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Simulation of olive grove gross primary production by the combination of ground and multi-sensor satellite data

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ABSTRACT

We developed and tested a methodology to estimate olive (*Olea europaea* L.) gross primary production (GPP) combining ground and multi-sensor satellite data. An eddy-covariance station placed in an olive grove in central Italy provided carbon and water fluxes over two years (2010–2011), which were used as reference to evaluate the performance of a GPP estimation methodology based on a Monteith type model (modified C-Fix) and driven by meteorological and satellite (NDVI) data. A major issue was related to the consideration of the two main olive grove components, i.e. olive trees and inter-tree ground vegetation: this issue was addressed by the separate simulation of carbon fluxes within the two ecosystem layers, followed by their recombination. In this way the eddy covariance GPP measurements were successfully reproduced, with the exception of two periods that followed tillage operations. For these periods measured GPP could be approximated by considering synthetic NDVI values which simulated the expected response of inter-tree ground vegetation to tillages.

1. Introduction

Olive (*Olea europaea* L.) is one of the most ancient cultivated fruit trees in the Mediterranean basin (Zohary and Spiegel Roy, 1975; Moriondo et al., 2008; Villalobos et al., 2012) where it plays a fundamental role by integrating agriculture, environment and landscape into a complex system. Although in recent years olive trees have been cultivated successfully in countries such as California, Australia, Argentina and South Africa (De Graaff and Eppink, 1999), olive is mainly grown in the Mediterranean area and dominates its rural landscape (Loumou and Giourga, 2003). This region includes about 700 million olive trees over 9 Mha, representing about 96% of areas cultivated worldwide (Vossen, 2007).

In addition to the agronomic and economic value, olive cultivation systems (agro-forestry stands, traditional groves and new intensive orchards) provide additional ecosystem services on local to regional scales by improving soil conservation and allowing high carbon sequestration (Sofo et al., 2005; Loumou and Giourga, 2003). Olive trees can also play a fundamental role on a global scale, given their long-term carbon storage capacity (Nieto et al., 2010). Consequently, the contribution that these ecosystems give to the global carbon cycle should not be neglected, especially considering that the Mediterranean basin is one of the regions most exposed to the risk of climate change (IPCC, 2007).

Gross primary production (GPP), defined as the overall carbon fixation rate through the process of photosynthesis, is a fundamental parameter for both local scale ecosystem monitoring and global scale carbon cycle and climate change research. Approximately, half of this amount is incorporated into new plant tissues such as leaves, roots and wood, and the other half is released back into the atmosphere through autotrophic respiration (Kotchenova et al., 2004).

The need for assessing ecosystem production over large areas has recently promoted the development of new strategies and techniques. Among these, one of the most widely applied is the Eddy Covariance method. This micrometeorological technique allows to measure turbulent fluxes (e.g. CO_2, H_2O, sensible heat) that are exchanged between vegetation canopy and the atmosphere (Baldocchi and Meyers, 1988; Stull, 1988; Baldocchi et al., 1996). Starting from the measurement of CO_2 net ecosystem exchange (NEE), a partitioning algorithm can be used to calculate GPP at ecosystem scale according to the equation: NEE = ecosystem respiration (Reco) − GPP. However, eddy covariance systems provide integrated CO_2 flux measurements over limited footprint areas, with sizes and shapes that vary with tower height, canopy physical characteristics and wind speed, and therefore do not allow observations over large areas (Osmond et al., 2004).

The lack of spatially extensive flux tower observations over large areas can be overcome through the combination of ground and

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remotely sensed data. Remote sensing provides information on photosynthetic processes of plants on several spatial and temporal scales (Veroustraete et al., 2002; Prince, 1990; Kumar and Monteith, 1981). In recent years the use of remote sensing allowed systematic observations to be made of vegetation and relevant ecosystem parameters, becoming a fundamental instrument for the characterization of vegetation structure and for estimating GPP at a broad scale (Keenan et al., 2012; Xiao et al., 2010; Yang et al., 2007; Behrenfeld et al., 2001; Running, 1999). In particular, many studies have shown that tree production can be efficiently simulated by Monteith's approach (Monteith, 1972), which combines measurements of incoming radiation and ecosystem radiation use efficiency with remotely sensed estimates of the fraction of absorbed photosynthetically active radiation (fAPAR). This approach has obtained great benefit from the recent availability of MODIS images, which presently represent the best descriptor of vegetation properties with moderate spatial resolution (250 m) and high temporal frequency (8–16 days) (Maselli et al., 2012).

The application of Monteith's approach to estimate olive grove GPP, however, involves particular complications due to the multi-layered nature of this ecosystem type. Olive groves are composed of trees and inter-tree ground vegetation which, showing different eco-physiological constraints to the photosynthetic process, must be treated separately in the simulation of ecosystem GPP.

In the light of these considerations, the current paper aims at developing and testing a new multi-step methodology capable of estimating olive grove GPP. The major novelty of the study is the modeling of GPP within a complex multi-layer agricultural ecosystem, which is obtained by simulating separately the behavior of the two main ecosystem components (ground vegetation and olive trees). In particular, a modified version of the parametric C-Fix model, which is driven by normalized difference vegetation index (NDVI) data (Veroustraete et al., 2004; Maselli et al., 2009), was applied to simulate the GPP of these two components. The modeling performances were assessed against GPP data derived from eddy covariance measurements taken in an olive grove in South Tuscany (Follonica, Central Italy) during the period 2010–2011.

2. Study area

The study was conducted on an olive grove situated in an agricultural area near Follonica (Gr), Tuscany (Central Italy, 42°56′ N, 10°46′ E). In Tuscany olive trees cover an area of 96,828 ha with a total production of 117,482 t (http://www.istat.it/it/). Around 49,300 farmers grow olives, representing 62% of Tuscan farms. Olive trees have a strong effect on the Tuscan landscape and land use, occupying about 11% of the regional utilized agricultural area (UAA). Olive tree cultivation contributes about 95 M€ to the value of regional agricultural production, which is approximately 4% of the total value of agricultural gross domestic product (GDP) (IRPET, 2011). Olive groves are mostly situated on plains and in hilly areas. However, given the heterogeneity of climatic and soil conditions in Tuscany, the distribution of olive groves varies in each administrative province (Maselli et al., forthcoming).

The experimental site at Follonica (Fig. 1) lies about 41 m above sea level, has a regular morphology and a southerly exposure and covers an area of about 6 ha. This olive grove dates back to 1993 and contains around 1500 trees of about 4 m in height. Olive canopy cover is about 25%, and inter-tree areas are covered by several herbaceous native species (*Cynodon dactylon*, *Trifolium campestre*, *Medicago polimorfa*, *Picris hieracioides*, *Geranium* sp., *Convolvus arvensis*, *Anagallis arvensis*, *Calendula arvensis*, *Rumex acetosella*, *Eruca sativa*, *Linula viscosa*, *Ordeum murino*, *Daucus carota*, *Bromus* sp.). Cropping management follows the typical tradition of the area, with no irrigation and superficial plowing (disc harrowing). During the study period, the site was plowed twice: the first time in late April 2010, the second in February 2011. The site was treated with inorganic fertilizer in spring 2010 and February 2011. Olive production in 2010 and 2011 was 3.1 t ha^{-1} and 4.1 t ha^{-1}, respectively.

The soil belongs to the clay-loam textural class, with 40% silt and 38% clay. Soil texture and depth were obtained from the soil map produced by the Tuscany Region (http://sit.lamma.rete.toscana.it/websuoli/). According to the classification of Thornthwaite (1948), the climate of the area can be described as mesothermic, between dry subhumid and semi-arid, with the high summer temperatures and mild winters that are typical of the Mediterranean climate (Table 1). Meteorological conditions differed in the two study years as shown in Fig. 2. The first year (2010) was markedly wetter than the second (2011),

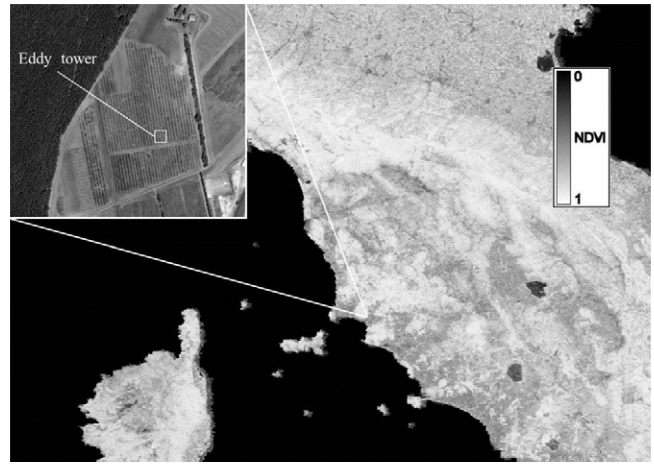

Fig. 1. MODIS NDVI image of June 2010 showing the position of the study area in Tuscany as well as its main features (enlarged box). NDVI window extends over 8–13° East Longitude, 42–45° North Latitude.

Table 1
Monthly mean temperature (°C), total rainfall (mm) and months with mean temperature <0 °C in the study area for 30 years average (MARS JRC data set), 2010 and 2011.

	Monthly mean temperature (°C)	Rainfall (mm)	Months with mean temperature <0 °C
30 years average (1980–2010)	15.2	626	–
2010	16	797	–
2011	16.8	367	–

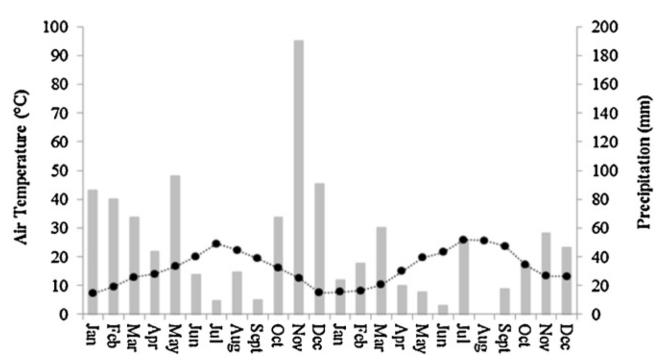

Fig. 2. Thermo-pluviometric diagram for study area. All monthly data derive from eddy covariance station.