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Satellite-based irrigation advisory services: A common tool for different experiences from Europe to Australia

Francesco Vuolo[a], Guido D'Urso[b,c,*], Carlo De Michele[c], Biagio Bianchi[d], Michael Cutting[e]

[a] University of Natural Resources and Life Sciences (BOKU), P. Jordan Str.82, Vienna, Austria
[b] Department of Agriculture, University of Naples Federico II, Via Università 100 Portici (NA), Italy
[c] Ariespace s.r.l., Spin-off company of the University of Naples Federico II, Centro Direz. Is.A/3, Naples, Italy
[d] Dept. Agriculture and Environm. Sci., University of Bari Aldo Moro, Via Orabona 4, Bari, Italy
[e] South Australian Murray-Darling Basin Natural Resources Management Board, Strathalbyn, South Australia

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A B S T R A C T

Earth Observation techniques are widely recognised in supporting the management of land and water resources and they are nowadays being transferred to operative applications. In this paper, we present the current status of a satellite-based irrigation advisory system based on dedicated webGIS or farmers and district managers, in three different agricultural systems and environments: Southern Italy, Austria and Southern Australia. Maps of canopy development (leaf area index, albedo and soil cover) are derived from high-resolution (20 m) multispectral satellite images, delivered in near real time (24–36 h) and processed by using in-situ agro-meteorological data. The outputs of this procedure are: (i) a personalised irrigation advice, based on the calculation of crop evapotranspiration under standard conditions (according to FAO-56 definition and by using the direct approach) by taking into account the actual canopy development and crop variability at sub-plot scale; (ii) timely delivery of the information, consisting in maps and suggested irrigation volume applications, timely published on a dedicated webGIS-site with access restricted to growers and basin authorities in order to better control the irrigation process and consequently improve its overall efficiency. The key-points of this procedure are: (a) personalised irrigation advice; (b) timely delivery of the information. Final users have provided important feedback on the usage of the information provided; i.e. farmers are able to recognise without difficulties their parcels on the images and they schedule the irrigations by taking into account the information provided. The crop heterogeneity captured by the high resolution images is considered as a valuable add-on information to identify the variability of soil texture and fertility, plant nutrition, or different performance of irrigation systems. All the farmers have evaluated positively the usefulness of the information provided, and in most cases an increase of irrigation efficiency was achieved, because of the reduction of water volumes.

1. Introduction

Earth Observation (EO) data and geo-spatial tools are more and more frequently used to support various agricultural practices. The first feasibility studies, description of methodologies and prototypes for precise crop management date back to the early 1980s. A review can be found in Moran et al. (1997). In the study, the authors analysed different aspects of information requirements and identified various areas of application (e.g. soil mapping, yield estimation, crop evapotranspiration, phenology, etc.) to which satellite-based remote sensing could contribute. They also highlighted the technical limitations of sensing instruments and provided recommendations for the integration of these technologies in crop management practices. In recent years, continuous advancements in space technologies brought new observing capabilities in terms of spectral, spatial and temporal resolutions and most of the critical issues described in Moran et al. (1997) are now overcome. Recent changes in pricing policy also allowed a cost-effective use of high spatial resolution imagery (10–30-m pixel size). For instance, free-of-charge access to Landsat 8 data (by U.S. Geological Survey – USGS – & NASA) is now available within less than 24 h of acquisition. The availability of free and open access data for scientific and commercial use is expected to

* Corresponding author at: Department of Agriculture, University of Naples Federico II, Via Università 100, Portici (NA), Italy. Tel.: +39 3472310830..
E-mail addresses: durso@unina.it, guido.durso@unina.it (G. D'Urso).

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further improve with the launch (scheduled for 2014) of Sentinel 2 missions, developed by European Space Agency (ESA) within the Copernicus initiative (former Global Monitoring for Environment and Security – GMES – programme). This initiative has also stimulated the development of various operational services and technical capacities at European level (NEREUS, 2012).

Thanks to these progresses, the use of remotely sensed data has become more common and will be further integrated in agriculture services to support management, monitoring and controlling activities at different spatial scales including precision farming (Lee et al., 2010). For instance, maps of biophysical parameters of vegetation are used in yield prediction models at administrative level (Doraiswamy et al., 2005; Ma et al., 2011; Rembold et al., 2013). Other examples are implemented at country or regional level to derive crop water needs from satellite estimates of biophysical parameters assimilated in agro-meteorological models (D'Urso et al., 2010), to monitor the nitrogen status and to apply fertilizer with variable rates (e.g., FarmSat) or to derive agronomical variables (Casa et al., 2012; Jégo et al., 2012). On the other hand, surface energy balance methods based on satellite observations in the thermal region (Bastiaanssen et al., 1998; Allen et al., 2007; Kustas and Anderson, 2009) have been developed and applied in many areas with the aim of determining actual evapotranspiration. These methods have shown their potentiality in assessing the water balance of irrigated areas and the corresponding water accounting practices (Allen et al., 2005; Anderson et al., 2007; Karimi et al., 2013) but their use for irrigation advisory services is constrained by the limited spatial and temporal resolution of E.O.-based thermal observations and by the complexity of algorithms for near real-time operational procedures (Osann Jochum et al., 2005). Reviews of different procedures to determine crop evapotranspiration and water requirements from remote sensing can be found in Courault et al. (2005) and Verstraeten et al. (2008).

Diversely, a temporal resolution of about 7–10 days between satellite observations is usually considered adequate to monitor the various phases of the crop development throughout the growing season. This temporal resolution can nowadays be assured by using different platforms or constellation of platforms carrying visible (VIS) and near infrared (NIR) sensing cameras.

The objective of this study is to present an advanced and fully operational irrigation advisory service based on the utilisation of VIS–NIR satellite observations for crop water management at field and irrigation scheme levels; the service has been implemented in three different countries, by using a similar webGIS platform but different names:

- **IRRISAT** (www.irrisat.it), a regional operational service supported by rural development funds in Southern Italy.
- **EO4Water** (www.eo4water.com), a case study of knowledge and technology transfer in Lower Austria funded by the Austrian Space Application Programme.
- **IRRIEYE** in Southern-Australia (www.irrieye.com), co-funded by South Australian Murray-Darling Basin Natural Resources Management Board.

The first concept of satellite-based irrigation advisory services was designed in the context of the DEMETER UE-RTD project in 2005 (D'Urso and Calera Belmonte, 2005). It was successively improved and automatised to meet the requirements of individual farmers with personalised weekly irrigation advices at field scale and regional level by using SMS (Vuolo et al., 2005; De Michele et al., 2009). The development of advisory services based on webGIS platforms has been initially developed within the PLEIADeS UE-project (www.pleiades.es) and further tested in SIRIUS (www.sirius-gmes.es). More recently, a similar application has been developed in California by NASA, within the TOPS Satellite Irrigation Management Support project (ecocast.arc.nasa.gov/simsi/).

Generally, the service concept is based on two main components: (a) the processing of time-series of high spatial resolution (10–30-m pixel size) images from satellite, currently available from public and commercial data providers, to timely monitor the crop growth; (b) the estimation of the crop water requirement by taking into account the actual canopy development throughout the growing season; (c) the adaptation and integration in local management practices & tools of easy to use geo-spatial technologies to make the information available to users and to support the decision-making process.

In this paper we give a detailed description of methodological approaches and processing chain, with results from the three applications in Europe and Australia.

2. Users' requirements in satellite-based irrigation advisory services

Irrigation advisory services are addressed to three different user segments:

- Farmers, small and large scale agri-businesses.
- Water managers at irrigation scheme or catchment level.
- Authorities in charge of water management (such as river basin authority, government), National Irrigation Plan Monitoring Office.

Maps of crop water requirements, irrigated areas, crop vigour and other products of the satellite image processing, can be aggregated over different temporal scales (weekly, monthly, etc.) and land management units (field, farm, district, etc.) to meet the requirements of different users.

The technological *implementation* of satellite-based irrigation advisory services needs to find a compromise between the following elements:

i. availability of ancillary input data, with no or minimal contribution from end-users;
ii. elaboration and processing time, with minimum possible time lag between E.O. acquisition date and information delivery to final users;
iii. accuracy of algorithms for deriving crop water requirements, with minimum possible parameterisation.

For example, it is difficult to provide an irrigation advisory service based on a daily soil water balance, which needs as input soil hydraulic characteristics and actual irrigation scheduling. If soil maps may be found at different level of detail and accuracy, actual irrigation volume and dates are very seldom available, unless automatic metering devices are installed or a continuous direct input is demanded to farmers for each individual plot.

The second requirement for near-real time processing of E.O. data generally conflicts with the generation of crop maps, which can be elaborated with some confidence only at the end of the irrigation season.

On the basis of these considerations, the irrigation advice provided by IRRISAT/EO4WATER/IRRIEYE described in this work is meant to limit excess water application, in order to achieve a better utilisation of water resources and cost savings (irrigation fees, equipment runtime, energy required for pumping and fertilizer consumption). The irrigation advisory service is delivered weekly and it is only concerning the suggested amount in the considered period, as defined later in Section 3, and not the scheduling, which is left to farmer's decision.

Table 1
EO-based irrigation advisory services: products delivered to final users.

Product characteristics	List of maps or text information	How products support the user needs
Static (updated once per growing season)	• Basic GIS layers (irrigation unit boundaries) (**vector layer**) • Irrigated areas and crop inventory (**maps and/or vector layer, before the end of the season**)	1. Support to visualisation, analysis and data interpretation 2. Control on irrigated areas
Dynamic (Updated with each new satellite acquisition or weekly)	• Colour composites (**maps**) • Leaf area index (LAI) (**maps**) • Crop coefficient (K_c) (**maps and graphical**) • Crop water requirements (**maps and graphical**) • Daily agro-meteorological data (**text and graphical**)	1. Basic agricultural and water planning. 2. Reduction of over-irrigation. 3. Monitoring of crop vigour
Cumulated over time of dynamic data (time interval is flexible)	• Total crop water consumption (e.g. decade or yearly for irrigation scheme) • Statistics and time-series data, graphical information per plot or aggregated to district level based on the irrigation or management unit boundaries (**text and graphical**)	1. Monitoring and control of exploitation plans. 2. Calculate seasonal crop specific crop water use.

In our experience, also based on agricultural mechanics applications, most farmers are not only interested in knowing the irrigation volumes but also the spatial and temporal distribution of some crop characteristics (i.e. crop vigour) over the growing season for each one of their fields; the information on canopy development, which is the result of all agronomic practices, can also be used for a better management of all crop inputs.

From the water managers perspective, this information has to be aggregated at the irrigation scheme level in order to reduce operation and maintenance (O&M) costs, depreciation of infrastructures and administration costs. At irrigation district and catchment scale, the knowledge of the spatial distribution of crop water requirements enables the water manager to better allocate the intra-scheme water distribution and to monitor and control the water exploitation plans. As a control tool, maps of the irrigated areas, derived from the analysis of time-series of EO data, can support the detection of non-authorised water abstractions. In Table 1 the standard set of products deployed to support the user needs are summarised.

However, the technological *adoption* of space-based solutions for crop/irrigation water management is a complex process. Favourable conditions depend on several technical, social and economic aspects (Baptista and Sousa, 2005). Among several factors, the connection with the users and the embedding of new technologies into standard practices remains the most critical issue. Especially in technology transfer projects, the local current practices and systems have to be considered for adapting the implementation of the innovation accordingly.

3. Methodological background for the estimation of crop water requirements in satellite-based irrigation advisory services

The standard approach proposed by Food and Agricultural Organization (FAO) (Allen et al., 1998) for calculating crop water requirements (CWR) can be adapted to remote sensing data. Crop water requirements (CWR) are commonly calculated as follows:

$$CWR = \left(ET_{crop} - P_n\right) \quad (1)$$

where ET_{crop} (mm) is the crop evapotranspiration under standard conditions i.e. crops grown in large fields under excellent agronomic and soil water conditions, (Allen et al., 1998); P_n, is effective precipitation depending on canopy development described by means of the Leaf Area Index *LAI*, and the fractional vegetation cover f_c, accordingly to Braden (1985):

$$P_n = P - a\mathrm{LAI}\left(1 - \frac{1}{a + \frac{fcp}{\mathrm{ALAI}}}\right) \quad (2)$$

where P is the precipitation above the canopy, a is an empirical parameter representing the crop saturation per unit foliage area ($\approx$2.8 mm d^{-1} for most crops). The calculation is done with reference to a given time interval, compatible with the temporal resolution of meteorological data.

In most operative scenarios, the reference evapotranspiration ET_0 (mm, on hourly or daily basis) is determined by using the FAO-56 and ASCE standard equations (Task Committee on Standardization of Reference Evapotranspiration, 2005). If weather data are not available, ET_0 can be derived from geostationary satellite data according to De Bruin et al. (2010). An operational product is distributed by Satellite Application Facility on Land Surface Analysis (LANDSAF: landsaf.meteo.pt/). Successively, ET_{crop} is derived by multiplying ET_0 with the crop coefficient value K_c, commonly attributed from a field evaluation of the crop development and phenological stage by using the tables proposed by the original authors and also reported in the FAO-56 procedure. The crop coefficient K_c is a proxy of the parameters describing the canopy development, i.e. LAI, surface albedo and crop height. The same canopy parameters entering the direct calculation of ET_{crop} are also influencing to a great extent the spectral response of a cropped surface, i.e. the way it appears from a remote sensor in the visible and infrared wavelengths.

Reflectance-based K_c values, incorporating the effects of soil type, crop, plant growth and crop management (Wiegand and Richardson, 1984), can be determined on a pixel-by-pixel basis by using satellite observations in the visible and near-infrared spectral domains to compute vegetation indexes values (Neale et al., 1989; Glenn et al., 2011). This approach has been applied also to canopies not covering uniformly the soil surface, such as vineyards, to determine the value of the basal crop coefficient (Campos et al., 2010). However, with the exception of limited experiments carried out by using micrometeorological techniques or lysimeter measurements, the attribution of crop coefficients (and consequently the correlation with observed reflectance values) is largely based on subjective field observations, with limited possibilities of validation based on measurements of canopy parameters.

An alternative approach was developed by D'Urso and Menenti (1995), for the direct calculation of ET_{crop}, based on

Penman–Monteith (P–M) equation as implemented in the FAO-56 procedure (*one-step approach*), herein indicated with "P-M FAO":

$$\mathrm{ET_{crop}} = \frac{86,400}{\lambda}\left[\frac{\Delta(R_n - G) + \rho c_p (e_s - e_a) C_a}{\Delta + \gamma\left(1 + C_a/C_s\right)}\right] \quad (3)$$

where $\mathrm{ET_{crop}}$ is expressed in mm d^{-1} and:λ is the latent heat of vaporisation of water (J kg^{-1})Δ is the slope of the saturated vapour pressure–temperature curve e_s (T) (kPa K^{-1})R_n is the net radiation flux density (W m^{-2})G is the heat flux density into the soil (W m^{-2})ρ is the air density (kg m^{-3})c_p is the air specific heat (J kg^{-1} K^{-1})$(e_s - e_a)$ is the vapour pressure deficit (kPa) at the given air temperature $T_a C_a$ is the *aerodynamic conductance* for heat transport (m s^{-1})γ is the thermodynamic psychrometric constant (kPa K^{-1}), andC_s is the *surface conductance* (m s^{-1}), depending on canopy transpiration and soil evaporation.

The minimum set of climatic data needed for the calculation of Eq. (3) are the air temperature T_a (°C), the relative humidity RH (%), the wind speed U_z (m s^{-1}), and the flux density of incoming short wave radiation $K^{\downarrow}$ (W m^{-2}). The remaining variables can be either directly measured or estimated from T_a, RH, U and $K^{\downarrow}$ (Jensen et al., 1990). This model considers the canopy as a "*big leaf*", with a surface area expressed by the LAI, a crop height h_c and a hemispherical spectrally integrated albedo r, which is needed to calculate R_n. By using the canopy values for a hypothetical grass reference crop i.e. h_c = 0.12 m; r = 0.23 and LAI = 2.88, Eq. (3) gives the reference crop evapotranspiration $\mathrm{ET_0}$.

The two conductance terms C_a and C_s are calculated as the inverse of the resistances defined by Allen et al. (1998):

$$C_a = \frac{k^2 U}{\ln\left(\frac{z_U - d}{z_{om}}\right)\ln\left(\frac{z_T - d}{z_{oh}}\right)} \quad (4)$$

$$C_s = 0.005LAI \quad \forall\ LAI \le 4$$

$$C_s = 0.02 \quad \forall\ LAI > 4 \quad (5)$$

In Eq. (4), k is the von Karman's constant (0.41), z_U and z_T are respectively the measurement heights for wind-speed and temperature, d is the zero-plane displacement height and the variables z_{0m}, z_{0h} represent the roughness lengths for momentum and heat respectively being estimated from canopy height h_c (Brutsaert, 1982). Consequently, C_a becomes essentially a function of wind speed and canopy height.

The surface conductance C_s depends on incoming solar radiation, vapour pressure deficit and soil water deficit. Under potential or "standard" conditions, i.e. when soil water availability for transpiration is not limited, C_s can be approximated by Eq. (5); similar expressions can be found in recent studies by Cleugh et al. (2007) and Yan et al. (2012), which can be considered valid for a wide range of irrigated crops.

The proposed approach eliminates the need for determining the value of a crop coefficient; nevertheless, due to its wide use in irrigation practice, it is also possible to derive an "analytical" crop coefficient K_c derived by Eq. (3) applied twice, for a given crop and the reference crop; hence, the resulting function depends on crop parameters and meteorological data (D'Urso and Menenti, 1995; D'Urso and Calera Belmonte, 2005):

$$K_c = \frac{\mathrm{ET_{crop}}}{\mathrm{ET_0}} = f\left(r, h_c, LAI; T_a, RH, U, K^{\downarrow}\right) \quad (6)$$

The P–M FAO calculations based on Eqs. (3)–(5) allow for mapping $\mathrm{ET_{crop}}$ with input data consisting of ground-based meteorological data and maps of the crop parameters r, h_c, LAI. These maps can be obtained from the processing of satellite images. A review of procedures to derive crop parameters from multispectral EO data can be found in D'Urso et al. (2010); the methodologies implemented in the current application are described in the next section. LAI is the most relevant parameter for estimating crop water requirements: its value is not only needed for calculating $\mathrm{ET_{crop}}$, but also for determining the fractional vegetation cover f_c and the effective precipitation P_n in Eq. (2). In a similar way, crop height h_c can be derived as a function of LAI, provided that crop type maps are available. In addition to this, EO based LAI and K_c maps also provide farmers with spatial data on the canopy development and uniformity, as a result of different agronomic practices in the field. A recent review of methods for LAI estimation from optical satellite data can be found in Vuolo et al. (2013). Semi-empirical methods can be used to derive LAI from surface reflectance in the visible and near-infrared ranges with satisfactory accuracy for the present aim without *a-priori* knowledge of crop types.

When the canopy does not cover completely the soil surface, a correction needs to be applied to consider soil evaporation. More complex EO approaches based on two-source schemes can be applied (Yan et al., 2012; Shuttleworth and Wallace, 1985) at the cost of a heavier parameterisation. We have compared the results of Shuttleworth and Wallace (S–W) model with the results of the P-M FAO model, by using five years of daily meteorological values acquired from a standard weather station in Southern Italy during summer months (irrigation season).

As shown in the plots of Fig. 1, for LAI = 0.5 and a surface resistance of the substrate (r_s^s) in the S–W model of 1000 s m^{-1} the resulting values are in close agreement; however, if the soil surface is wet, the surface resistance r_s^s can be as low as 500 s m^{-1} hence P–M FAO is about 20–25% lower than S–W. On the basis of these considerations, in our elaborations of the CWR, we have considered a minimum threshold value of $\mathrm{ET_{crop}}$ = 0.4 $\mathrm{ET_0}$ for LAI ≤ 0.5 to correct for soil evaporation.

The validation of $\mathrm{ET_{crop}}$ has been carried out by using micrometeorological techniques in well-watered plots (D'Urso et al., 2010), as well as cross-comparison of different methods in irrigated crops (Rubio et al., 2005). In Fig. 2 the results of this validation for a case-study in Sardinia are presented for a corn irrigated field (starting from the emergence stage) and for an alfalfa crop. These plots confirm the close agreement between average hourly values of $\mathrm{ET_{crop}}$ estimated by using the described methodology and the corresponding flux measurements made by eddy-covariance.

The IRRISAT/EO4WATER/IRRIEYE advisory service is based on the approach described above, which is suitable for a fast generation of EO products in an operative processing chain in order to distribute the "*personalised*" information to users in "near real-time", i.e. between 24 and 48 h after the satellite acquisition, thus fulfilling the implementation requirements outlined in Section 2.

4. Description of the processing chain and data used

The processing chain in IRRISAT/EO4Water/IRRIEYE advisory service is mainly composed of three stages:

- *Before the irrigation season*: selection of EO data provider and programming request.
- *Within 48 h from each image acquisition:*
- Pre-processing of EO images.
- EO-based crop development products.
- Calculation of CWR and suggested irrigation depth (pixel-scale and plot scale).
- Delivery of information to final users.

The selection of the EO data is driven by the spatial, spectral and temporal resolution of the considered system. The minimum requirements are: 30 m spatial resolution, availability of green, red

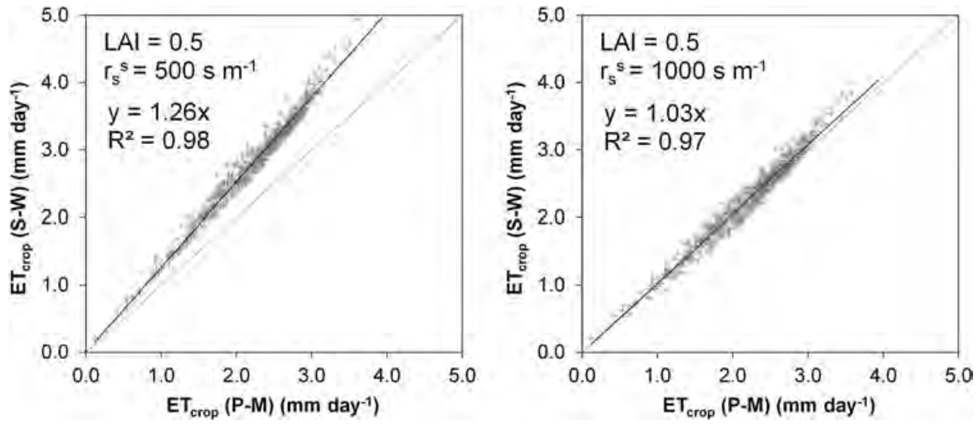

Fig. 1. Comparison of evapotranspiration ET_p calculated by means of Eq. (3) and the two-sources model of Shuttleworth and Wallace (1985) for LAI = 0.5 and two different values for substrate resistance r_s^s (LEFT: high wetness conditions: 500 s m^{-1}; RIGHT: medium wetness conditions: 1000 s m^{-1}). Meteorological input refers to five years of daily data acquired from June to September, Sele Plain, Campania, Italy.

and near-infrared bands, 7–9 days repeat cycle with viewing angle less than 20° from nadir. In addition, data delivery has to be done by FTP within 24–48 h from overpass ("rush" service).

Within the advisory service, the Spanish DEIMOS-1 EO system (www.deimos-imaging.com) has been chosen since it meets these requirements. The *weekly* temporal resolution is possible thanks to the availability of a constellation (DMC-II), composed of four platforms of similar characteristics: large swath (600 km); IFOV at ground 22 m; three spectral bands (0.52–0.60; 0.63–0.69; 0.77–0.90 μm) with 8 bit radiometric resolution. Images are already distributed in UTM WGS84 geographical reference system, with nearest–neighbor pixel re-sampling, and delivered via FTP in near-real time (24–36 h). The elaborations performed after image delivery are sketched in Fig. 3.

The quality check in step (a) of Fig. 3 consists in assessing the integrity of the image data and the presence of scattered clouds (normally images with clouds covering more than 20% of the image are rejected). The geometrical correction already performed by the data provider may be eventually verified in terms of accuracy by overlaying and comparing a reference map. The atmospheric correction, needed to eliminate or compensate diffusion and scattering by atmosphere, is performed by using the radiative transfer model inversion implemented in the module ATCOR of ERDAS Imagine commercial software with standard atmospheric profiles (Geosystem Gmbh, 2014). Invariant target within the image are used to find the most appropriate atmospheric parameters to be used in the elaboration.

The numbered sequence of elaborations for deriving EO-based crop development maps is shown in the box (b) of Fig. 3. The albedo (r) needed for deriving the net radiant flux in Eq. (3) is an approximation of the hemispherical and spectrally integrated surface albedo; considering the limited spectral resolution of EO data normally available, the albedo is calculated as a weighted sum of surface spectral reflectance ρ_λ derived from the atmospheric correction, with broadband coefficients w_λ representing the corresponding fraction of the solar irradiance in each sensor band (D'Urso and Calera Belmonte, 2005):

$$r = \sum\nolimits_{\lambda=1}^{n} \rho_\lambda w_\lambda \tag{7}$$

The LAI is derived from surface reflectance by applying the model CLAIR (Clevers, 1989):

$$\mathrm{LAI} = -\frac{1}{\alpha}\ln\left(1 - \frac{\mathrm{WDVI}}{\mathrm{WDVI}_\infty}\right) \tag{8}$$

where α is an empirical shape parameter, mainly depending on canopy architecture, which is determined from field measurements (as shown later, 0.34–0.35 for Italy and Austria and 0.22 for Australia, with prevailing tree crops); WDVI is the Weighted Difference Vegetation Index, and WDVI_∞ is the asymptotic valued for LAI→∞. The WDVI is given by

$$\mathrm{WDVI} = \rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}\frac{\rho_{\mathrm{s,NIR}}}{\rho_{\mathrm{s,red}}} \tag{9}$$

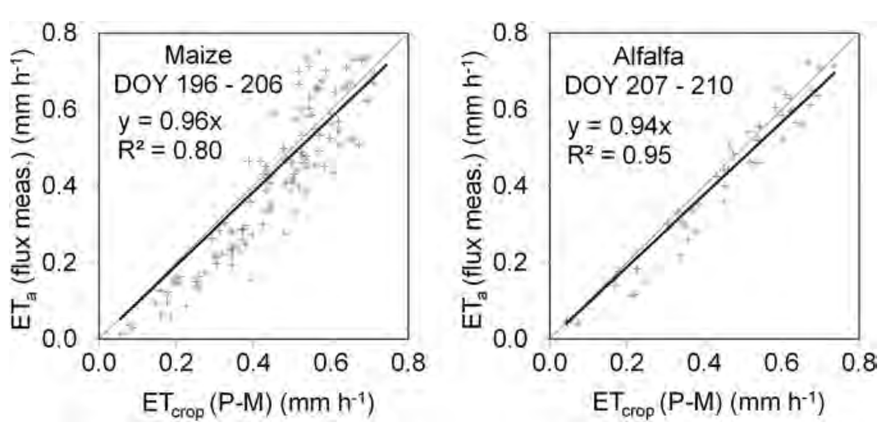

Fig. 2. Field validation of evapotranspiration under standard conditions ET_p, Eq. (3), in corn and alfalfa irrigated crops by means of Eddy Covariance measurements; Sardinia experimental farm, summer 2010.

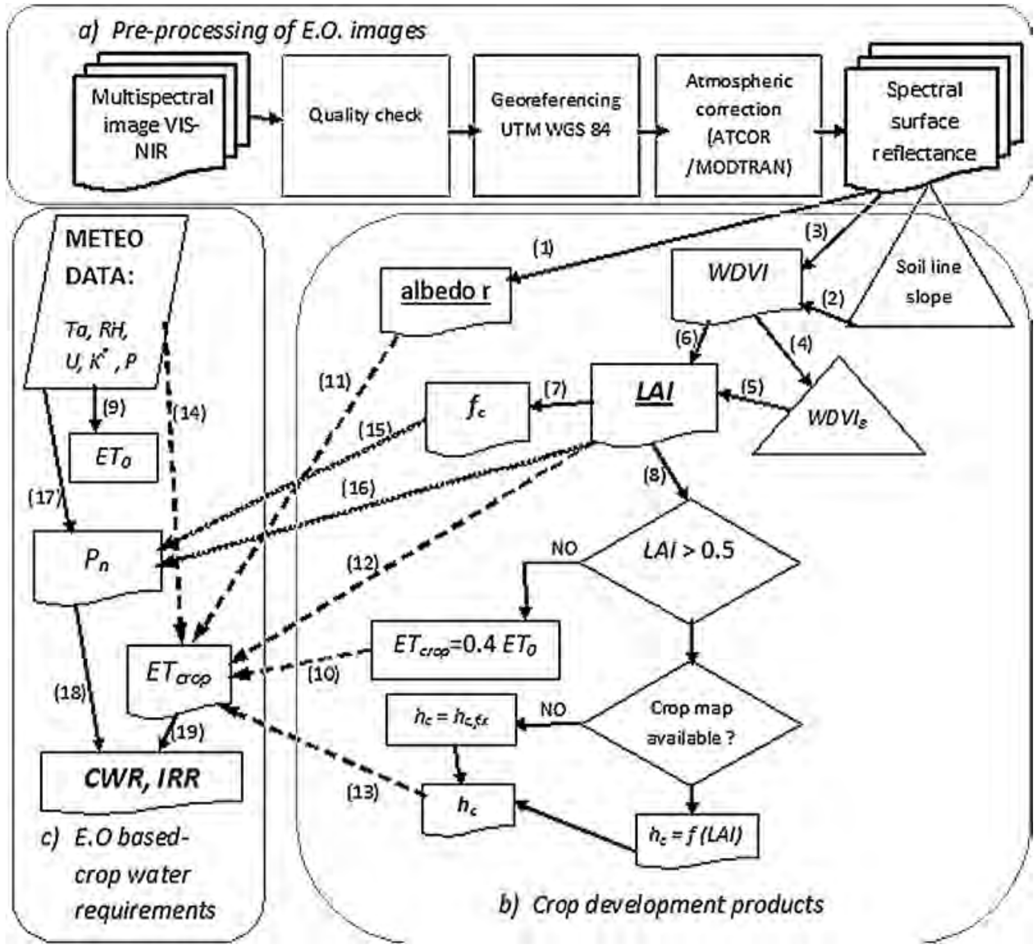

Fig. 3. Flow-chart of the processing chain after image delivery; symbols are reported in the text.

Hence, the analytical procedure for producing LAI maps from satellite-based images of spectral surface reflectance can be summarised in the following steps:

- identification of the soil-line slope in Eq. (9) (ratio of average bare soil reflectance in NIR and red bands $\rho_{s,NIR}$, $\rho_{s,red}$ usually between 0.9 and 1.3);
- calculation of the Weighted Difference Vegetation Index WDVI by means of Eq. (9);
- identification of $WDVI_\infty$ in correspondence of pixels with maximum vegetation cover (usually between 0.55 and 0.75);
- calculation of LAI by means of Eq. (8).

It should be noticed that the selection and utilisation of image-based parameters such as the soil-line slope (in Eq. (9)) and $WDVI_\infty$ may allow for a detection and partial compensation of existing errors in the atmospheric correction procedure, in the case that they are resulting outside the intervals given above.

The fractional vegetation cover f_c is derived from LAI by using a polynomial empirical expression, which coefficients are determined from field measurements and are valid for a wide range of crops:

$$f_c = -0.0038\text{LAI}^4 + 0.054\text{LAI}^3 - 0.30\text{LAI}^2 + 0.82\text{LAI} \quad \forall\ \text{LAI} \le 5 \tag{10}$$

Crop height h_c can be derived in a similar way, but a crop specific relationship has to be determined empirically. When this information or the crop maps is not available, h_c is fixed to 0.4 m. The assumption made is that the influence of crop height h_c on the value of ET_{crop} is small for different LAI values; in the plots of Fig. 4, we have compared the calculation of ET_{crop} for h_c = 0.4 and 1.0 m and different LAI values, with the same meteorological dataset of Fig. 1. The assumption of a fixed value for h_c is acceptable for daily intervals under the considered meteorological conditions, which are characterised by a larger radiation term of P-M FAO (first addendum in Eq. (3)) – compared to the aerodynamic term. This approximation eliminates the need for crop type maps which are not timely available, i.e. classification of EO data for this purpose can be done only at the end of the irrigation season.

The canopy parameters r, h_c, LAI can be considered as constant for a time period of approx. Seven days from the date of the satellite overpass. Finally, it is possible to calculate ET_{crop} by using the P-M FAO Eq. (3), by using the daily meteorological data observed during the previous 7 days or since the previous satellite acquisition; in a similar way, the net precipitation P_n is derived from Eq. (2) and the crop water requirements CWR from Eq. (1). The pixel-based *CWR* map is transformed into a vector map by means of digitised plot boundaries. The resulting irrigation advice for the generic plot i is then calculated from a simple water balance which on a given day j writes as follows:

$$d_{i,j} = d_{i,j-1} + \frac{\text{IRR}_{i,j-1}}{\eta_i} - \text{CWR}_{i,j-1} \tag{11}$$

with $\text{IRR}_{i,j-1}$ representing the irrigation depth in plot i on the previous day, $d_{i,j}$ the soil water depletion (starting from a given initial value of day 0) and η_i the on-farm irrigation efficiency (where information on the irrigation methods is available). In the simplest form,

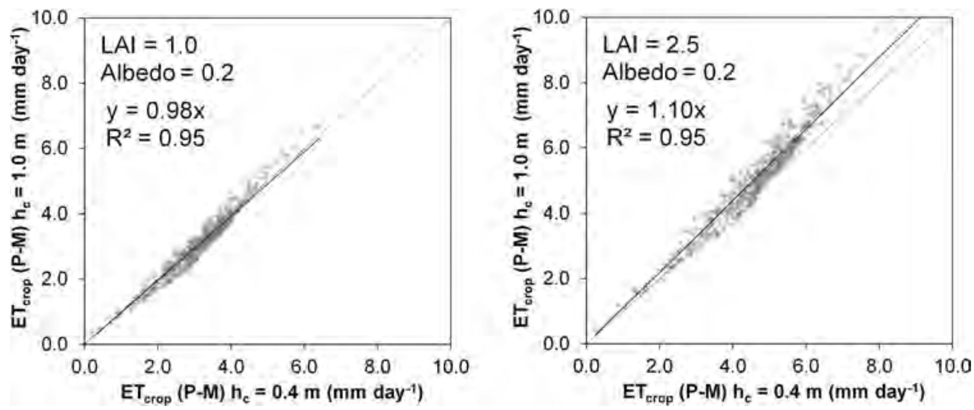

Fig. 4. Comparison of evapotranspiration ET_p, calculated for five years of summer daily meteo data by using Eq. (3), Sele plain, Campania, Italy, for h_c = 0.4 and 1 m and two different LAI values.

i.e. when no additional information on soil properties and local hydrological conditions is known, the maximum irrigation depth is given by:

$$\mathrm{IRR}_{i,j} = -d_{i,j} \quad d_{i,j} < 0 \tag{12}$$

$$\mathrm{IRR}_{i,j} = 0 \quad d_{i,j} \geq 0$$

Volumes are then calculated by multiplying $\mathrm{IRR}_{i,j}$ for the plot extension a_i, commonly derived from the webGIS.

The last step is the delivery of the irrigation advice to final users. The authors of this work have developed a common webGIS tool which has been implemented in three different areas: Southern Italy, Lower Austria and Southern Australia. The distribution of the information to farmers and irrigation agencies is done through a dedicated web mapping tool, developed in an open-source software environment. The structure of the webGIS has been slightly adapted to each area for considering the local users requirements, accordingly to the criteria outlined in Table 1. The service implemented in Italy is called "IRRISAT" (www.irrisat.it), in Southern Australia "IrriEye" (www.irrieye.com), in Austria, Marchfeld region, "EO4Water" (www.eo4water.com).

The dedicated webGIS-site is the main repository for the maps and irrigation suggested volume applications, which are timely published, with access restricted to farmers and water authorities, in order to better control the irrigation process and consequently improve its overall efficiency. Once the user is logged in, the interface window is organised in two frames: MAP and DATA. In the MAP frame (left, Fig. 5) the user will find:

- Tools for browsing and querying maps.
- Boundaries of the irrigated plots.

In the DATA frame (right panel, Fig. 5), instead:

- The plot details (crop, irrigation method)
- The temporal series of ET_{crop}, effective rainfall and irrigation applications.

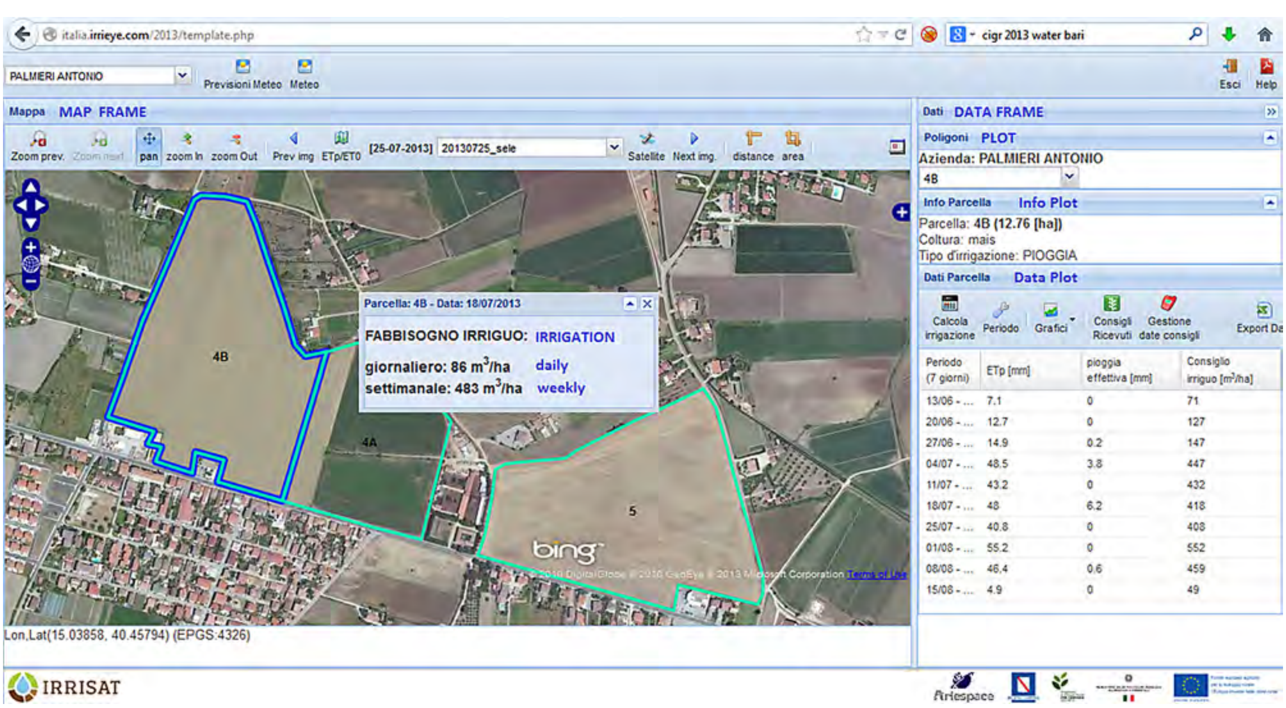

Fig. 5. IRRISAT dedicated webGIS interface for the farmers.

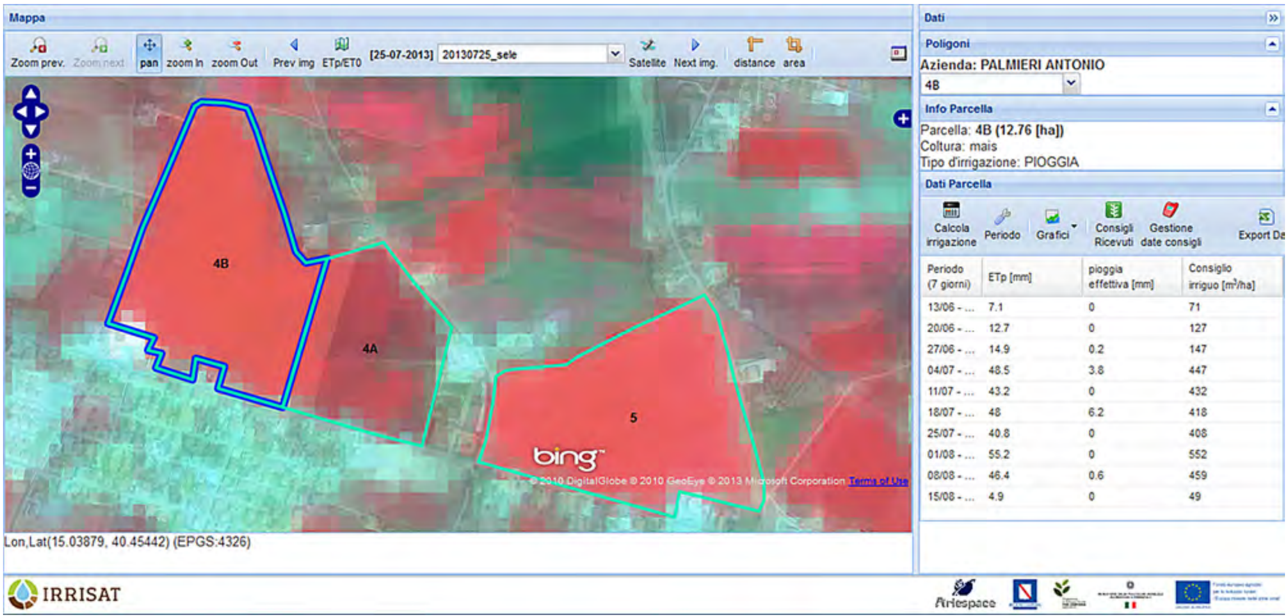

Fig. 6. Satellite image overlay in false colours.

The standard background is a Google or Bing satellite imagery, but the user can overlay the satellite image acquired on a given date by selecting "Satellite" from the tool bar in the map frame. The DEIMOS satellite for a given date can be overlaid in false colours, with the intensity of red proportional to the crop vigour (Fig. 6). In addition, the user can visualise the ration ET_{crop}/ET_0, representing the "analytical" crop coefficient of Eq. (6); in the corresponding map shown in Fig. 7, where highest values are presented with blue tonalities, the user can visualise the growth uniformity within the selected plot.

Average values of the main variables, i.e., ET_{crop}, P_n, IRR, for each plot are calculated by the system and they can be displayed in graphical form from the DATA panel of the user interface (Fig. 8). The user can select the integration time interval for these variables accordingly to his scheduling practice.

The information in the DATA panel is also sent via SMS to the farmer; a summary report is sent by However, more and more farmers have appreciated the dedicated webGIS interface, due to its intuitive use and richness of information.

A similar interface has been developed for the Irrigation Consortia and Water User associations. The tool allows for evaluating crop water requirements aggregated at district level, for a more efficient management of the conveyance and distribution network. The webGIS tools are going to be further expanded to link the financial management of the irrigation fees at farm level to the crop water requirements.

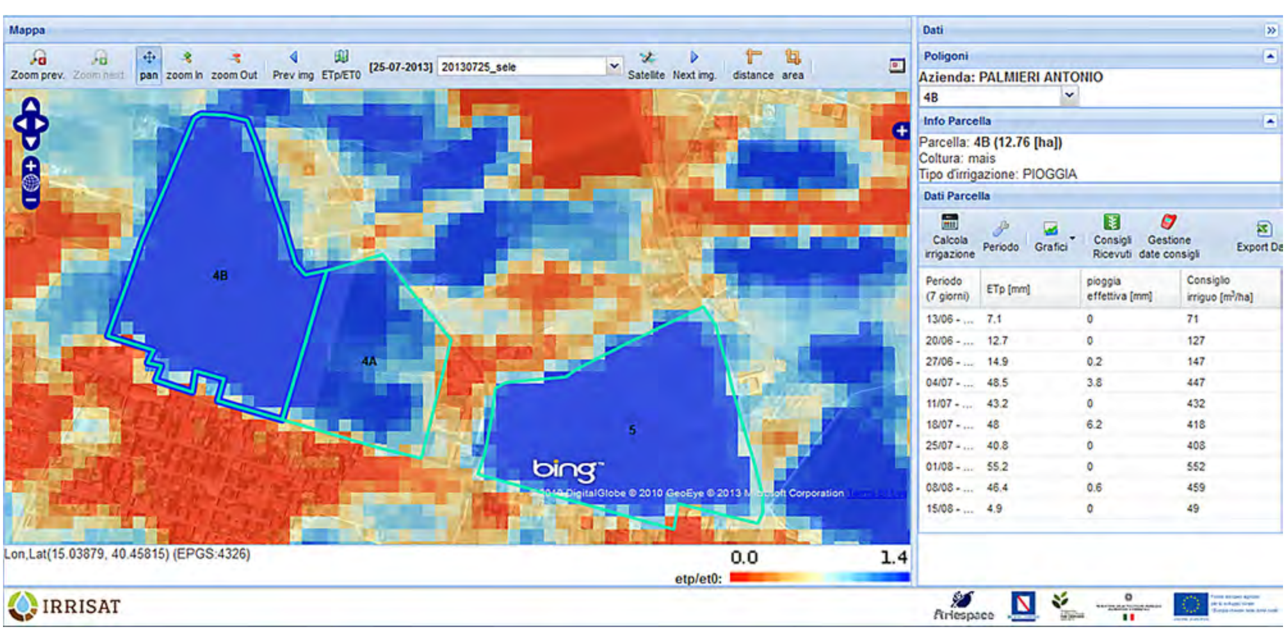

Fig. 7. ET_p/ET_0 or analytical crop coefficient map overlay (red tones: low values). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. Graphs of the temporal evolution of average values of ET_p, effective precipitation and crop water requirements for a selected plot.

5. Experiences of IMPLEMENTATIONS in Europe and in Australia

5.1. Italy, Campania Region: IRRISAT

IRRISAT is the Irrigation Advisory Service based on near-real time distribution of EO products, already operative in the Campania region since 2007. The service is implemented in the framework of the Rural Development Plan of the Campania Region, Measure 124 Health Check (www.irrisat.it), as a further step for the implementation of E.U. Directive n.60/2000 in the agricultural sector. In 2013, the service has covered four different Water User Association (irrigation consortia), with more than 660 farmers and a total extension of 5500 ha (Table 2).

In IRRISAT, a set of 12 DEIMOS-1 images have been acquired from mid-June to early September 2012 and 2013, with an average temporal resolution of about 7 days. LAI maps have been derived by using Eq. (8) with $\alpha = 0.35$, which value has been determined in previous field campaigns within the same area (D'Urso and Calera Belmonte, 2005) by means of a portable LAI digital meter (Licor LAI-2000). The accuracy of canopy parameters estimation in IRRISAT is checked from periodic field measurements performed in coincidence of the satellite acquisitions. During 2012, geo-referenced measurements of LAI with the same instrument were collected in 10 plots with maize and alfalfa fields on a weekly basis and then compared with the estimates from satellite; an example of this comparison in a maize field is given in Fig. 9. We notice here the under-estimation for LAI > 3.5 from E.O. data, due to the known saturation effect of vegetation indexes. However, the resulting effect on ETcrop is negligeable, due to the asymptotic behaviour of Eq. (3) for high LAI values. The validation campaign on LAI has shown that the empirical calibration parameter α in Eq. (8) can be considered as temporally "stable", thus eliminating the need for LAI calibration every year.

A comparison between the irrigation volumes suggested by IRRISAT and actual ones at farm and district levels is often difficult due to the scarce availability of field data. This evaluation has been

Table 2
Summary of IRRISAT service in Campania region, Italy, irrigation season 2012.

Irrigation district	Farmers	Plots	Extension ha
Destra Sele	353	704	1935.60
Paestum	209	416	1166.48
Sannio-Alifano	29	208	782.57
Volturno	78	465	1618.92
Total	669	1793	5503.57

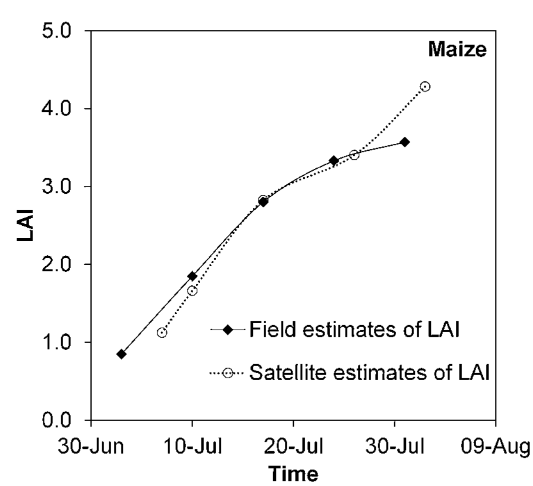

Fig. 9. Temporal evolution of LAI estimated from satellite image analysis and from field measurements carried out by using a LAI Licor 2000 portable analyser, in a corn irrigated field, Campania, Italy.

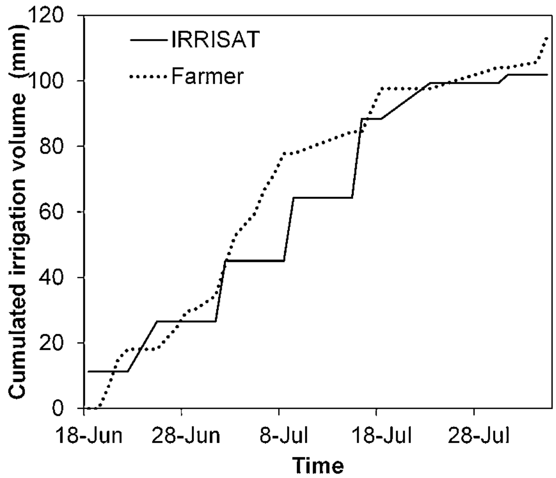

Fig. 10. Cumulative irrigation depth suggested by IRRISAT and applied by a farmer in a corn field of 7.7 ha during 2012.

possible in selected farms and irrigation districts within the IRRISAT areas where automatic registrations of water withdrawals from the distribution network were available. An example of the comparison at farm scale is shown in Fig. 10, whilst the plot in Fig. 11 is referred to a district in the Sele river plain. On average, farmers apply 15% more irrigation than the IRRISAT volume, which can be considered as a substantial agreement. Over irrigation is observed at the beginning of the season and in coincidence of precipitation events (as in mid-September); this latter finding is partially due to the lag between advice time and irrigation application.

All the farmers evaluated positively the usefulness of the information provided, especially when it was made readily available by means of SMS or weekly reports. It was proven that the adoption of IRRISAT service produced an increase of irrigation efficiency, because of the reduction of water volumes compared to traditional practice. Accordingly to the estimation made by local water managers and authorities, the traditional applied irrigation volumes were varying between 4500 and 6000 m^3/ha for maize and between 6500 and 12,000 m^3/ha for alfalfa; during last years, since the introduction of metering devices at the outlets of the irrigation network, the irrigation volumes have been progressively reduced, but they are still higher than crop water requirements given by IRRISAT, which are between 3500 and 4500 m^3/ha for maize and

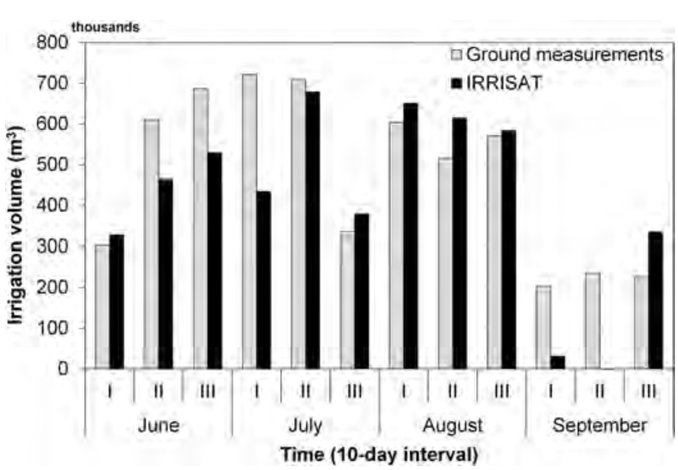

Fig. 11. Comparison for the irrigation district "Boscariello", Destra Sele Consortium, 1200 ha, between measured and IRRISAT suggested volumes, for 10 days periods during the irrigation season 2012.

between 5000 and 10,000 m^3/ha for alfalfa. This means that the adoption of IRRISAT can introduce important savings in water resources, with possible increments of production and quality. To this respect, we have noticed that in small extension farms the irrigation efficiency is lower and farmers are also more reluctant than others to fully adopt IRRISAT in the irrigation scheduling. One possible reason resides in the restriction of economic resources for labour force and irrigation equipment; since water pricing is not yet subjected to metering controls, it is simply easier to keep irrigation going for an excessive amount of time; in addition to this, inefficient and dated equipment are often used. Diversely, when the farm extension is above ten-twelve hectares, we found farmers more motivated to deal with innovative technologies and ready to understand the importance of testing a reduction of irrigation volumes. As such the possible impact of IRRISAT technology in the context of water pricing evolution in southern Italy may be of some relevance.

As mentioned in Section 2, crop heterogeneity captured by the satellite images has been considered by farmers as a valuable information to identify the existing variability, in some cases already known from personal field experience; other features were also evidenced, i.e. variability of soil texture and fertility, plant nutrition, different performance of irrigation systems.

5.2. Austria, Marchfeld region: EO4Water

EO4Water (Earth observation technologies for rural water management) is a research project funded by the Austrian Space Applications Programme (under *Die Österreichische Forschungsförderungsgesellschaft* – FFG) to test and demonstrate the transferability of satellite technologies for mapping water needs in Marchfeld region, one of the major crop production areas of Lower Austria. In this area, with more than 60,000 ha of crop land (~21,000 regularly irrigated) there is a strong need and a potential demand for applications that support efficient water management process. The climate is semi-arid with annual precipitations of less than 550 mm (about 250–300 mm from May to September). Crops such as vegetables and sugarbeet (which is one of the most water demanding crops in this area) require between 200 and 600 mm of water for kg dry matter. For summer crops with high biomass potential this can reach a total water demand for the growing period of around 800 mm, which clearly cannot be provided by precipitation under current climatic conditions.

On the one hand, farmers in Marchfeld are very interested in improving the efficiency of irrigation. Indeed, this may result in reduced operation costs, and in yield stability as required to accomplish production contracts. On the other hand, there is an increased ecological awareness among consumers about local, high-quality and fresh food, how it is produced and whether the water footprint in the various production steps is sustainable.

The overall duration of the project is 2 years, with a technical campaign in the first year (2012) and a second operational campaign during the second year (2013) of the project. The total coverage is more than 1700 ha, which corresponds to approx. 8–10% of the total summer cropped area (~21,000 ha – estimates based on 2010 satellite data). In year 1 we also conducted experimental and validation activities. Based on DEIMOS-1 acquisitions, the following steps have been performed: (1) calibration and validation of a semi-empirical model to estimate LAI; (2) estimation of crop water needs and preliminary comparison with irrigation volumes at district and at field scale. In this work we focus on activity 2.

Field campaigns were carried out contemporaneously to each satellite acquisition in 2012 to calibrate a site-specific LAI-WDVI model. In total 51 indirect ground measurements of LAI were carried to cover a range of crop types and phenological conditions. The

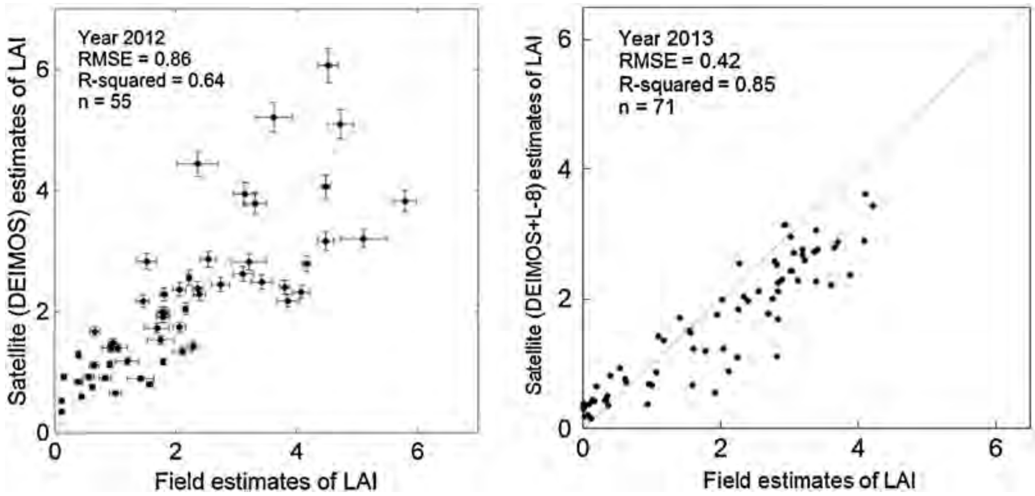

Fig. 12. Scatterplot of satellite-based vs. field estimates of LAI for the two years; Marchfeld, Austria.

measurements protocols and the tuning procedures were described in Vuolo et al. (2013). Ground measurements were repeated in the year 2013 ($n = 71$) during different campaigns throughout the growing season and compared to Landsat-8 and DEIMOS-1 LAI estimates. Fig. 12 shows the scatterplot of satellite-based vs. field estimates of LAI for the two years. LAI estimates were obtained using an image-specific tuning of the soil-line slope and $WDVI_{\infty}$ and a constant α coefficient value of 0.34 as described in Vuolo et al. (2013).

The satellite estimations were in line with the ground measurements with a very high coefficient of determination ($R^2 = 0.85$) and a Root Mean Square Error (RMSE) of 0.42. The improvements compared to the year 2012 (RMSE = 0.86) are partially explained by the fact that in the year 2013 measurements were carried out in the same locations (eight fields) and therefore they caught a lower crop variability compared to the year 2012.

An estimation of maximum crop water needs at irrigation scheme level (Marchfeld area) during the growing season was achieved for the year 2010 (using archived Landsat-5 data) and 2012 (using DEIMOS-1 data). Results were compared with the overall irrigation volumes distributed in the area over the irrigation season (June–August) during past years. For a comparison at the field scale, two sugarbeet parcels have been selected during the irrigation period (end of May to the end of August – year 2012); in Fig. 13 the satellite-based K_c curves are compared with the standard FAO tables; and we compared these volumes with satellite-based estimations of crop water needs. In this case, satellite data did not cover the entire growing period and the first image was acquired only on June 17th. Therefore, K_c curves for the initial and development growth stages were constructed knowing the planting date (March 15th) and the duration of each growth stage. It is possible to notice that crop development variability determines a lower ET_{crop} than the one resulting from standard K_c values.

Cumulative CWRs have been calculated by using Eq. (1)a; the correspondent supplied volumes for the parcels are compared in Fig. 14a and b. We notice an overall good agreement between the estimated and the provided irrigation volumes. For parcel "a", the cumulated irrigation volume resulted slightly lower than the maximum water need throughout the growing season. For parcel "b", irrigation volumes also followed the trend of the estimated crop water need. However, in this latter case, the trend followed the higher envelop of the maximum water need curve and exceeded the maximum volumes near the end of the growing season.

We miss detailed information on the crop management and soil conditions that would allow us to interpret the differences in growth and water use between the two parcels (same cultivar and climatic conditions); therefore we can only speculate on possibilites. Although parcel "b" received slightly more water than parcel "a" (Fig. 14), the crop development depicted in Fig. 13 shows that parcel "a" reached a maximum K_c value of 1.1, while parcel "b" only reached a value of 0.9. The differences in the maximum K_c might be explained by varying soil conditions between the two parcels or due to an initial crop water stress, or a combination of both factors.

Sugarbeet is most sensitive to water shortage during initial and early plant development stages. Parcel "a" received a first irrigation (not considered in the graph because very early in the season) soon after planting (March 26th, 20 mm) and a second irrigation already at the end of May. In contrast, parcel "b" recevied the first irrigation only on June 12th. The timing of irrigation at the beginning of the season might explain the differences in the maximum crop growth. Despite these initial differences, irrigation scheduling was kept very similar for the two parcels, with an additional irrigation near the end of August for parcel "b". A common managemet practice is to induce soil water stress late in the season to increase sucrose concentration in the beet root (with small reduction in root yield). According to the FAO-56, "when this type of water stress is practised, the value for K_c end is reduced from 1.0 to 0.6". As we look closer to Fig. 13(a), we can observe a reduction of the K_c value. In contrast, this reduction cannot be observed in Fig. 13(b). This data suggest that an increase in water volumes later in the season would not help the plant to recover from the initial water stress. Instead of using the standard water volumes, irrigation for parcel "b" could have been modified to the satellite-based estimated volumes to maximise water economy and to achieve a late-season (before the harvest) water stress (which does not seem to happen in this case). In both cases, we notice that the use of standard FAO-56 K_c values would result in an over-irrigation.

5.3. Southern Australia, Murray Darling: IrriEye

The South Australian Murray-Darling Basin Natural Resources Management Board has chosen the district of Bookpurnong for a case-study started in 2011 and continued throughout the irrigation season 2012–2013 over an area of about 1100 ha (of which 470 ha citrus, 480 ha vines – wine grapes). A near-real time trial based on the acquisition of multispectral high resolution images from the Spanish satellite DEIMOS-1 has been planned between September and March. The required meteorological data have been downloaded from the specific section of the S.A. Murray-Darling Basin website (www.aws-samdbnrm.sa.gov.au). An intensive campaign of field measurement of LAI in the three main tree crops present

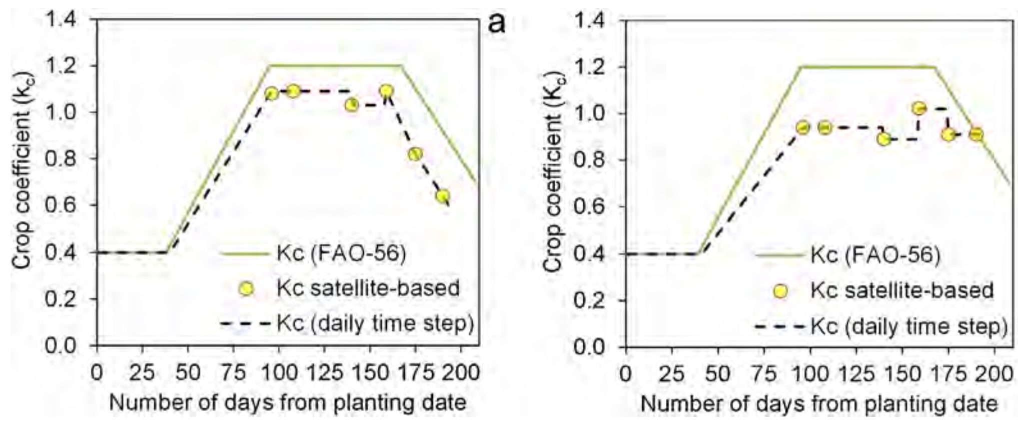

Fig. 13. Satellite-based K_c (dots) and standard K_c (green line) values for two sugar beet parcels (200 day growing period). Sugar beet was planted on March 15th. First irrigation occurred on May 28th (day 73) and June 12th (day 87), irrigation season 2012, for parcel "a" and "b" respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

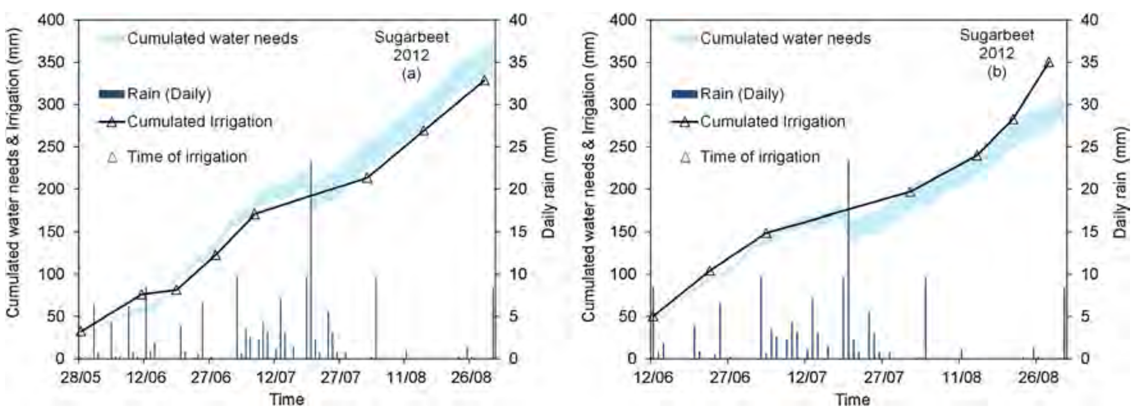

Fig. 14. Satellite-based estimations of crop water needs vs. supplied irrigation volumes for parcel "a" (left) and "b" (right). The blue area indicates the range of values of crop water requirements for total and effective precipitation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the area has allowed for a site specific calibration of the CLAIR model (Fig. 15); the resulting value of the α of Eq. (8) has resulted equal to 0.22; the lower value compared to the corresponding in Italy and Austria, where herbaceous crops are dominant, is due to the canopy structure of tree crops.

The graph on Fig. 16 indicates the variation of crop coefficient determined from satellite images for the citrus fields analysed and the comparison with the standard values currently adopted in the irrigation practice in the area, based on FAO tables (calculated from fractional vegetation cover; Eq. (98) in Allen et al., 1998). We notice that for citrus the average satellite values are consistent with FAO, but we also notice a large variability in the satellite-based values.

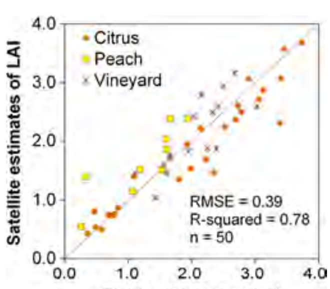

Fig. 15. Comparison of satellite-based estimates of LAI vs. field measurements for the prevailing tree crops in the Bookpournong area, Southern Australia, IRRIEYE campaign 2013.

This can be explained by differences in the tree management, as well as in the presence of understory. However, when we consider the cumulative irrigation volumes at farm scale, we notice a substantial concordance between satellite-based irrigation volumes and actual applications (2.8 vs. 3.1 measured Ml/ha for citrus; 2.8 vs. 2.7 measured for vineyards; Bill Ruediger Farm, Bookpournong). It should be outlined that this comparison does not include water availability derived from precipitations which have been higher than average during the observation period. These findings confirm the applicability of the procedure for the estimation of CWR described in Section 2 for tree crops; however, further validation is needed for a complete accuracy assessment in this case.

The current irrigation scheduling in Bookpurnong is based on robust meteorological information, but it considers standard values of crop coefficients from FAO tables and although this approach might be satisfactory at basin level, it does not consider the large variability of crop development at the farm level, due to different soil conditions and agronomic practices. The satellite-based crop coefficients, which take into account these effects in an implicit way, allow for a site-specific evaluation of irrigation volumes and offer significant potential to achieve substantial improvements in water and energy efficiency at basin and farm levels and on the final quality of production. The intuitive web-interface gives the growers the ability to monitor the canopy development at plot level in near-real time and additionally, the evaluation of net precipitation, thanks to a better calculation of canopy interception based from satellite LAI values may reduce the irrigation application.

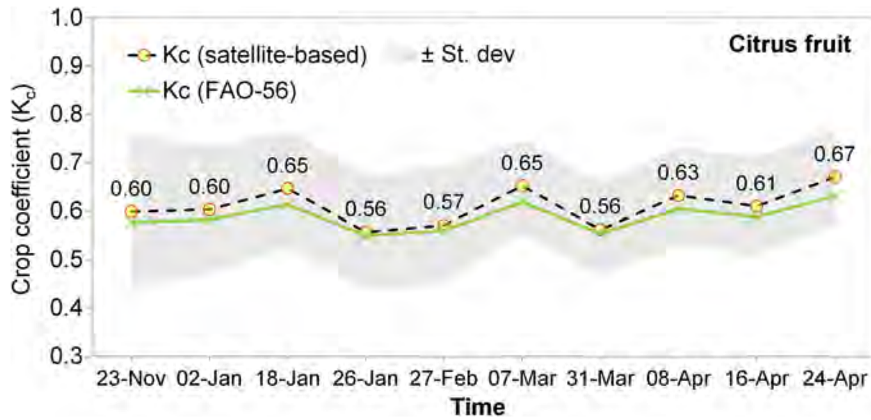

Fig. 16. Comparison of citrus crop coefficients (average and ±st.dev.) estimated from IRRIEYE and from FAO table, currently used in the Bookpournong area, South Australia.

From the experiences carried in Europe and in Australia, we are able to evaluate the overall cost of satellite-based irrigation services like IRRISAT/EO4Water/IrriEye. The cost to the final users is strongly dependent on the extension of irrigated area within each satellite image and the number of acquisitions, i.e. above 3000 ha the final cost is estimated around 8–10 €/ha with 10–11 acquisitions during the entire irrigation season. The further expected reductions of market prices of high resolution satellite images will certainly make the IRRISAT/EO4Water/IrriEye services even more cost-effective in the near future.

6. Concluding remarks

The three applications of the satellite-based webGIS irrigation advisory service, in spite of the environmental and climatic differences, evidence strong similarities in the response from the user's side. The satellite-based crop water requirement procedure adopted in the irrigation advisory services IRRISAT/EO4Water and IRRIEY implicitly takes into account the presence of variability of crop development at plot level, due to different soil conditions and agronomic practices. Consequently, satellite-based irrigation volumes give a site-specific evaluation of irrigation volumes, which can be substantially different from estimations based on standard K_c tables. These differences are of course smoothed out when considering aggregated spatial or temporal scales; however, an irrigation scheduling based on the effective crop development may bring substantial advantages either on the rationale use of water and energy at basin and farm levels or on the final quality of production. Compared to crop-coefficient approach, this method allows for an accuracy assessment based on objective measurements of LAI.

The information on ET_{crop}, evaluated on the basis of the effective crop development, provides an upper limit to the amount of water to be applied by farmers; in many contexts, by convincing farmers in limiting their applications within ET_{crop} it is possible to achieve consistent savings of water resources.

The intuitive web-interface gives the growers the possibility to monitor the canopy development at plot level in near-real time; in addition, an evaluation of net precipitation, thanks to a better calculation of canopy interception based from satellite LAI values, may reduce the irrigation application. The knowledge of crop development variability can be easily integrated into modern crop management practices, i.e. high-level accuracy GPS-compatible controllers used on automatic agricultural machineries, sprayer auto-shut-off systems, spreader or drill auto-section controls.

However, feedback from final users (both farmers and irrigation water managers) is essential to improve the effectiveness of the service in terms of water use optimisation, especially during the early stage of service implementation.

Acknowledgements

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