REMOTE SENSING TECHNIQUES TO IMPROVE ON-FARM IRRIGATION EFFICIENCY

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INTRODUCTION

The potentiality of Earth Observation techniques in supporting the management of land and water resources has been nowadays widely recognised, based on more than twenty-five years of multi-temporal and multi-spectral observations integrated with traditional ground reference data. During recent years, Earth Observation techniques are more and more transferred to applications for supporting land and water management.

In this paper, we present an operational procedure for improving the efficiency of irrigation at farm level, based on the integrated use of Earth Observation data and Information Technologies. The prototype of this methodology has been developed by a consortium of European research institutions in three irrigated areas in Spain, Italy and Portugal within the EU-funded project "DEMETER" (http://www.demeter-ec.net/) and further extended to other areas within the "PLEIADeS" project (http://www.pleiades.es). During 2006 and 2007, the procedure has been implemented operationally in two irrigation districts in the Campania Region, Italy (http://www.sito.regione.campania.it/agricoltura/irrigazione/paginainiziale-prci-2007.html).

MATERIALS AND METHODS

The theoretical background for the estimation of crop water requirements from satellite data is based on the standard methods of F.A.O.-Paper 56 (F.A.O., 1998):

i) the approach based on the crop coefficient concept, K_c, defined as the the ratio of total evapotranspiration ET by reference evapotranspiration ET_0;

ii) the direct calculation, "one-step" approach, based on the application of the Penman-Monteith equation with appropriate values of canopy variable such as the surface albedo α and the Leaf Area Index (LAI).

The concept of so-called "crop coefficient" K_c, still widely used for irrigation practices, may result of practical usefulness to calculate the evapotranspiration ET_p of a canopy under stardard conditions i.e. unlimited soil water availability, pest and disease-free crop. Accordingly to F.A.O. Paper 56 procedure, it is possible to define a reference evapotranspiration ET_0, by using agrometeorological data, and thus:

$$ET_p = K_c ET_0 \tag{1}$$

The value of K_c can be either extracted from tables or estimated from field and/or remote observations. Field observations are routinely used by several Irrigation Advisory Services, but they often lack of objectivity in the evaluation and they are difficult to carry out over extensive areas.

To this respect, the potentiality of remote sensing techniques in irrigation and water resources management is now widely acknowledged (Bausch, 1995; Choudhury et al., 1994; Neale et al., 1989). Several algorithms for retrieving biophysical parameters of vegetation, such as *LAI*, biomass density and canopy roughness from remote sensing data with different spatial and temporal resolution have been successfully tried out in many different environments (Baret et al., 2007). On this baseline, experimental studies carried out in the context of Demeter and Pleiades projects have assessed the direct correspondence between the spectral response of cropped surfaces and the corresponding value of evapotranspiration and crop coefficient K_c (D'Urso et al., 2006). One important advantage of deriving crop coefficients from spectral measurements is that K_c values do not depend on variables such as planting date and density, but on the effective cover; as such, the spectral K_c value includes the variability within the same crop type due to actual farming practices.

Two different kinds of procedures have been developed and tested for the operational estimation of crop water requirement from Earth Observation to support irrigation advisory services. The first type of approach is based on empirical relationships between the canopy reflectance expressed by means of radiometric Vegetation Indexes and the value of the basal crop coefficient; the second type of procedures relies on the direct application of the Penman-Monteith equation with canopy parameters estimated from satellite imagery, in analogy to the direct calculation proposed by F.A.O. (Monteith et al., 2007). In this latter case, assuming a minimum stomatal resistance of 100 sm^{-1} (Kelliher et al., 1995) the value of ET_p can be calculated from the following equation:

$$ET_p = \frac{86400}{\lambda}\left[\frac{s\left(1-0.4e^{-0.5LAI}\right)\left(1-\alpha\right)\left(K^{\downarrow}+L^{*}\right)+c_p\rho_a\left(e_s-e_a\right)U/124}{s+\gamma\left(1+U/0.62LAI\right)}\right] \quad \text{(mm/d)} \qquad (2)$$

where $K^{\downarrow}$ is the incoming solar radiation and U the wind speed; the other variables, namely L* (net longwave radiation), c_p (air specific heat), ρ_a (air density), $(e_s{-}e_a)$ (vapour pressure deficit), λ (latent heat of vaporisation of water) and γ (thermodynamic psychrometric constant) are calculated from air temperature and humidity at 2.0 m reference height. This equation is valid under conditions of high solar irradiance (typical summer condition in Mediterranean climate) and for LAI>0.5; adaptations might be needed under different climatic conditions.

Equation (2) can be applied by using ground-based meteorological data and satellite-based estimation of the two canopy parameters needed for the calculation, namely the surface albedo α and Leaf Area Index (D'Urso et al., 1995; 2006). The conceptual framework is depicted in fig.1. From the combination of Eqs.(1) and (2), we derive an analytical expression of the crop coefficient, K_c, strictly dependent on the meteorological data and the canopy parameters α and LAI.

Simplified methods are available to estimate surface albedo α and Leaf Area Index from satellite-based surface reflectance with satisfactory accuracy for the present application. Broad-band sensors in the visible and near-infrared, i.e. Landsat, SPOT, IRS, Terra-Aster, have been intensively used for deriving maps of α and LAI. A combination of different satellites can be found to define a "virtual constellation"; so doing it is possible to achieve a revisit time of 7-10 days, in order to adequately follow the phonological development of crops during the irrigation season.

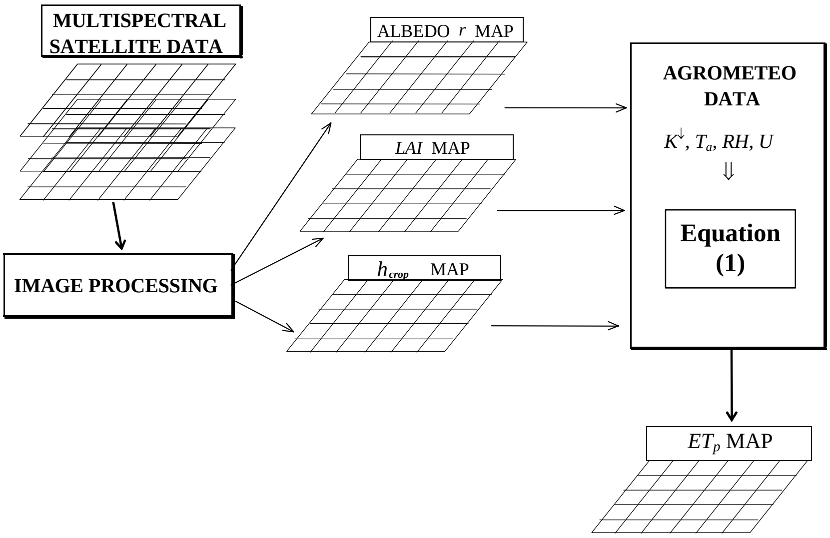


FIGURE 1 Conceptual framework for mapping evapotranspiration under standard conditions by using satellite data (D'Urso et al., 1995).

For the estimation of α from Earth Observation data we need to solve three main problems: the directional integration of spectral radiance detected by the sensor, the spectral integration to obtain the planetary albedo, that is at top-of-atmosphere height, and the correction of atmospheric effects in each spectral band for deriving the surface albedo. The current sensor capabilities (broad-band, near-nadir view) impose several simplifications. Considering that radiance measurements are performed at different wavelengths, the spectral integration is approximated in discrete form, as expressed by the following relationship (Menenti et al., 1989):

$$\alpha = \pi \int_0^{\infty} \frac{K^{\uparrow}(\lambda)}{K^{\downarrow}(\lambda)} d\lambda \cong \pi \sum_{\lambda_1}^{\lambda_n} \frac{K_{\lambda}^{\uparrow}\left(d^0\right)^2}{E_{\lambda}^0 \cos \vartheta^0} \tag{3}$$

In Eq.(3) the spectral radiance reflected from the surface, $K^{\uparrow}{}_{\lambda}$ (W m^{-2}), and the extraterrestrial solar irradiance, $E^0{}_{\lambda}$ (W m^{-2}), are integrated values over the width of each spectral band λ_i; θ^0 and d^0 are respectively the solar zenith angle and the sun-earth distance in Astronomical Units. By grouping these quantities in a set of band-coefficients (which are sensor-dependent), Eq.(2) can be simplified in the following expression:

$$\alpha = \sum_{\lambda} w_{\lambda} \rho_{\lambda} \qquad \lambda = 1,2,....,n \tag{4}$$

where ρ_{λ} represent the spectral reflectance (corrected for atmospheric effects) in the generic band. The coefficients w_{λ} can be calculated for each sensor type and applied to calculate α for the given image acquisition.

Simple and feasible approaches based on empirical relationships between *LAI* and nadir-viewing measurements in the red and infrared bands has been have been defined by several authors. These methods implicitly assume that all other factors, except *LAI*, influencing the spectral response of canopy are fixed. In the DEMETER and PLEIADES projects, we have used the model CLAIR (Clevers, 1989), based on the *Weighted Difference Vegetation Index* (*WDVI*) which is defined as follows:

$$WDVI = \rho_i - \rho_r \frac{\rho_{si}}{\rho_{sr}} \tag{5}$$

where ρ_r and ρ_i indicate the reflectance of observed canopy in the red and infrared bands respectively, while ρ_{sr} and ρ_{si} are the corresponding values for bare soil conditions; the ratio ρ_{si}/ρ_{sr} can be takes as a constant, in analogy with the "soil line concept" (Baret et al., 1993). The *WDVI* index has the advantage to reduce to a great extent the influence of soil background on the surface reflectance values; diversely, it is quite sensitive to the atmospheric effects, thus it requires a reliable radiometric correction. The *LAI* is related to *WDVI* of the observed surface through the expression:

$$LAI = -\frac{1}{\omega} \ln\left(1 - \frac{WDVI}{WDVI_{\infty}}\right) \tag{6}$$

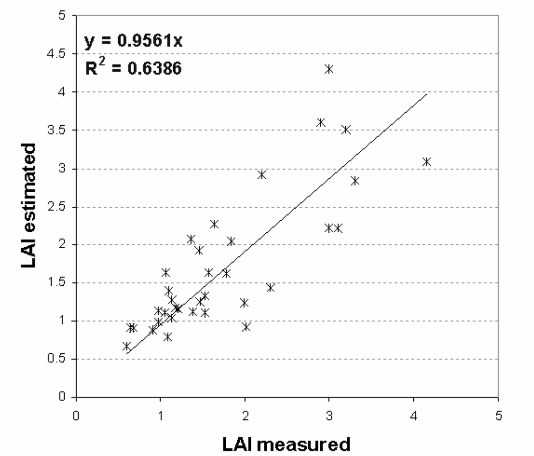


FIGURE 2 Validation of empirical estimation of LAI on the basis of field measurements on different crop types, Sele River Plain, Italy. Eq.(6) has been applied with ω=0.33 and $WDVI_{\infty}$=0.55.

In Eq.(6), ω is an extinction coefficient to be determined from simultaneous measurements of *LAI* and *WDVI*; $WDVI_{\infty}$ is the asymptotical value of *WDVI* for $LAI \rightarrow \infty$. This approach has been validated by field measurements and by means of numerical models simulating the reflectance of leaf and canopy in a wide range of conditions in different sites (D'Urso et al., 1995). By using independent measurement data-sets collected during several field campaigns, calibration and validation of Eq.(6) has been carried out. The value of ρ_{si}/ρ_{sr} has resulted 1.115, with ω=0.33 and $WDVI_{\infty}$=0.55 (fig.2).

When a more complete radiometric information is available, i.e. by using TERRA-ASTER data or new generation of satellite with super-spectral capabilities, it is possible to apply physically-based model of vegetation radiative transfer to estimate canopy albedo and *LAI*, without invoking restricting assumptions as in the semi-empirical models. A possibility is offered by a fast and robust inversion techniques based on the construction of a look up table (LUT) (Weiss et al., 2000) from the widespread SAIL – model (Verhoef, 1984) combined with PROSPECT (Jacquemoud & Baret, 1990) to “PROSAILh” (e.g., Baret et al., 2007; Weiss et al., 2000). This combined model takes into account the effect of soil background, the optical properties of the leaves, which are related to pigments and leaves water content. As such, diversely Eqs.(4)-(6), an higher amount of spectral information is required to achieve a satisfactory level of accuracy in the results (Richter et al., 2007). A remarkable difference between the empirical methods and the physically-based PROSAILh model is the possibility of considering the influence of illumination and observation geometry on the canopy reflectance, otherwise considered as a Lambertian reflector.

The approach described here, based on the combination of canopy parameters estimated from E.O. data and the Eq.(2), has been validated by using independent measurements of ET_a obtained from micro-meteorological instrumentations during different field campaigns. For example, in the case of maize and alfalfa field under well-watered conditions, the comparison between ET_a and ET_p derived from satellite-based data has evidenced a very high correlation.

PROCESSING AND I.C.T. DELIVERY OF INFORMATION TO FINAL USERS

Semi-automatic procedures have been developed in order to elaborate ET_p maps from E.O. data in the minimum possible time. The key-points of this procedure are: a) personalised irrigation advice; b) timely delivery of the information. Once the data are acquired by the satellite, i.e. at 10:00 a.m. day 1, the raw image is available via FTP within 12 hours at the processing center. The following processing steps are then applied: geometric correction (based on Ground Control Points), atmospheric correction, calculation of canopy parameters (albedo, *LAI*, K_c).

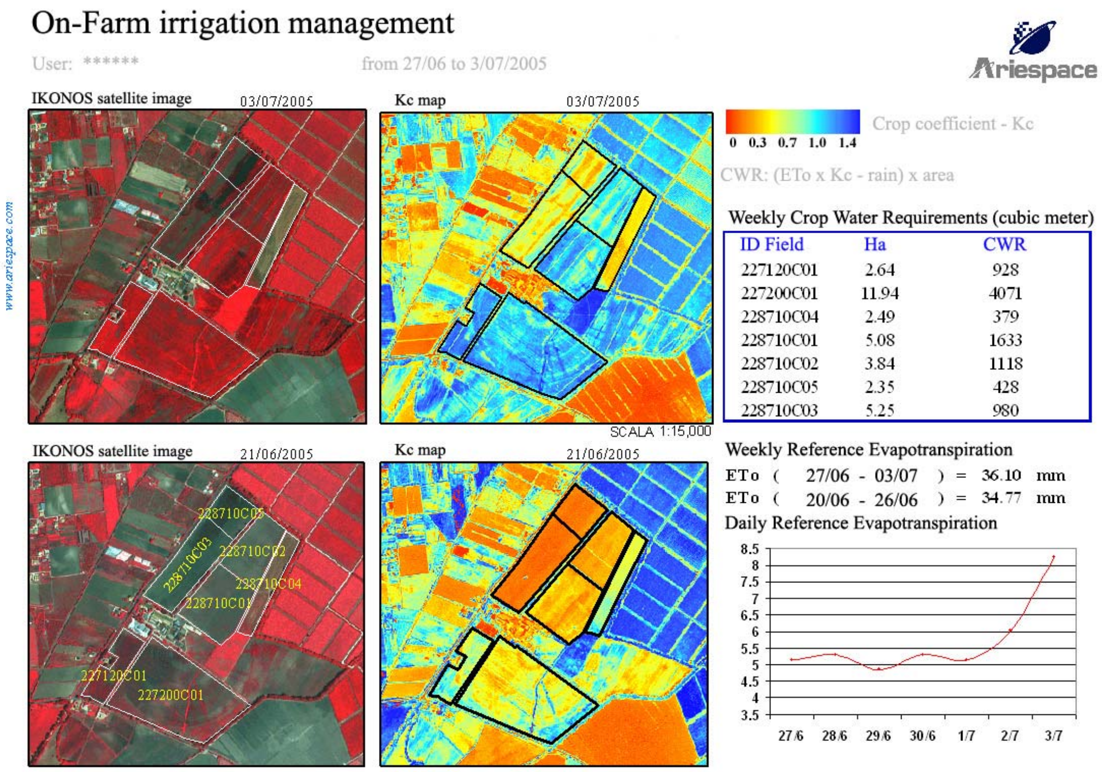
This processing is generally completed within 24 hrs from image download, i.e. at 12:00, day 2. At the end of this processing phase, the following products are ready: 1) color combination maps, 2) Crop Coefficient maps – from both approaches, 3) meteorological data (Precipitation, Reference Evapotranspiration) and 4) crop water requirements data. These products are directly delivered to each farmer by using I.T. in two ways: (1) simple text report by using SMS; (2) standard report, by MMS and e-mail, including images of the fields in false colors combination and a Kc map. The entire process is completed around 15:00 hrs, day 2. An example of the derived product is shown in figure 3.

This service has been operating in two irrigated areas of Campania Region (Southern Italy) during 2006 and 2007. The total cost of the advisory service, based on weekly reports, has been evaluated on the basis of 6 images from Landsat-5 and SPOT per irrigation season (60 days), over an extension of approximately 10 000 ha of irrigated land. The resulting cost is on the order of 2 € per hectare per year, including personnel cost for data processing and product generation; however, this value is strictly dependent on the density of irrigated area within the image acquisition.

During these campaigns the farmers were able to recognize without difficulties their parcels on the images and they scheduled the irrigations by taking into account the information provided. The crop heterogeneity captured by the high resolution images was considered as a valuable add-on information to identify the variability of soil texture and fertility, plant nutrition, or different performance of irrigation systems.

If the actually given water volumes are known, it is then possible to evaluate the irrigation efficiency at different spatial and temporal scales. In a better way, crop water requirement information can be distributed to farmers in order to avoid the application of excessive amounts of irrigation water (and increase efficiency). An example is shown in Fig.4, where the suggested volumes are compared with the actual applied ones.

All the farmers evaluated positively the usefulness of the information provided, especially when it was made readily available by means of the MMS or e-mail weekly reports, and in most cases an increase of irrigation efficiency was achieved, because of the reduction of water volumes.


On-Farm irrigation management

User: ******

from 27/06 to 3/07/2005

CWR: (ETo x Kc - rain) x area

Weekly Crop Water Requirements (cubic meter)

ID Field	Ha	CWR
227120C01	2.64	928
227200C01	11.94	4071
228710C04	2.49	379
228710C01	5.08	1633
228710C02	3.84	1118
228710C05	2.35	428
228710C03	5.25	980

Weekly Reference Evapotranspiration

ETo (27/06 - 03/07) = 36.10 mm

ETo (20/06 - 26/06) = 34.77 mm

Daily Reference Evapotranspiration

FIGURE 3 Example of information distributed to farmers via MMS (mobile phones) and E-mail: colour composite derived from high resolution satellite images and K_c map for a period of 4-7 days.

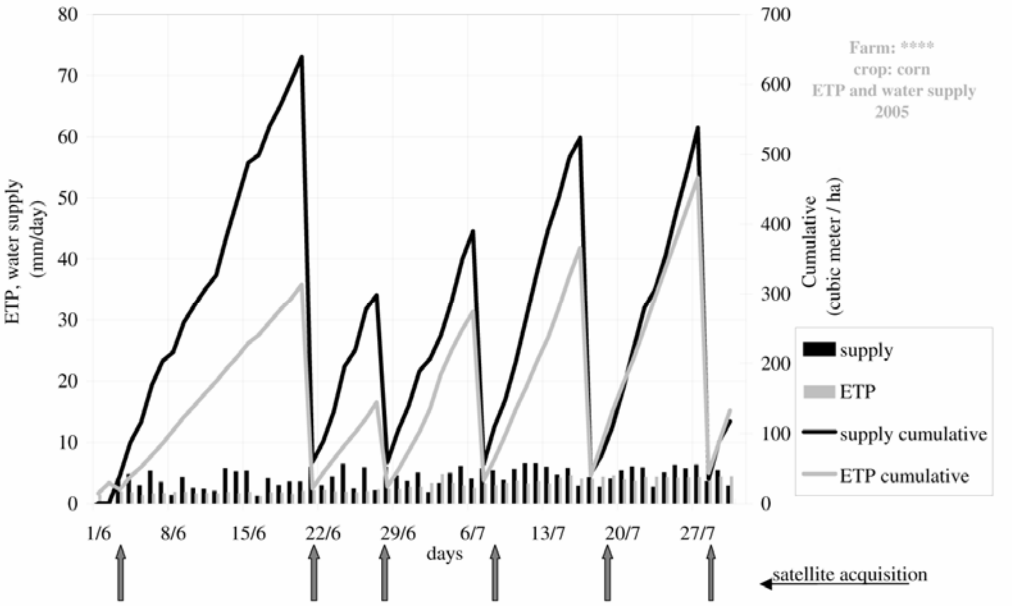


FIGURE 4. Comparison between the water volume supplied with irrigation and the crop water requirement estimated from E.O. data (bars:daily; lines: cumulate values). Data refer to a corn field with sprinkler irrigation. The farm has received weekly reports, for scheduling irrigation from the information provided.

CONCLUDING REMARKS

From the experience briefly presented here, it is possible to conclude that satellite remote sensing represent a mature technology ready to be transferred to operational applications in real-time

(Calera et al., 2005). Basic and advanced products, such as evapotranspiration and crop water requirements maps, based on satellite images and personalized for each farm and each parcel are delivered by using new Information Technology media (D'Urso et al., 2006).

In the near future, thanks to improvements in the spatial and radiometric accuracy of new sensors, a more accurate estimation of this type of applications can be achieved. Thanks to the development of fast-access to Web resources, the time lag between satellite acquisition and availability of data to the final user has sharply decreased.

It is not difficult to positively assess the “cost-benefit” effectiveness of using E.O.data in operational contexts, with tangible benefits for a better management of water resources in irrigated areas.

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REFERENCES

Baret F., Jacquemoud S., Hanocq J. F. (1993). About the soil line concept in remote sensing. Advances in Space Research, 13, 5, 281-284

Baret, F., Hagolle, O., Geiger, B., Bicheron, P., Miras, B., Huc, M., Berthelot, B., Nino, F., Weiss, M, Samain, O., Roujean, J.L., Leroy, M. (2007). LAI, fAPAR and fCover CYCLOPES global products derived from VEGETATION. Part 1: Principles of the algorithm. Remote Sensing of Environment 110 (3), 275-286

Bausch W.C. (1995). Remote sensing of crop coefficients for improving the irrigation scheduling of corn. Agric. Water Manag., 27: 55-68

Calera, A., A.M. Jochum, A.Cuesta, A. Montoro, and P. López Fuster (2005). Irrigation management from space: Towards user-friendly products. Irrig. Drain. Systems, 19, 337-353

Choudhury B.J., Ahmed N.U., Idso S.B., Reginato R.J., Daughtry C.S.T. (1994). Relations between evaporation coefficients and vegetation indices studied by model simulations. Remote Sensing of Environment, 50: 1-17

Clevers J.G.P.W. (1989). The application of a weighted infrared-red vegetation index for estimating leaf area index by correcting for soil moisture. Remote Sensing of Environment, 29: 25-37

D'Urso G., Menenti M. (1995). Mapping crop coefficients in irrigated areas from Landsat TM images; Proceed. European Symposium on Satellite Remote Sensing II, Europto, Paris, sett.'95; SPIE, Intern. Soc. Optical Engineering; 2585: 41-47

D'Urso G., Calera Belmonte A. (2006). Operative approaches to determine crop water requirements from Earth Observation data: methodologies and applications. In D'Urso G., Osann Jochum M.A., Moreno J. (Eds.): Earth Observation for vegetation monitoring and water management”, Conference Proceedings Naples, 2005, 9-10 Nov., published by American Inst. Physics, Vol. 852: 14-25

FAO (1998). Crop evapotranspiration. Guidelines for computing crop water requirements. Irrigation and drainage Paper no.56, Food and Agriculture Organis., Rome

Jacquemoud, S. & Baret, F. (1990). PROSPECT: A model of leaf optical properties spectra. Remote Sensing of Environment, 34, 75-91

Kelliher F.M., Leuning R., Raupach M.R., Schulze E.D. (1995). Maximum conductances for evaporation from global vegetation types. Agricultural Forest Meteorology, 73: 1-16

Menenti M., Bastiaanssen W.G.M., van Eick D. (1989). Determinantion of surface hemispherical reflectance with Thematic Mapper data. Remote Sensing of Environment, 28: 327-337

Monteith J.L., Unsworth M.H. (2007). Principles of Environmental Physics. 3rd Ed., Academic Press, London, pp.440

Moran M.S., Jackson R.D. (1991). Assessing the spatial distribution of evapotranspiration using remotely sensed inputs. Journal Environmental Quality, 20, 725-737

Neale, C.M. U., Bausch, W.C., and Heermann, D.F. (1989). Development of Reflectance-Based Crop Coefficients for Corn. Transactions of ASAE, 32(6): 1891-1899

Price J.C. (1992). Estimating Leaf Area Index from remotely sensed data. Proc. IGARSS '92 (Houston), 1: 1500-1502

Richter, K., Vuolo, F., D’Urso, G., Dini, L. (2007). Evaluation of different methods for the retrieval of LAI using high resolution airborne data. In: SPIE’s conference proceedings: Remote Sensing for Agriculture, Ecosystems, and Hydrology, M. Owe, G. D'Urso, C. M. Neale (Eds), vol. 6742, Florence, Italy, September 2007

Verhoef, W. (1984). Light scattering by leaf layers with application to canopy reflectance modeling: the SAIL Model. Remote Sensing of Environment, 16, 125-141

Weiss, M., Baret, F., Myneni, R.B., Pragnère, A. & Knyazikhin, Y. (2000). Investigation of a model inversion technique to estimate canopy biophysical variables from spectral and directional reflectance data. Agronomie, 20, 3-22

Authors' biography

Guido D'Urso is Full Professor of Irrigation and Water Management at the University of Naples Federico II, with a PhD in Environmental Sciences from the Agricultural University of Wageningen (NL). He has fifteen years of experience in soil hydrology and remote sensing applied to water management related problems.
He has been actively involved since early '90s in the study of techniques for the interpretation of Earth Observation data for water management in agriculture and spatial analysis of hydrological processes. Improved observation techniques and analyses of the reflectance behaviour of vegetated surfaces have been investigated for a better estimation of land surface parameters, such as Leaf Area Index, and water balance terms, i.e. evapotranspiration, in the context of research projects and field campaigns in Europe.
Other research activities are concerning the application of distributed agro-hydrological models for water management and irrigation and the development of techniques for the determination of soil water content from active microwave sensing.
He has coordinated several national and international research projects in the field of water management for agriculture. His research is documented by more than 60 publications on scientific journal, congress proceedings and specialized books.

Francesco Vuolo is research scientist at ARIESPACE s.r.l. (Italy) a spin-off company of the University of Naples "Federico II" operating in the field of remote sensing and environmental research. He holds a Doctorate in Management of Agricultural and Forestry Resources from the University of Naples Federico II (IT). His research interest covers the field of the retrieval of biophysical vegetation parameters from hyper-spectral and high-resolution E.O. data, evapotranspiration and irrigation water requirements. He was involved in planning of field campaign for biophysical and radiometric vegetation parameters acquisition and E.O. data and algorithms validation (ESA SPARC RFQ/3-10824/03/NL/FF and 18307/04/NL/FF - NERC MC04/28).

Carlo de Michele got his "Laurea" in Civil Engineering – Hydraulic Section at the University of Naples, Italy, in 2004. His main expertises are in GIS applications to water use management and in the development of integrated decision support system for environmental monitoring. He has been involved in national and international projects (U.E. DEMETER-EVG2-2001-00042). He is the C.E.O. of ARIESPACE s.r.l. (www.ariespace.com).