), 1400–1406 (22919855).