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Fluorescence, PRI and canopy temperature for water stress detection in cereal crops

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ABSTRACT

Narrow-band multispectral remote sensing techniques and thermal imagery were investigated for water stress detection in cereal crops. Visible and near infrared AISA Eagle (Specim, Finland) and thermal AHS-160 (Sensytech Inc., USA) imageries were acquired with an airborne survey on a farm-level experimental site where maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.) were grown with three different irrigation treatments. Vegetation biophysical and eco-physiological measurements were collected concurrently with the airborne campaign. Leaf fluorescence yield ($\Delta F/F_m{}'$) resulted to be a good indirect measure of water stress. Therefore, $\Delta F/F_m{}'$ measurements were compared against remotely sensed indicators: (i) the Photochemical Reflectance Index (PRI), (ii) the sun-induced chlorophyll fluorescence at 760 nm (F_{760}), retrieved by the Fraunhofer line depth method and (iii) the canopy temperature (T_C) calculated decoupling soil and vegetation contributions. T_C was related to $\Delta F/F_m{}'$ with the highest determination coefficient ($R^2 = 0.65$), followed by PRI_{586} (reference band at 586 nm) ($R^2 = 0.51$). The relationship with F_{760} was significant but weaker ($R^2 = 0.36$). The coefficient of determination increased up to 0.54 when pigment concentration was considered by multiplying $\Delta F/F_m{}'$ and chlorophyll content, confirming the close relationship between passive fluorescence signal, pigment content and light photosystem efficiency. PRI_{586}, F_{760} and T_C maps were produced in maize and sorghum plots. The differences in the average values of PRI_{586}, F_{760} and T_C extracted from the plots with different water treatments showed that water treatments were well discriminated in maize plots by the three remotely sensed indicators. This was confirmed by the visual observation of the PRI_{586}, F_{760} and T_C maps, while in sorghum plots, F_{760} and T_C appeared more sensitive to water stress compared to PRI_{586}.

Introduction

Remote sensing techniques can provide very useful information about the spatial and temporal variability of many important crop characteristics, which are difficult to monitor through traditional field measurements. In particular, narrow-band multispectral remote sensing techniques, based on radiance measurements acquired in a high number of contiguous narrow-bands in the solar domain, are frequently employed for precision farming and vegetation stress detection (Haboudane et al., 2002; Panigada et al., 2010; Whiting et al., 2006). The most promising of these techniques is represented by the passive measurement of sun-induced fluorescence in the O_2-A band (F_{760}), proposed as a direct indicator of photosynthesis (Meroni and Colombo, 2006; Meroni et al., 2008; Rossini et al., 2010; Zarco-Tejada et al., 2013a), and by the Photochemical Reflectance Index (PRI), a normalized difference of reflectance at 531 nm and reflectance at a reference band in the visible domain. The PRI is in fact related to the de-epoxidation cycle of xanthophylls

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and to heat dissipation increasing under water stress conditions. When the light absorbed by the plants exceeds photosynthetic demand, dissipation occurs to avoid light-induced oxidative damage (Gamon et al., 1992). Moreover, differently from traditional optical indices sensing the greenness of vegetation, F_{760} and PRI can detect plant stress from an early stage of water deficit (Perez-Priego et al., 2005; Rossini et al., 2013; Zarco-Tejada et al., 2009), potentially providing an early detection tool in precision farming.

Progresses in the challenging issue of retrieving the fluorescence signal from remote have been reached also thanks to the remote sensing community involved in the preliminary study for the FLuorescence EXplorer (FLEX) mission of the European Space Agency, which proposes to launch a satellite for the global monitoring of steady-state chlorophyll fluorescence in terrestrial ecosystems. Recently, the first global maps of terrestrial fluorescence have been produced using the high spectral resolution interferometer aboard the Japanese Greenhouse gases Observing SATellite (GOSAT) (Frankenberg et al., 2011; Guanter et al., 2012). They have been shown to be related to global maps of photosynthesis but the role of the environmental factors driving their spatial and temporal patterns still deserve further investigations.

The PRI has been tested in vegetation stress detection and a number of studies demonstrated the feasibility of using it to track at leaf and canopy level photosynthesis changes caused by oxidative stress conditions with varying degrees of success (Gerosa et al., 2009; Meroni et al., 2008, 2009; Panigada et al., 2009; Römer et al., 2012). However, only few studies have focused on the use of PRI from remote sensing imagery in the context of precision agriculture for water stress detection to support agricultural management practices (Rossini et al., 2013; Suarez et al., 2008, 2009, 2010; Zarco-Tejada et al., 2012). Gamon et al. (1990, 1992) demonstrated that there are different acceptable combinations of PRI normalization and that the ideal reference waveband can slightly vary between experiments and treatments. Although the most accepted and common PRI formulation uses the waveband at 570 nm as normalization band, Hernandez-Clemente et al. (2011) proposed the formulation with the normalization band at 512 nm as the best performing one to minimize structural and illumination effects.

Beside PRI and fluorescence, remote observations in the thermal domain have also been used for water stress detection in agriculture long since (Fuchs and Tanner, 1966; Jackson et al., 1981) and have been consolidated through years (Ballester et al., 2013; Sepulcre-Canto et al., 2006, 2008; Zia et al., 2013). The relationship between plant water stress and canopy temperature (T_C) is well known, due to the fact that water deficit induces a decrease of leaf stomatal conductance with a consequent reduction of the evapotranspiration rate and an increase of leaf/canopy temperature (Li et al., 2013). Recent studies proved the feasibility of high spatial resolution thermal imagery collected from unmanned aerial vehicles to map canopy stomatal conductance in tree crops (i.e. vineyard and olive trees) (Baluja et al., 2012; Berni et al., 2009a; Fuentes et al., 2012; Zarco-Tejada et al., 2012) through crown targeting. This is hardly achievable in row crops where the soil background is somehow influencing the signal in most of the crop phenological phases unless very high spatial resolution (i.e. 20 cm) is available.

The possibility of exploiting the remotely sensed F_{760}, PRI and T_C to infer the actual photosynthetic performance may be of great interest in agricultural management practices. Recent studies have attempted to include surface temperature in radiative transfer models (van der Tol et al., 2009) or to link, within a soil-vegetation-atmosphere-transfer scheme, temperature and optical indices (French et al., 2005). To our knowledge however, hyperspectral optical indices, fluorescence and thermal imageries have been poorly investigated at field level with remotely sensed data and there is still a strong need to compare their performances. Recently, only Zarco-Tejada et al. (2009, 2012) investigated the possibility to detect water stress in orchards by combining optical indices, fluorescence and temperature.

In Italy, maize is the second most cultivated cereal and it represents almost the 17% of the national production (3.5 million hectares), a percentage that is expected to grow in the next years (USDA, 2012). Maize is mainly cultivated in the North of Italy, particularly in the Po Valley where abundant water allows farmers to irrigate over the summer when rainfall is scarce. Future crop management scenarios are expected to be characterized by an increased attention to ecological sustainability also through a more efficient water management. A more rational and effective use of irrigation is needed also because forecasted climatic changes will lead to an increase in water demand due to more frequent drought events, as already experienced in recent years in the Po Valley area. Drought-effect mitigation strategies are already taking place by using drought resistant cereals (i.e. sorghum) that are integrated to maize cultivation.

In this study we evaluated the feasibility of detecting maize and sorghum water stress by combining hyperspectral and thermal imageries collected from airborne sensors on a farm-level field experiment with different water irrigation treatments imposed. For this purpose an airborne campaign was conducted with an AISA Eagle (Specim, Finland), an AHS-160 (Sensytech Inc., USA) and a CASI (Itres, Canada) hyperspectral sensors. The objective was to investigate the possibility to infer vegetation biophysical parameters and eco-physiological processes describing the plant status by means of PRI and F_{760} computed from AISA Eagle radiance in the optical domain and T_C estimated from AHS-160 radiance in the optical domain. More in detail we aimed to: (i) test different PRI formulations for water stress detection in maize and sorghum by changing the normalization band from 510 nm to 620 nm, (ii) test the performances of F_{760} retrieved by an operational "image-based" algorithm, (iii) derive a map of T_C using an unmixing algorithm to separate the canopy and soil T contributions when crown targeting is not feasible, and (iv) evaluate and compare these remotely sensed indicators for water stress monitoring in cereal row crops.

Materials and methods

Experimental design

The experiment consisted in a split-plot design with four blocks (Fig. 1). In each block three water regimes (rainfed, water deficit imposed between stem elongation and flowering and full irrigation, Irr0, Irr1 and Irr2, respectively) were randomly assigned, while two crop species (maize and sorghum) were assigned to split plots (subplots defined by water regime). Each subplot was divided in two more plots, the first one not fertilized, the second one fertilized with 100 kg N ha^{-1} to enhance the variability of the biophysical parameters.

Plot size was 15 m × 16.5 m with a total study area of about 1.2 ha centered at latitude 44°58′49.00″ N and longitude 9°40′48.50″ E, elevation 87 m a.s.l. Soils were very deep, non calcaric soils, developed on alluvial (gravelly deposits) fans forming the southern part of Po Valley by the Apennine relieves. Surface texture was silty loam (i.e. sand 17%, clay 16.8% and silt 66.2%).

Sowing was carried out on June 3rd 2010, after the harvest of a preceding winter crop of *Lolium multiflorum*. Immediately after sowing three irrigations with a traveling sprinkler were carried out on the whole trial to favor rapid and homogeneous crop establishment. Both maize and sorghum were completely emerged by June 11th. The field campaign was held 46 days after sowing between July 19th and 22nd 2010 (Day Of the Year: DOY 200 and 203, respectively) when plants were in their pre-flowering stem elongation stage (Lancashire et al., 1991) with an average of 10 leaves emerged.