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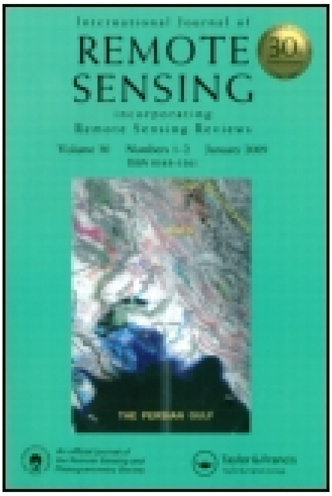

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The utility of MODIS-sPRI for investigating the photosynthetic light-use efficiency in a Mediterranean deciduous forest

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The present study investigated the utility of Moderate Resolution Imaging Spectroradiometer (MODIS)-derived sPRI (scaled photochemical reflectance index) and its relationship to photosynthetic light-use efficiency (LUE) calculated from eddy covariance tower data. The analysis was performed over two consecutive years (2003–2004) in a Mediterranean *Quercus cerris* L. forest site in Italy. Temperature and rainfall conditions differed markedly over the study period, with 2003 being a notable drought year and 2004 a non-drought year. MODIS ocean bands 11 (centred at 531 nm) and 12 (centred at 551 nm) were used for calculating sPRI. LUE exhibited substantial variability within 2003 and 2004, and a moderate relationship between MODIS-sPRI and LUE was observed during the wet year, and for backscattering scenes. This demonstrated the capacity of sPRI to detect xanthophyll cycle activation by vegetation during high light conditions. However, our results show that sPRI should be used with care, particularly under severe water stress conditions, when an increased influence of confounding factors, such canopy structure, illumination, and viewing angles, is observed.

1. Introduction

Terrestrial ecosystems are closely integrated with the climate system, particularly via the global carbon cycle, as large reservoirs and regulators of atmospheric carbon dioxide concentrations. Forests dominate terrestrial ecosystems, therefore a fundamental issue in global change research is the understanding of forest functional response to climate anomalies (Law et al. 2002).

Numerous efforts have been made during the last two decades to elucidate the relationship between climatic variables and key forest ecosystem processes using a variety of methods, including canopy spectral reflectance measurements, which represent a rapid approach to assess vegetation status and functionality (Demmig-Adams and Adams 2006; Hall et al. 2008; Hall, Hilker, and Coops 2011; Hilker et al. 2008, 2009, 2010). For example, reflectance vegetation indices have been applied to estimate canopy photosynthetic capacity, and net primary productivity over large areas (e.g. Gamon et al. 1990; Peñuelas and Filella 1998). In particular, the photochemical reflectance index (PRI; Gamon, Peñuelas, and Field 1992) was proposed to estimate photosynthetic light-use efficiency (LUE), and it was reported that LUE temporal and spatial variation patterns are related to stress conditions (Barton and North 2001). When light absorbed from leaves exceeds the

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capacity of photosynthetic reactions, the xanthophyll cycle pigments provide a means to dissipate the excess light through heat production, and subsequently protect the photosynthetic apparatus (Demmig-Adams 1990). The xanthophyll cycle pigment interconversion can be detected in leaves from a reflectance change at different wavelengths in the green region, and the PRI has been proposed as a non-destructive assessment of leaf physiological properties (Peñuelas, Filella, and Gamon 1995). The PRI is calculated as follows:

$$\mathrm{PRI} = \frac{R_{531} - R_{\mathrm{ref}}}{R_{531} + R_{\mathrm{ref}}}, \tag{1}$$

where R_{531} denotes the leaf reflectance at 531 nm, and R_{ref} is the reflectance at a reference wavelength (Demmig-Adams 1990; Thenot, Méthy, and Winkel 2002); most recent studies have adopted the 570 nm wavelength as a reference (Meroni et al. 2008; Peguero-Pina et al. 2008; Rascher and Pieruschka 2008; Ripullone et al. 2011).

The relationship between PRI and ecosystem LUE has been demonstrated for cases where the PRI was obtained from hyperspectral data acquired by aircraft (Rahman et al. 2001), helicopter-mounted sensors (Nichol et al. 2000), and satellite sensor data (Goerner, Reichstein, and Rambal 2009; Xie, Gao, and Gao 2009; Coops et al. 2010; Hilker et al. 2011). In recent years, numerous studies have been also performed utilizing the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor, carried on the Terra and Aqua satellites, which provides data useful for studying and analysing a wide range of land-cover and time-series changes (Ishimura et al. 2011). In several cases, MODIS-derived PRI was found to rather effectively track ecosystem LUE; however, some limitations in the method were evident (Rahman et al. 2004; Drolet et al. 2005, 2008; Garbulsky, Peñuelas, Ourcival, et al. 2008; Garbulsky, Peñuelas, Papale, et al. 2008). For instance, Goerner et al. (2010) suggested MODIS-derived PRI should be used with care when exploring seasonal LUE variation under severe water stress conditions as the data might translate into important confounding factors on the PRI−LUE relationship.

The study presented in this paper further investigates factors that confound the PRI−LUE relationship, with the objective of testing the utility of MODIS-derived PRI to investigate forest canopy functionality under extreme climatic conditions. We examined seasonal variability in eddy covariance LUE in a coppice forest of Turkey oak (*Quercus cerris* L.) located in a Mediterranean ecosystem, and the capacity of a satellite (MODIS)-derived PRI time series to track these variables across the two following climatically contrasting years: 2003, which was an exceptionally dry drought year (Ciais et al. 2005), and 2004, which exhibited wetter than normal conditions.

2. Methods

2.1. Study site

The study site is located in the Mediterranean forest of Roccarespampani (42° 23′ N, 11° 51′ E, 220–240 m above sea level) near Viterbo in Central Italy. It is an intensively managed forest, extending over more than 1250 ha, predominantly dominated by Turkey oak (*Q. cerris* L.); pubescent oak (*Quercus pubescens*), cork oak (*Quercus suber*), and holm oak (*Quercus ilex*) sporadically occur, with sweet broom (*Ruscus aculeatus*) and thorn trees (*Crataegus monogyna*) as the main understory species. Overall, canopy structure and composition can be considered homogeneous over quite a large area. The forest is a ‘coppice with standards’, and a rotation length of 15–20 years between coppicing

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(Rey et al. 2002). Currently, the forest is arranged as a chromo sequence of forest plots, each of approximately 80 ha, with coppice shoots in the range of 0–20 years (Tedeschi et al. 2006). In the measurement years (2003 and 2004), the forest was a mosaic of forest plots in which the coppice component spanned all age classes between 0 and 20 years. The average annual temperature is 15.1°C, and the annual rainfall is 876 mm. The rainfall distribution is irregular, with a drought period in summer of approximately 2 months. The soil is a 90 cm Luvisol on volcanic bedrock. No carbonates are present in the soil profile. The leaf area index (LAI), a major indicator of stress in forests (Latifi and Galos 2010), ranged between 3.2 and 4.5 m^{-2} m^{-2}, and basal area between 9 and 25 m^2 ha^{-1}.

2.2. Climate data

Precipitation and temperature records were obtained from the nearby weather station at Viterbo, Italy. Continuous data covering the 2002–2007 period were utilized, which was based on climate and eddy covariance data availability and MODIS data. Daily or monthly air temperature means, and daily or monthly precipitation totals were used to study seasonal climate heterogeneity.

2.3. Eddy covariance data

Time-series data were collected from 1 January 2003 to 31 December 2004, which included carbon dioxide and water vapour eddy covariance fluxes, and corresponding meteorological data, i.e. air and soil temperature and photosynthetically active radiation (PAR). All data were downloaded from the CarboEurope IP Ecosystem Component Database (http://gaia.agraria.unitus.it/database/) in text-based data base form. The data are described as ‘level 3 data’ by the CarboEurope organization, which indicates that erroneous data have been removed, and data have been corrected using CarboEurope network standard procedures (Papale et al. 2006).

2.3.1. Gross primary productivity estimates

Gross primary production (GPP) was estimated from eddy covariance carbon dioxide (CO_2) flux. CO_2 flux gross estimates require application of the sum of the Net Ecosystem Exchange (NEE), measured by the flux tower, and contributions from ecosystem respiration (R_{eco}), comprising autotrophic (e.g. roots, plants) and heterotrophic (e.g. microbes, fungi, bacteria) carbon losses (Lloyd and Taylor 1994), as follows:

$$\mathrm{GPP} = \mathrm{NEE} + R_{\mathrm{eco}}. \tag{2}$$

Night-time CO_2 flux values were excluded from further analyses if the PAR was above 5 μmol m^{-2} $s^{-1,}$ and the friction velocity ($u*$) was below a 0.3 m s^{-1} threshold; under these conditions, it is likely the eddy covariance assumptions of spatial homogeneity and stationarity are violated. Night-time one half-hour CO_2 fluxes were plotted against air temperature (Goulden et al. 1997), and in the following step, daytime ecosystem respiration was estimated using the following exponential equation:

$$R_{\mathrm{eco}} = R_0 \mathrm{e}^{\left(bT^{\exp -\frac{1}{2}\left(\frac{\theta-\theta_0}{c}\right)^2} \right)}, \tag{3}$$

where T represents air temperature, b and c are empirical factors, the parameter R_0 corresponds to respiration at a temperature of 0°C, θ is the volumetric soil moisture content, and θ_0 describes the soil moisture where effects are minimal.

Daily one half-hour GPP was subsequently calculated, according to Equation (2), as the algebraic sum of NEE and R_{eco} for each piece of day-time one half-hour flux data from January 2003 until December 2004. GPP and PAR one half-hour values were averaged for each day.

2.3.2. *Gross LUE estimates*

One half-hour canopy LUE values were calculated using values of mean GPP ($\overline{\mathrm{GPP}}$), estimated from CO_2 flux measurements, as follows:

$$\mathrm{LUE} = \frac{\overline{\mathrm{GPP}}}{\overline{\mathrm{APAR}}}, \tag{4}$$

where $\overline{\mathrm{APAR}}$ is the one half-hour mean absorbed PAR incident upon the canopy. A daily LUE value was calculated by averaging the values of LUE for each 30 min period between 00:30 and 24:00 (local time). In addition, means were calculated by averaging the LUE value around solar noon, during the MODIS overpass time, where solar noon was defined as the period between 11:00 and 12:00 (local time).

2.4. *MODIS data*

The MODIS absorbed PAR (fPAR), LAI, and normalized difference vegetation index (NDVI) data fractions, generated with the Collection 5 algorithm, were downloaded directly from the MODIS ASCII DAAC website, http://daac.ornl.gov/cgi-bin/MODIS/GR_col5_1/mod_viz.html. The fPAR and LAI products are provided daily, and have 1 km spatial and 8-day temporal resolutions; NDVI data have 250 m spatial and 16-day temporal resolutions.

Scenes chosen for PRI and NDVI analyses were selected to represent the period when the canopy was fully developed, between days 152 and 244 (June 1 to August 31). For PRI and NDVI calculations, scenes were downloaded from http://ladsweb.nascom.nasa.gov/. MOD021 Km contains the at-aperture, calibrated radiances for the 36 MODIS spectral bands at a 1 km spatial resolution. The cloud mask product (Terra MODIS Level-2 atmosphere product – MOD35_L2) was applied to minimize cloud cover effects on NDVI calculations and to determine sensor and solar zenith angles required for PRI calculations.

The vegetation indices were calculated using Interactive Data Language, 6.2/ENVI, 4.2 software (Concorezzo, Italy). Before calculating the PRI and NDVI, it was necessary to run the geolocation routine for the MODIS scenes. For each selected scene, the 1 km pixel dimension closest to the flux tower was identified using the latitude and longitude from the flux tower coordinates.

The PRI was calculated using MODIS band 11 (centred at 531 nm) to detect the xanthophyll cycle signal. MODIS lacks a narrow band at 570 nm, therefore different potential reference bands were tested, including bands 12 (centred at 551 nm) and 13 (centred at 667 nm) (Drolet et al. 2005). Sunny sky conditions were selected using the PAR value observed from the flux tower. We did not use cloud mask information to calculate sPRI because by using bands 11, 12, and 13 the atmospheric effects were similar

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due to these bands being located close together in the visible spectrum. Moreover, atmospheric transmissivity in this part of the spectrum is very high and stable, and therefore atmospheric corrections would have very small effects (Vermote, Saleous, and Justice 2002). Atmospheric correction was not applied, consistent with other studies (Garbulsky, Peñuelas, Ourcival, et al. 2008), which found that for close wavelengths atmospheric correction was not necessary. Scenes with PAR exceeding 800 µmol m^{-2} s^{-1} were selected to identify only days with sunny sky conditions. A visual inspection was also conducted. All acquisitions collected with a view zenith angle greater than 40° at the image centre were rejected to reduce potential noise associated with spatial integration of the radiance signal over large areas. In total, 71 scenes for 2003 and 74 images for 2004 were used.

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2.4.1. *MODIS PRI and NDVI calculations*

The PRI and the NDVI were calculated from the MODIS scenes as follows:

$$\mathrm{PRI} = \frac{\rho_{531} - \rho_{\mathrm{ref}}}{\rho_{531} + \rho_{\mathrm{ref}}}, \tag{5}$$

$$\mathrm{NDVI} = \frac{\rho_{857} - \rho_{647}}{\rho_{857} + \rho_{647}}, \tag{6}$$

where ρ is the reflectance at a given wavelength (in nm) indicated by the suffix, with 'ref' indicating the reference wavelength. We tested MODIS bands 12 (546–556 nm) and 13 (662–672 nm) as potential reference bands.

The PRI was scaled using the following mathematical transformation to ensure that all values were positive (Drolet et al. 2005; Goerner, Reichstein, and Rambal 2009):

$$\mathrm{sPRI} = \frac{\mathrm{PRI} + 1}{2}. \tag{7}$$

The data set was partitioned into backscattering and forward scattering scenes (Drolet et al. 2005). It was necessary to define relative azimuth angles (RAAs) and relative zenith angles (RZAs) to define backscattering and forward scattering. RAA is the difference between sensor and solar azimuth, and RZA the difference between sensor and solar zenith. Backscattering reflectance scenes were characterized as those with RAAs less than or equal to 60° and RZAs less than or equal to 10°. Forward scatter pixels were those showing RAAs greater than 60° and RZAs less than or equal to 10°.

3. Results

The effectiveness of the sPRI derived from MODIS data was explored over a deciduous canopy on a Mediterranean site supporting Turkey oak (*Q. cerris* L.) forest over the course of two years, 2003 and 2004. The multitemporal NDVI and PRI series for the 2003 and 2004 green period were also investigated.

3.1. Meteorological conditions

The Roccarespampani site exhibited typical Mediterranean climate conditions in the dry and wet years, including an extended summer drought from early June until early October 2003. The minimal precipitation during 2003 indicated a drought year (Figure 1).

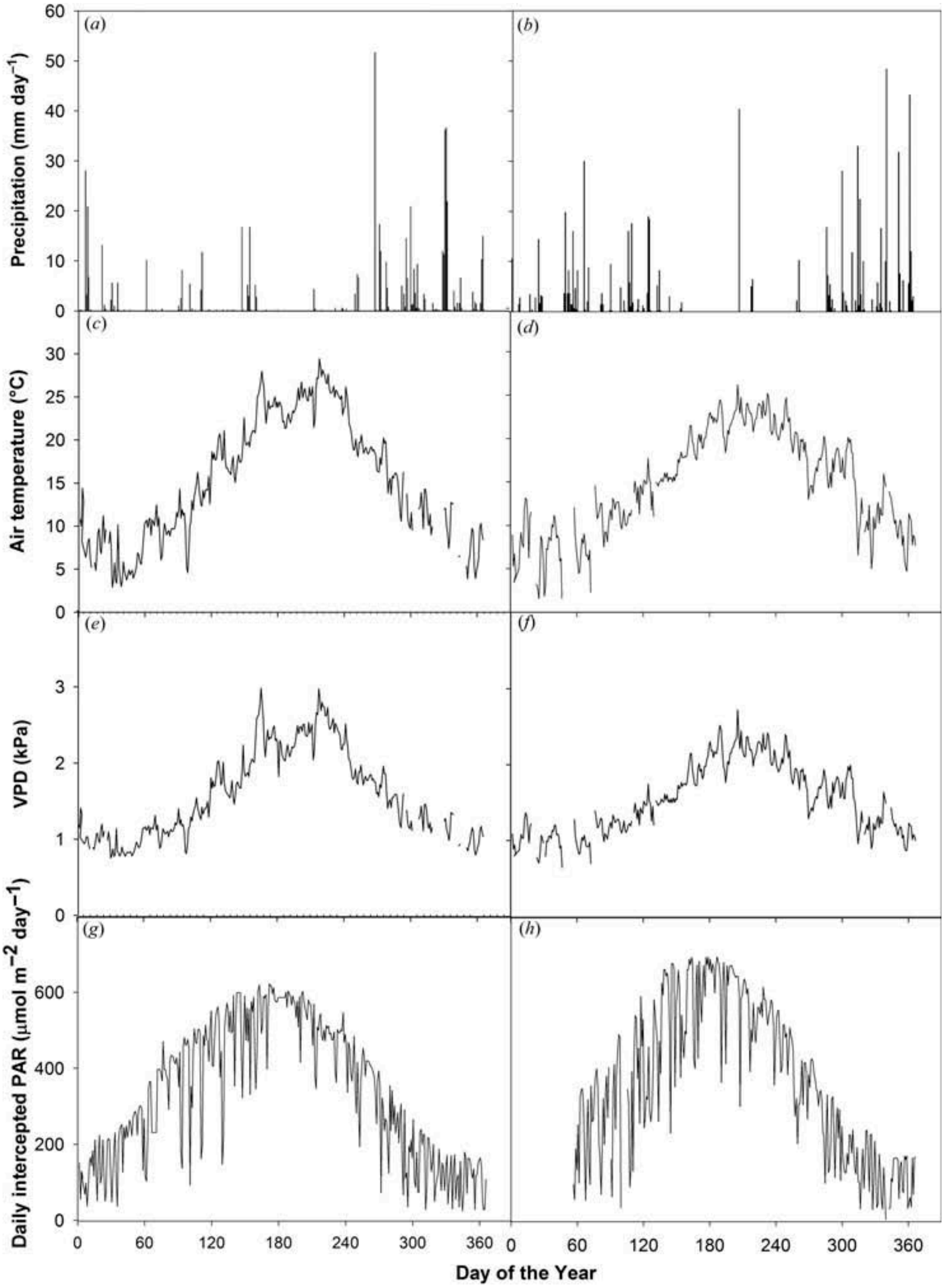

Figure 1. Daily rainfall sums for 2003 (*a*) and 2004 (*b*); daily air temperature means for 2003 (*c*) and 2004 (*d*); vapour pressure deficit (VPD) for 2003 (*e*) and 2004 (*f*); and intercepted photosynthetic active radiation (PAR) for 2003 (*g*) and 2004 (*h*).

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Table 1. Monthly rainfall (in mm) during 2003 and 2004.

Month	2003	2004
January	71.20	43.60
February	3.60	62.80
March	5.20	56.40
April	29.80	63.00
May	12.80	58.60
June	3.20	2.40
July	0.80	40.40
August	4.92	11.40
September	8.88	12.60
October	109.00	71.60
November	133.00	96.00
December	65.80	189.80

The precipitation levels were very low during the summer 2003, and higher than average precipitation levels occurred during the summer of 2004 (Figure 1). Rainfall was unusually low from June to the end of August 2003: measurements showed a low of 8.92 mm (the rainfall sum from June to August 2003) and a maximum of 54.20 mm recorded during the same months in 2004 (Table 1). Thus for this study, 2003 was considered the dry year and 2004 the wet year.

3.2. GPP and LUE

A marked seasonality in GPP was observed at midday, especially in 2003. As expected, the high productivity (GPP) followed oak tree bud-break in early May; a notable drop in GPP and LUE is notable in 2003, and the decrease began in July. Interestingly, GPP peaked higher in 2003, with the exception that no notable decrease occurred in July, August, and September 2004, which shows the impact of drought. A similar pattern was exhibited in the LUE values (Figure 2(*a*)). Midday GPP ranged from 0.3 g C m^{-2} day^{-1} (grammes of carbon per square metre per day) in the month with the lowest productivity (January), to 36 g C m^{-2} day^{-1}, in the month with the highest productivity (May) in 2003; and from 0.3 to 31 g C m^{-2} day^{-1} in 2004.

LUE ranged from 0.02 to 1.99 g C m^{-2} day^{-1} for 2003, and 0.03 to 1.72 g C m^{-2} day^{-1} for 2004, with minimum values in summer and maximum values in spring. In particular, LUE exhibited a decline until the beginning of August, when another increase was observed. Another peak occurred in late October followed by another decrease that ended in December; then values remained low until early May, when LUE began to increase again. The GPP and LUE patterns were consistent with each other (Figure 2(*b*)).

3.3. LAI and fPAR

LAI and fPAR data obtained from the standard 8-day MODIS LAI/fPAR product exhibited geographically and ecologically meaningful patterns, which were consistent with known phenological behaviour in the Mediterranean area. fPAR

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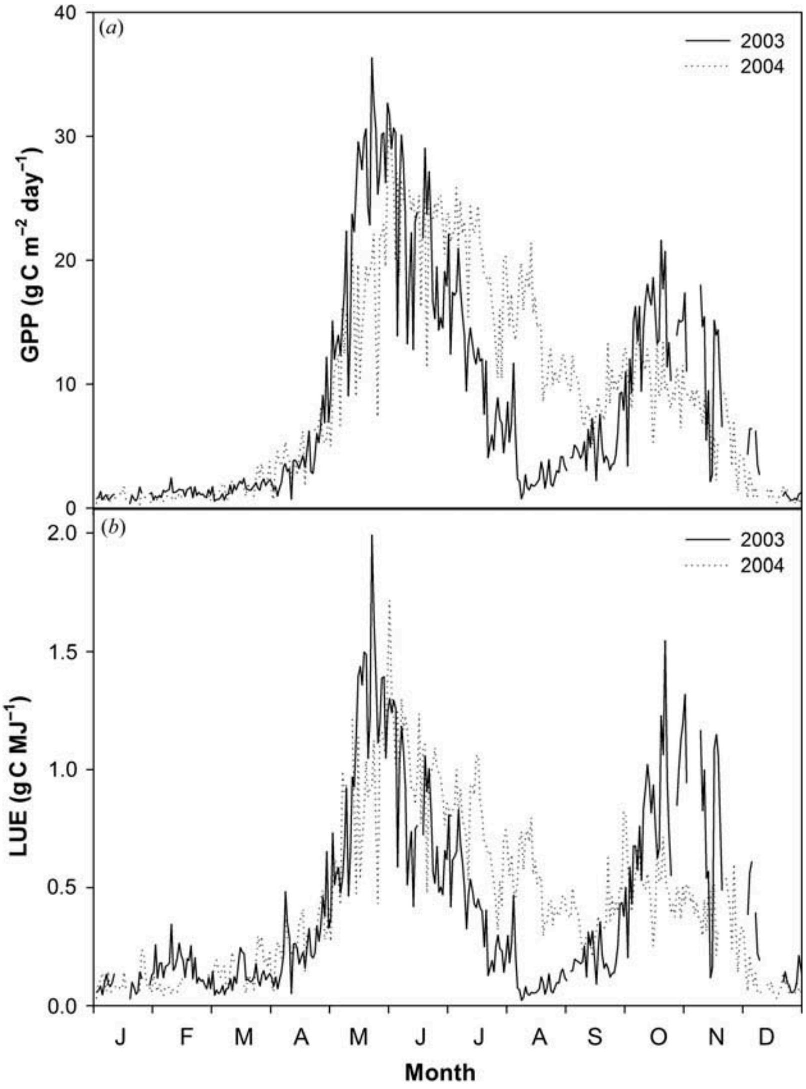

Figure 2. Daily gross primary production (GPP) (*a*) and daily light-use efficiency (LUE) (*b*) estimated from eddy covariance data during 2003 and 2004. Data were calculated by averaging every one half-hour GPP measurements from 11:00 to 15:00.

showed seasonal variations congruent with those of the LAI, characterized by green up onset at the beginning of spring, and approximate uniformity during the green period (May–September). Dormancy onset was observed in late November.

3.4. Seasonal variation in vegetation indices

The NDVI (Figures 3(*a*) and (*b*)) exhibited higher values with the onset of vegetation growth activity. NDVI was quite stable throughout the growing season, with minor

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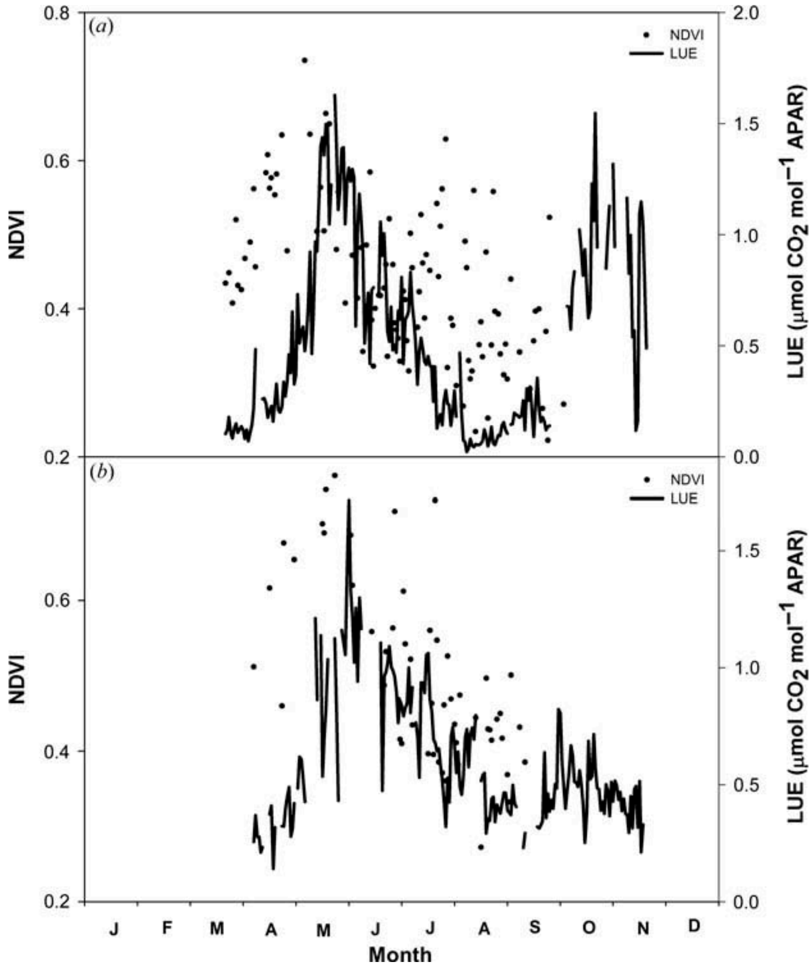

Figure 3. Normalized difference vegetation index (NDVI) seasonal dynamics calculated using MODIS data (solid circles); LUE (broken line). Graphs are for 2003 (*a*) and 2004 (*b*).

day-to-day variability (Sims and Gamon 2003), which can change based on vegetation water content (Peñuelas et al. 1997).

In contrast to the nearly constant NDVI values, the sPRI exhibited a seasonal pattern. During the 2004 wetter year (Figures 4(*c*) and (*d*)), the sPRI mirrored the annual LUE changes, showing a strong summer decline corresponding to the maximum annual temperatures and reaching the lowest values at the beginning of the autumn period. In the drier year (Figures 4(*a*) and (*b*)), the sPRI was stable during the plant-growing season.

3.5. Relationship between NDVI and sPRI with LUE

Although the NDVI and sPRI showed a positive relationship with LUE, there was considerable scatter in the NDVI relationship with the LUE, showing very weak correlations (Table 2).

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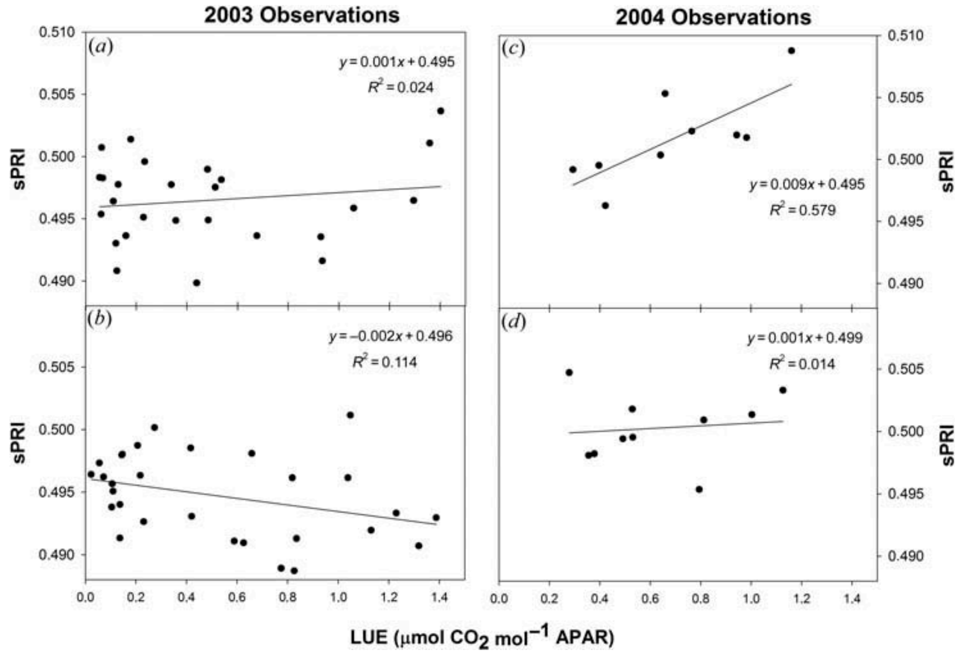

Figure 4. Relationship between sPRI derived from MODIS reflectance data, using band 11 (531 nm) and band 12 (551 nm) as reference bands, and LUE derived from eddy covariance data. Backscatter and forward scattering data were respectively applied for 2003 (*a* and *b*) and 2004 (*c* and *d*).

Table 2. Coefficient of correlation for the relationship between vegetation indices and LUE.

Year	NDVI and LUE	sPRI and LUE (forward data)	sPRI and LUE (backscattering data)
2003	0.004	0.11	0.02
2004	0.18	0.01	0.58

Significant correlations were not detected between sPRI and LUE when data from all MODIS scenes (from March to November) were used (Figure 5), therefore the data set was partitioned into backscattering and forward scattering scenes (Drolet et al. 2005). The use of band 13 as a reference band produced a poor correlation. In addition, sPRI data were analysed separately for both 2003 and 2004 − by plotting sPRI data *versus* LUE data (results not shown) − and a low correlation was observed. Different results were observed with band 12 as the reference band; a relationship with LUE throughout the 2003 growing season was not detected, when either a backscattering or forward scatter scene was used (coefficient of determination, R^2 = 0.02 and 0.11, respectively) (Table 2). However, it is important to note that a weak relationship between sPRI and LUE was found when forward scattering data from 2004 were used. An improvement in the regression was indicated when backscattering data from the wet year of 2004 were used: R^2 was then equal to 0.58 for the relationship between sPRI and LUE (Figure 4(*c*)).

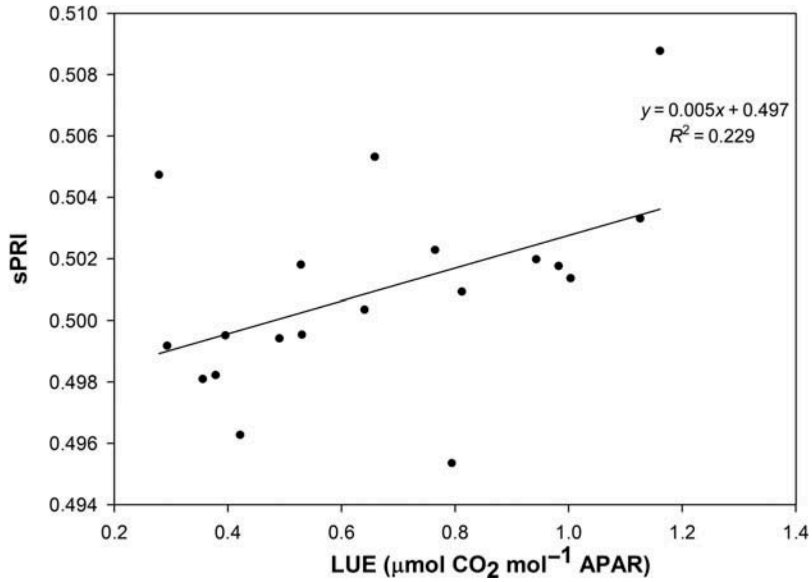

Figure 5. Relationship between sPRI derived from MODIS reflectance data, using all data from band 11 (531 nm) and band 12 (551 nm) as reference bands, and LUE derived from eddy covariance data for 2004.

4. Discussion

The present study demonstrated seasonal variability in LUE, and a limited capacity for MODIS PRI to track seasonal changes under water-limited conditions, i.e. drought. MODIS is a sensor that facilitates near-global daily Earth observations in a wide spectral range (0.14−15 μm) and high geolocation accuracy. Another MODIS advantage is that it has a spectral band centred at 531 nm, which allows PRI calculations. The primary MODIS disadvantage is the absence of a 570 nm spectral band. Therefore, another reference band must be considered for PRI calculations as the sensor was not designed to monitor vegetation.

Previous studies have demonstrated the efficacy of other sensors to detect PRI and xanthophyll cycle activity, such as the Compact High Resolution Imaging Spectrometer/Project for On-Board Autonomy (CHRIS/PROBA) (Hilker et al. 2010, 2011). However, although multiangular data acquisitions are obtained by CHRIS/PROBA, the principal disadvantages of its angular sampling strategy include time to build a multiangle data set (days), and the comparatively coarse sensor spatial resolution, and overpass infrequency (Quaife et al. 2001).

Generally, at the leaf and small plot scale, former studies report PRI was a viable LUE indicator (Peñuelas, Filella, and Gamon 1995; Gamon et al. 1995; Gamon and Qiu 1999). In the current study, we did not use the 570 nm band as a reference due to its absence in MODIS. Thus, we tested other reference bands. The best correlation between MODIS sPRI and flux-tower LUE was found when using MODIS ocean bands. Band 12 (centred at 551 nm) as reference yielded a good correlation between sPRI and LUE for all the clear days considered.

The work presented here explored two contrasting years: 2003 and 2004. Ciais et al. (2005) reported 2003 as particularly extreme climatically, and summer temperatures in Europe rose to levels well in excess of normal summer averages. Across much of

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Central Europe, monthly mean June–August temperatures exceeded the long-term average by more than 6°C and annual precipitation was 50% below average (Ciais et al. 2005).

A comparison of GPP and LUE patterns for the study period showed lower values for both parameters in July and August 2003. In summer 2003, water deficits caused (i) apparent stomatal closure and leaf senescence; (ii) high values of R_{eco}, due to increased temperatures; and (iii) a generalized GPP decrease relative to 2004. NDVI is expected to track similar seasonal events that represent general phenological forest attributes (Kramer, Leinonen, and Loustau 2000; Loustau et al. 1991). Overall, the temporal dynamics during the plant-growing season (May–September) detected by NDVI were closely associated with observed GPP and LUE dynamics, and showed sensitivity to the phenological changes in the canopy. We found a very weak relationship between NDVI and LUE, which was also observed in previous studies (Sims et al. 2006; Goerner, Reichstein, and Rambal 2009). These results were likely due to the high sensitivity of NDVI to solar elevation angle effects and lack of sensitivity to a changing canopy physiology for a constant canopy structure (Goerner, Reichstein, and Rambal 2009). Furthermore, the NDVI values exhibited considerable scatter, probably due to variability in chlorophyll content and/or the influence of other canopy characteristics.

We also tested the potential of two different spectral bands as references: bands 12 and 13, with the band at 531 nm. We concluded from our analysis that the sPRI calculated using band 12 provided a better correlation with LUE than the sPRI calculated with band 13, consistent with the results of Drolet et al. (2005).

During 2004 (the wetter year), the relationship between sPRI and LUE was best ($R^2 = 0.58$) for backscattered angles (Figure 4(*c*)), indicating a sPRI response to changing LUE. The different PRI response compared to NDVI could be due to the extreme environmental conditions, primarily temperature and relative humidity, and increasing photon exposure over the course of the summer, resulting in increased environmental stress.

5. Conclusion

We determined values of NEE, ecosystem respiration (R_{eco}), GPP, and LUE at a canopy scale from a Mediterranean oak forest site over two years that exhibited contrasting climatic conditions. In addition, we estimated the possibility of using sPRI calculated from MODIS data to detect LUE changes. Consistent with the annual cycles, LUE and GPP showed seasonal and interannual variability, indicating dependence on environmental factors, including leaf biomass, photon irradiance, air temperature, and related foliar pigment content per area. However, regression analysis showed that sPRI and LUE were poorly related during the 2003 drought year, presumably because the sensor might not have been able to capture the vegetation signal because of changes in canopy properties caused by drought.

Overall, our results confirm that any generalization of PRI application at an ecosystem and biospheric scale is problematic (Grace et al. 2007) and suggest sPRI has a limited capacity to track seasonal LUE changes. This result was previously observed in boreal forests (Nichol et al. 2000, 2002; Drolet et al. 2005) and has now also been demonstrated for a Mediterranean deciduous forest.

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