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Modelling and analyzing the water and carbon dynamics of Mediterranean macchia by the use of ground and remote sensing data

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ABSTRACT

Mediterranean ecosystems are particularly vulnerable to the environmental changes which have occurred in the last decades. Evaluating the ecosystem response to these changes is therefore a top priority, particularly concerning water and carbon dynamics. The Pianosa Island is a well known test site where numerous environmental surveys have been performed to fully characterize the most typical vegetation type, Mediterranean macchia. A first measurement campaign concerning both vegetation and soil properties was performed in 2001, and was repeated in 2010 only for soil properties. Vegetation cover was characterized again by means of an aircraft high resolution LiDAR dataset taken in 2009. Additional medium and low spatial resolution satellite images (Landsat OLI and MODIS) and aircraft photos were recovered from various sources. The availability of these datasets offers a unique opportunity to develop and test a methodology capable of modelling and analyzing the water and carbon dynamics of Mediterranean macchia during the 2001–2010 decade. To this aim, simulation procedures integrating remotely sensed and ancillary data were first tuned towards the available observations of vegetation biomass and soil carbon content. These procedures were then applied to produce daily estimates of macchia actual evapotranspiration (AET), gross primary production (GPP) and net ecosystem exchange (NEE), whose accuracy was assessed against corresponding eddy covariance flux tower observations taken in two years (2007–2008). The results obtained are satisfactory and support the capability of the modelling approach to reproduce both the water and carbon dynamics of macchia during the study decade. From an ecological viewpoint, both fluxes are increasing in this time period, mainly depending on similarly increasing spring rainfall. The macchia ecosystem behaves as a net sink of carbon, which is stored primarily in soil (≅90%) and secondarily in vegetation.

1. Introduction

The Mediterranean climate is characterized by mild winters and hot and dry summers, with rainfall maxima occurring in spring and autumn (Bolle et al., 2006). The combination of high temperature and low rainfall produces frequent summer droughts to which local vegetation is usually adapted (Scarascia-Mugnozza et al., 2000). Additional ecological factors are due to the human being, who has settled in Mediterranean areas since ancient times, interacting with local vegetation through numerous activities (i.e. grazing, farming, fires, etc.). This has made the environment highly differentiated and fragmented, producing delicate ecological equilibriums which are particularly vulnerable to global changes (Giorgi and Lionello, 2008). Investigating how Mediterranean ecosystems react to major environmental factors is therefore an issue of primary scientific and practical importance (Ciais et al., 2005; Chiesi et al., 2007).

The main ecosystem processes are related to the dynamics of water and carbon, which have been widely investigated at various spatial and temporal scales (Sahoo et al., 2011; Law and Waring, 2015; Yang and Zhang, 2016). The most traditional investigation methods are based on extensive ground surveys aimed at estimating the quantity and activity of plant biomass. These methods are economically expensive and time-consuming and must be repeated frequently to follow rapid variations in time. An alternative method which has been proposed relatively recently to assess water and carbon fluxes at ecosystem level is based on the eddycovariance technique (Aubinet et al., 2000). This technique has the advantage of providing theoretically continuous data series, so that the tempo-

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ral evolution of water and carbon fluxes can be followed for several years. As a disadvantage, the eddycovariance technique provides measurements which refer only to the footprint area around the tower, whose extension varies with the site characteristics and the equipment used to collect the measurements. Some methods have been developed to extend flux tower point measurements over the land surface (Papale and Valentini, 2003), but this operation remains problematic in large, heterogeneous regions. Moreover, collecting flux tower data for entire decades is practically laborious and expensive, so that most of the existing datasets are referred to limited and/or discontinuous time periods (see http://www.europe-fluxdata.eu/home).

An alternative opportunity to investigate vegetation processes at a variety of spatial and temporal scales is offered by remote sensing techniques, mainly depending on the data type utilized (Waring and Running, 2007). Remotely sensed vegetation indices, in particular, have been related to several ecosystem attributes such as the green leaf area index (LAI), the fractional vegetation cover (FVC), the fraction of absorbed photosyntetically active radiation (fAPAR), etc. (Bannari et al., 1995). Among these indices, the normalized difference vegetation index (NDVI) is still the most widely used, also due to the current availability of long-term global archives from different satellite sensors (e.g. NOAA-AVHRR, Spot-VEGETATION, MODIS and Proba-V). Numerous methods have been developed to integrate NDVI and ancillary data for the characterization of major ecosystem processes, such as actual evapotranspiration (AET), gross primary production (GPP) and net ecosystem exchange (NEE) (Mu et al., 2011; Maselli et al., 2014a, 2009a; Jung et al., 2008; Chirici et al., 2016). These methods are therefore potentially suitable to simulate and analyze the water and carbon dynamics of terrestrial ecosystems at different spatio-temporal scales.

Such operations, however, require also proper observations of woody biomass, which is generally quantified as growing stock volume (Zhou et al., 2002). Woody biomass, in fact, is an important regulator of ecosystem resistance to water loss (Eggemeyer et al., 2009) and is associated with the amount of living and respiring tissues, which are major determinant of net carbon exchange (Waring and Running, 2007; Maselli et al., 2009a). While large area estimates of growing stock volume have been indirectly derived from optical observations (Lu, 2006; Kumar et al., 2015), the most straightforward method to obtain such estimates is provided by LiDAR techniques, which can yield canopy height models (CHMs) directly informative on vegetation height and structure (Lefsky et al., 2002). The potential of both aircraft and spaceborne LiDAR techniques to predict growing stock volume at various spatial scales has actually been demonstrated in a great number of publications (Zhao et al., 2009; Montaghi et al., 2013).

The analysis of ecosystem water and carbon dynamics over long time periods is therefore an open and challenging issue, which requires the use of different datasets and simulation methods. While process based models can be proficiently applied for this purpose (Johnsen et al., 2001; Kang et al., 2006; Chiesi et al., 2007), a more effective strategy would consists of integrating direct observations of ecosystem conditions derived from remotely sensed and ancillary data sources (Maselli et al., 2009a). The combination of optical and LiDAR remote sensing data to monitor the carbon storage of boreal forests has been recently investigated by Hopkinson et al. (2016). In that case temperature and radiation were the main climatic drivers of vegetation growth, but carbon accumulation was mainly regulated by forest management. No studies have instead investigated Mediterranean ecosystems, whose vegetation dynamics is mostly determined by water limitation and is profoundly affected by long-term disturbances (Scarascia-Mugnozza et al., 2000; Maselli et al., 2014b).

The Pianosa Island offers a unique opportunity for studying these ecosystems due to its geographical characteristics and history. This relatively small Island, which is close to the Tuscan coast (Central Italy), was for less than one century an agricultural penal colony, where prisoners were forced to work in the fields. At the end of the 1990s all activities of the penal colony were interrupted and since then all lands previously occupied by agriculture have not been disturbed. Thus, the Island of Pianosa is representative for Mediterranean ecosystems where natural vegetation is re-colonizing the abandoned lands and a number of secondary succession stages can be found. Since 2000 the Island has been the site of the Pianosa_Lab project, an innovative research infrastructure for long-term monitoring the exchange of greenhouse gases between the biosphere and the atmosphere in Mediterranean ecosystems. In this research framework, various datasets were collected and an eddy covariance flux tower was installed to fully understand which are the environmental drivers and limiting factors affecting the water and carbon dynamics of the main ecosystems (Inglima et al., 2009; Vaccari et al., 2012; Scartazza et al., 2014). Among these, Mediterranean macchia (equivalent to the Spanish "maquis"), which is mostly composed of xerophylous brushes, is likely the most characteristic (Colom et al., 2004).

Reconstructing the water and carbon dynamics of Mediterranean macchia in the Pianosa Island is therefore an important research topic, which could cast light on the response of this vegetation type to major eco-climatic drivers. The current paper aims at addressing this issue for the 2001–2010 decade by developing and applying a modelling strategy which can optimally utilize the available data sources. This was achieved using site information on vegetation and soil collected during the Pianosa_Lab project, integrated with meteorological observations, satellite images at different spatial and temporal resolutions and aircraft LiDAR data. The obtained daily estimates of water and carbon fluxes were finally assessed versus independent eddycovariance observations of AET, GPP and NEE, taken in two years (2007–2008).

The paper is organized as follows. The study area and the remote sensing and ancillary data utilized are introducted in the next section. The methodology applied is then briefly described, followed by the results achieved. A discussion section reports on the advantages and limitations of this approach, while main conclusions are drawn in the final section.

2. Study area and data

2.1. Study area

Pianosa Island (Long. 10°04′44″E, Lat. 42°35′07″N) is the fifth, by extension, of the seven islands of the National Park of Tuscan Archipelago (Fig. 1), with a surface area of 10.2 km^2 and a coastal perimeter of approximately 20 km (De Giuli, 1970). The name of the island derives from the Latin "Planasia", which recalls its flat morphology with some small undulations; the highest elevation is about 29 m a.s.l., while the average is about 18 m. The flat morphology makes the climate drier than that of the surrounding islands of the Archipelago, with rainfall patterns occurring mostly from September to January (Fig. 2). The average annual temperature is 16.1 °C and the average annual rainfall is about 500 mm (Baraldi et al., 2004).

The original vegetation of the island was presumably represented by Mediterranean macchia, dominated by a mixture of sclerophyllous and deciduous trees, bushes and grassland. This vegetation was strongly affected by the agricultural activities of the penal colony and today survives mainly along the coastal perimeter. The macchia ecosystem of the island is typical of calcareous soil and is dominated by the presence of *Juniperus phoenicia, Rosmarinus officinalis*, and *Cistus* spp., mixed with various herbaceous species (Baldini, 2000; Colom et al., 2004). Patches of this plant commu-