Agricultural and Forest Meteorology 260–261 (2018) 118–130

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

CO_2 and H_2O flux partitioning in a Mediterranean cropping system

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ARTICLE INFO

Keywords:
Transpiration
Evaporation
Photosynthesis
Respiration
Water use efficiency

ABSTRACT

The flux-variance similarity (FVS) partitioning method to estimate transpiration/photosynthesis and evaporation/respiration, using only high frequency Eddy Covariance (EC) measurements, was studied. The FVS method was applied to two crops in successive growing seasons of a typical cropping system in Mediterranean region: fava bean followed by winter wheat. FVS applies the flux-variance arguments derived from Monin-Obukhov similarity theory separately to the stomatal (photosynthesis and transpiration) and non-stomatal (respiration and evaporation) processes. The leaf-level water use efficiency, an input of FVS method, is here calculated by using EC outputs and estimated humidity after the direct measurement of surface infrared temperature. The two experimental seasons were characterized by exceptionally rainy periods (262 mm in 85 days in 2014, 344 mm in 149 days in 2015). Nevertheless, the partitioning results are consistent with expected trends and absolute values of flux components throughout both seasons. In particular, heterotrophic soil respiration measured by chamber systems and modelled FVS respiration components are comparable at the beginning and at the end of the growing crop cycles, when crop biomass and leaf area are very low. Furthermore, the coupling of FVS method and root exclusion method for measuring soil respiration is able to give the heterotrophic and autotrophic components of respiration. Finally, the results showed that the succession fava bean to wheat permits a mitigation of the loss of carbon to the atmosphere and increases carbon sequestration.

1. Introduction

Accurate knowledge of how water vapour (H_2O) and carbon dioxide (CO_2) fluxes are distributed in evaporation (E), transpiration (T), respiration (R) and photosynthesis (P) components, is essential to all studies on climate changing and, in general, to the evaluation and quantification of the contribution of agricultural practices to greenhouse gas (GHG) exchange, crop productivity, and resources use efficiency.

Several different methods have been developed to partition crop evapotranspiration ($ET = E + T$) and net ecosystem exchange ($NEE = P–R$) in their components, starting from direct field measurement or estimation of ET and NEE. In particular, ET partitioning is usually based on micrometeorological ET measurements coupled to methods for estimating one of the above-mentioned components, such as: (i) modelling of E by soil resistance and energy balance approaches (Shuttleworth and Wallace, 1985), (ii) microlysimeters (e.g., Singer et al., 2010) and flux chambers for measuring E (e.g., Stannard and Weltz, 2006; Daikoku et al., 2008; Raz-Yaseef et al., 2010), and (iii) sap flow technique for estimating T (e.g., Kurpius et al., 2003; Unsworth et al., 2004; Rana et al., 2005; Tang et al., 2006). Other methods to partition ET into E and T are based on long-term estimated water use efficiency (WUE, e.g. Zhou et al., 2016) and isotopic approaches(e.g. Berkelhammer et al., 2016).

The most common method for the NEE partitioning in R and P uses nonlinear regressions built on semi-empirical relationships between these fluxes and meteorological drivers (e.g. Reichstein et al., 2005; Stoy et al., 2006; Suleau et al., 2011). Since plants photosynthesise only with light, nighttime NEE is often used to parameterize a simple model of R as a function of soil temperature. Then, the measured NEE is subtracted from the modelled daytime respiration to calculate the assimilation in terms of gross primary production (GPP, Reichstein et al., 2005). Based on the physiological response to the solar radiation, another method fits NEE to a light response curve, determining R by using the intercept of the curve as incoming shortwave radiation approaches zero (Lasslop et al., 2009). Other methods, based on measurements at leaf (Blonquist et al., 2011) or soil (Epron et al., 2001) scales, have also been developed.

Furthermore, a combination of model results and soil respiration measurements permits the separation of R in its two components:

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https://doi.org/10.1016/j.agrformet.2018.06.007
Received 30 January 2018; Received in revised form 1 June 2018; Accepted 6 June 2018

autotrophic respiration, from plants (AR, above ground plus root respiration), and heterotrophic respiration (HR), which results from litter and soil organic matter decomposition produced by soil micro-organisms (e.g. Mäkiranta et al., 2008; Suleau et al., 2011). These different mechanisms respond differently to climate, environment and plant development, thus it is desirable to isolate the components of R.

All the above cited methods for partitioning H_2O and CO_2 fluxes unfortunately need a large number of variables to be measured in the field both for inputs and for calibrating model parameters. Moreover, the methods based on infrequent or sparse measurements (soil temperature, sap flow, microlysimeters, chambers) could suffer from scaling issues such as the mismatch in footprints between the field scale derived by micrometeorological methods such as eddy covariance (EC) (Kaimal and Finnigan, 1994) and the localized fluxes obtained by the other instruments. Since CO_2 and H_2O fluxes are currently measured through many networks of EC stations around the world (Baldocchi et al., 2001), a flux partitioning method just based on EC measurements could be useful for theoretical and practical purposes.

A relatively new method, called flux-variance similarity (FVS) partitioning, estimates transpiration/photosynthesis and evaporation/respiration using only high frequency EC measurements. First proposed by Scanlon and Sahu (2008), the theoretical basis of the method was presented with an example of its application to a couple of days over a vegetated surface. In subsequent studies, the FVS method was developed and applied to a whole growing season for a maize crop (Scanlon and Kustas, 2010), a grass field (Good et al., 2014), and irrigated sugarcane and peach orchard(Anderson et al., 2017), and over a decade to a temperate forest (Sulman et al., 2016).

The FVS approach applies the flux-variance similarity, which derives from Monin-Obukhov similarity theory, separately to the stomatal (i.e. P and T) and non-stomatal (i.e. R and E) processes. The authors of the above-mentioned studies found reasonable values using FVS in all published cases, but did not verify the partitioned fluxes with independent measurements, except Sulman et al. (2016) for the forest site, who compared evaporation and respiration by FVS with measured fluxes by sub-canopy EC towers.

The FVS method provides analytical expressions to partition CO_2 and H_2O fluxes simultaneously; it needs as inputs (i) the variables commonly derived from high frequency EC measurements and (ii) the leaf-level water use efficiency (WUE) for the analysed crop. Therefore, it should be sufficient to measure at high frequency the CO_2 and H_2O concentrations and vertical wind speed to derive the hourly fluxes and to generate the partitioned fluxes. It was found that the FVS approach is very sensitive to errors in estimating WUE especially in complex canopies and during dry periods (Palatella et al., 2014; Sulman et al., 2016). Moreover, Scanlon and Sahu (2008) and others have applied the FVS partitioning method to the turbulent statistics of H_2O and CO_2 that were first filtered via wavelets analysis in an effort to remove large-scale, low-frequency atmospheric processes not responsible for localized land-atmosphere exchange, which can add uncertainty to the partitioned components.

In this study, an experiment was designed to collect ET and NEE data by the EC method in a typical Mediterranean cropping system (fava bean – winter wheat), with a focus on the partitioning of the CO_2 flux into respiration and photosynthesis terms. In an effort to constrain and evaluate these partitioned fluxes, EC data were coupled with independent heterotrophic R measurements, performed by chamber systems. The aims are: (i) to perform qualitatively and quantitative evaluation of the FVS method, (ii) to analyse the partitioned fluxes of H_2O and CO_2 along the crop growing seasons, (iii) to split and analyse the autotrophic and heterotrophic terms of soil-crop respiration and (iv) to study the carbon exchange over two successional crop growth cycles.

2. Materials and methods

2.1. The site and the crops

The field site was the CREA-AA Research Unit experimental farm located in southern Italy (Rutigliano - Bari, 41° 01′ N, 17° 01′E, altitude 147 m a.s.l.). The site is characterised by Mediterranean semi-arid climate, with mild winters and warm/dry summers. On average, the rain is 535 mm year^{-1}, mainly distributed between the autumn and the late winter. The annual water deficit (reference evapotranspiration - rain) is 560 mm (Campi et al., 2009). The soil, classified as “Lithic Rhodoxeralf”, is characterised by clay texture, stable structure, shallow profile (0.6–1 m), and, because of a cracked limestone subsoil, fast drainage. On average, its Total Organic Carbon (TOC) content is 12.0 g kg^{-1}. Such a low value is due to high temperatures reached during the spring - summer seasons. The field capacity (FC) and the permanent wilting point (WP) volumetric water contents are equal to 36 and 22%, respectively. Therefore, with a bulk density of 1.15 Mg m^{-3}, the available soil water ranges from 80 to 140 mm (De Benedetto et al., 2012).

The measurements were carried out in two crops of a typical rainfed succession of the Mediterranean region: fava bean followed by winter wheat. Main tillage was conducted in the autumn 2013 as medium-depth ploughing (0.3 m). Seed bed preparation was conducted immediately before sowing, by a pass with a disk harrow. Neither water nor fertilizer was applied. The fava bean (cv. *Colombino*) crop, was sown on 19th February 2014 on an area of about 2.5 ha, with a plant density of 48,000 plants ha^{-1}. The plants’ fresh biomass was ploughed-in as green manure on 22th May 2014 when the crop was at flowering phenological stage. The winter wheat (cv. *Saragolla*) was sown on 2nd December 2014 on the same area where the fava bean crop was cultivated, with a plant density of 51,000 plants ha^{-1}. Main tillage and seed bed preparation was carried out as previously described for the fava bean crop. Pre-plant fertiliser was distributed at a rate of 50 kg P_2O_5ha^{-1} (triple superphosphate), 100 kg ha^{-1} of urea was distributed when the crop covered completely the soil (17th February 2015); no water was applied as irrigation. The wheat was harvested on 5th June 2015.

During both seasonal growing cycles, plants were harvested weekly or bi-weekly with randomised samples (25 × 25 cm^2). On each sample, the weight of fresh biomass (FB) and dry matter (DM), the leaf area index (LAI) and the height of plants were measured. The percentage of carbon (C) content in the harvested biomass was determined in triplicate using an elemental analyser (EA-1108 model, Fisons Instruments, Crawley, UK).

The crop development stages were recorded daily, and in this study the following simplified growth periods are considered:

- fava bean
  - emergence: from germination until complete soil coverage
  - vegetative development: from full soil coverage until plant maximum extension
  - flowering: from appearance of first flowers until green manure
- wheat
  - emergence: from germination until complete soil coverage
  - vegetative development: from first node visible until head in the boot
  - flowering: heads completely emerged and kernels ripe
  - maturation and senescence: from the end of ripening until harvest

2.2. Micrometeorological measurements

To avoid disturbance to the seed germination, the EC flux tower was established in the field at the emergence of fava bean and wheat crops for making continuous measurements. The setup consisted of a three-dimensional sonic anemometer (USA-1, Metek GmbH, Germany) for