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Monitoring water stress in Mediterranean semi-natural vegetation with satellite and meteorological data

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ABSTRACT

In arid and semi-arid environments, the characterization of the inter-annual variations of the light use efficiency ε due to water stress still relies mostly on meteorological data. Thus the GPP estimation based on procedures exclusively driven by remote sensing data has not found yet a widespread use. In this work, the potential to characterize the water stress in semi-natural vegetation of three spectral indices (*NDWI*, *SIWSI* and *NDI7*) – from MODIS broad spectral bands – has been analyzed in comparison to a meteorological factor (C_{ws}). The study comprises 70 sites (belonging to 7 different ecosystems) uniformly distributed over Tuscany, and three eddy covariance tower sites. An operational methodology, which combines meteorological and MODIS data, to characterize the inter-annual variations of ε due to summer water stress is proposed. Its main advantage is that it relies on existing series of meteorological data characterizing each site and allows calculating a typical C_{ws} profile that can be "updated" (C^*_{ws}) for the actual conditions using MODIS spectral indices. The results confirm that the modified C^*_{ws} can be used as a proxy of water stress that does not require concurrent information on meteorological data.
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1. Introduction

In Mediterranean areas, the coincidence of the dry season with the period of maximum solar irradiation and temperature creates particular problems for annual vegetation growth, which is strongly limited by summer water availability (Bolle et al., 2006). Water stress affects the vegetation production by a reduction of the leaf area, the stomatal conductance and the CO_2 uptake and hence of the photosynthesis, and by a slowdown of root elevation and development (Verstraeten et al., 2006). The gross primary production (*GPP*), which corresponds to total ecosystem photosynthesis, is an essential parameter to characterize most relevant ecosystem processes. It can be modeled using the Monteith's approach (1972) as the product of the *APAR* (*viz.* the photosynthetic active radiation, *PAR*, absorbed by the canopy) and ε (the light use efficiency in the conversion of *APAR* into photosynthetically fixed CO_2). The *APAR* in turn can be obtained as the product of the f_{APAR} (fraction of *PAR* that is absorbed) and the incident *PAR*, whereas ε can be estimated from a maximum value (ε_{max}) corresponding to the optimal ecosystem functioning and depending on the plant functional type (Garbulsky et al., 2009; Heinsch et al., 2003), which is down-regulated through the use of several dimensionless scalars (varying from 0 to 1) that quantify different stress conditions.

Relying on the use of eddy covariance (EC) flux tower data several authors have shown that ε of Mediterranean forests is strongly reduced during dry summer spells (Allard et al., 2008; Garbulsky et al., 2008; Moreno et al., 2012) and presents an inter-annual variability depending on the intensity and duration of the summer water stress period. Therefore, as the water stress is the main factor controlling the inter-annual variations of ε in Mediterranean ecosystems, it is crucial to define appropriate scalars to account for its temporal variability (i.e., the factors that modify the maximum ε defined under non-stress conditions). These 'water stress scalars' can be derived from both meteorological and remotely sensed data. For example, the MODIS approach uses the daily average vapor pressure deficit, which generally tends to underestimate the effect of water stress (Hansen et al., 2000; Running et al., 2004). The CASA water scalar is derived from a local water budget that takes into account the actual and potential evapotranspiration (*AET* and *PET*, respectively) (Field et al., 1995; Potter et al., 1993). Maselli et al. (2009a) uses the same theoretical foundation to introduce an index, C_{ws}, which is aimed to capture the short-term effect of water stress. Significant correlations have been found between inter-annual variations of ε from flux tower stations and C_{ws}. Its main drawback is the need of meteorological data since the network of weather stations can be sparse or non-existent. This justifies

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Table 1
Main characteristics of the 70 sites selected in Tuscany (10 per forest type, FT). The FT number follows a gradient of decreasing xeric condition. For each FT, the minimum and maximum values of elevation, mean annual temperature and annual precipitation over the 10 sites are provided.

	FT	Elevation (m)	Mean annual temperature (°C)	Annual precipitation (mm)
1	Mediterranean macchia	67–436	13.9–15.9	590–739
2	Holm oak	121–482	13.6–15.4	701–923
3	Plane/hilly conifers	2–576	12.2–15.7	642–1182
4	Deciduous oaks	165–915	10.5–15.0	703–1551
5	Chestnut	420–888	10.7–12.6	949–2013
6	Beech	904–1540	6.6–10.7	994–1709
7	Mountain conifers	934–1364	6.6–10.0	1213–2067

the search for spectral indices sensitive to the short-term effect of water stress on vegetation.

Several attempts have been made to estimate the decrease of ε due to water stress through the use of remotely sensed spectral indices (Coops et al., 2010). These studies, however, have provided diverse results, since the spectral responses of plants to varying eco-physiological conditions are often complex and delayed (Maselli et al., 2009a). Moreover, and especially in water-limited ecosystems, many spectral indices are sensitive not only to leaf water content but also to LAI and pigment content, which often vary simultaneously (Danson and Bowyer, 2004). A relatively novel spectral index is the Photochemical Reflectance Index (*PRI*) (Gamon et al., 1990, 1992), based on the remote sensing of the xanthophyll plant pigment effect on the reflectance in the narrow band centered at 531 nm. *PRI* is claimed to be a photosynthetic efficiency indicator across a wide range of conditions, species and functional types, because it also correlates with chlorophyll/carotenoid ratios (Filella et al., 2009) and can be used to monitor early water stress (Naumann et al., 2010; Sarlikioti et al., 2010; Suárez et al., 2009; Thenot et al., 2002). However, the *PRI* efficiency at ecosystem level (MODIS pixel) is still elusive and no conclusive results have been obtained yet to track the inter-annual variability of ε as a consequence of the water stress. *PRI* is a narrow band spectral index and it has a very low signal and a rather high noise level. The reflectance change in the 531 band expected from xanthophylls conversion in presence of water stress is, at MODIS pixel scale, of the same magnitude order than the sensor noise (Coops et al., 2010; Hall et al., 2008). However, *PRI* is more affected by external factors such as illumination and view geometry (Drolet et al., 2008). In particular, Moreno et al. (2012) showed that in an evergreen coniferous ecosystem whose seasonal growth is limited by water availability in summer, most (around 70%) of the correlation between ε and *PRI* was explained by the *PRI* inter-annual variability due to the illumination and viewing conditions.

To avoid reflectance changes of the same magnitude order of sensor noise, some other spectral indices using broader bands can be used. In particular, as water stress produces a decrease of plant water and chlorophyll content, both affecting the vegetation reflectance, this stress can be theoretically assessed from spectral indices related to leaf water content (Danson et al., 1992; Zarco-Tejada et al., 2003). The water content decrease is noticeable during early stages mainly in the 0.9–2.5 μm (comprising the near infrared, NIR, and the short wave infrared, SWIR, spectral regions), mainly in bands centered at 1.45, 1.94, and 2.50 μm (Carter, 1991). However, the decrease of chlorophyll content (Goerner et al., 2011) – noticeable in visible (VIS) wavebands – requires more prolonged periods of drought. Several authors have demonstrated linkages between reflectance and different water content related indices using ground data (Ceccato et al., 2002; Fensholt and Sandholt, 2003; Clevers, 2008) as well as radiative transfer models at leaf and canopy level (Tarantola et al., 2001; Ceccato et al., 2002; Zarco-Tejada et al., 2003; Trombetti et al., 2008). Most of these indices are obtained from the normalized difference between the NIR reflectance and a SWIR reflectance; for example the Normalized Difference Water Index (*NDWI*) (Gao, 1996), the Shortwave Infrared Water Stress Index (*SIWSI*) (Fensholt and Sandholt, 2003), and the Normalized Difference Water Index 7 (*NDI7*) (Rubio et al., 2006).

In this work, the potential to characterize the water stress in natural vegetation of several 'water content indices' – from MODIS broader spectral bands – has been analyzed. The MODIS bands used to obtain these indices present a higher spatial resolution (500 m instead of 1000 m) and a double width (of about 20–50 nm) as compared with the bands used to calculate *PRI*. Moreover, they are atmospherically corrected, and the BRDF parameters are known (in particular the k_0). Therefore these indices present a lower noise level, a better spatial resolution, and a higher processing level (corrected from atmospheric effects as well as from angular since they are calculated from nadir reflectance).

The study comprises 70 sites (belonging to 7 different ecosystems) uniformly distributed over Tuscany (Central Italy). Since the dependence on ground meteorological data cannot be completely avoided at present, our main goal is to propose an operational methodology for the characterization of the inter-annual variations of ε due to summer water stress which combines meteorological and MODIS data. The main advantage of this methodology is that it relies on existing series of meteorological data characterizing each site, which are "updated" for the actual conditions using MODIS spectral indices.

2. Materials and methods

2.1. Study area

Tuscany (9°–12° E, 42°–44° N) has extremely heterogeneous morphological and land cover features. Its climate ranges from Mediterranean to temperate warm or cool following the altitudinal and latitudinal gradients and the distance from the sea (Rapetti and Vittorini, 1995). Forests cover about half of the region and are mostly placed in the inner hilly and mountainous areas. The dominant forest species are various oaks, both evergreen (*Quercus ilex* L.) and deciduous (*Quercus pubescens* Willd. and *Quercus cerris* L.), Mediterranean pines (*Pinus pinaster* Ait., *Pinus pinea* L.), chestnut (*Castanea sativa* Mill.), beech (*Fagus sylvatica* L.) and spruce (*Abies alba* Mill.). Mediterranean macchia is widespread in the most arid zones near the coast and in the islands.

2.2. Data

2.2.1. Ancillary data

The spatial distribution of Tuscany forests was derived from the map of Arrigoni et al. (1998). The 18 classes reported by this map were grouped, following eco-physiological criteria, into the seven forest types (FTs) shown in Table 1. Within each FT ten sites of at least 1 km^2 were selected as representative of relevant eco-climatic conditions (Maselli et al., 2009b) paying attention to avoid discontinuities or boundary areas. The spatial distribution of the 70 sites

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