Combination of ground and satellite data for the operational estimation of daily evapotranspiration

Marta Chiesi1*, Bernardo Rapi1, Piero Battista1, Luca Fibbi2, Bernardo Gozzini2, Ramona Magno2, Antonio Raschi1 and Fabio Maselli1

1 IBIMET-CNR, Via Madonna del Piano 10, 50019, Sesto Fiorentino (FI), Italy
2 LAMMA, Via Madonna del Piano 10, 50019, Sesto Fiorentino (FI), Italy
*Corresponding author, e-mail address: m.chiesi@ibimet.cnr.it

Abstract
A recent paper of our research group has proposed a simplified “water balance” model which predicts actual evapotranspiration (ETₐ) based on ground and remotely sensed data. The model combines estimates of potential evapotranspiration (ET₀) and of fractional vegetation cover derived from NDVI in order to separately simulate transpirative and evaporative processes. The new method, named NDVI-Cws, was validated against latent heat measurements taken by the eddy covariance technique over various vegetation types in Central Italy. The current paper extends this validation to three other test sites in Tuscany for which reference data are obtained from different sources. In the first two sites (non-irrigated winter wheat and irrigated maize fields) seasonal reference ETA data series are obtained by the WinEtro model. In situ transpiration measurements are instead used as reference data for a deciduous oak forest stand. The ETₐ and transpiration estimates of the NDVI-Cws method are very similar to the reference data in terms of both annual totals and seasonal evolutions. Examples are finally provided of the model application for operationally monitoring ETₐ in Tuscany.

Keywords: MODIS, VGT, NDVI, Kc, sap-flow, WinEtro.

Introduction
Actual evapotranspiration (ETₐ) is a major term of terrestrial water budgets which must be known as accurately as possible for numerous scientific and operational tasks. For example, estimates of ETₐ are needed for natural and agricultural resource management, particularly for planning possible responses to ongoing climate changes [Mutibwa and Irmak, 2013]. Preferentially, such estimates should be available at great temporal frequency (hourly/daily) and with high spatial resolution (tens/hundreds of meters), especially in areas having heterogeneous and fragmented vegetation cover [Bolle et al., 2006]. Since the launch of the first meteorological and earth observation satellites, remote sensing techniques have been seen as a possible means to obtain information on ETₐ at different
spatial and temporal scales. Several studies have been conducted on this subject using various types of satellite data [e.g. Rocha et al., 2012]. “Energy balance” methods, which use thermal infrared imagery to estimate the latent heat of evapotranspiration, generally suffer from problems of undersampling in the spatial or temporal domains [Senay et al., 2012]. The alternative “water balance” methods, which reproduce the water transport through soil and vegetation, are therefore usually preferred for operational ET_{A} monitoring. The most common of these methods are based on a simple modification of the classical time-varying crop coefficient (Kc) model, which is widely utilized by the Food and Agricultural Organization (FAO) [Allen et al., 1998]. In practice, Kc is derived from multitemporal vegetation index profiles and is used to modify estimated potential evapotranspiration (ET_{0}) through the formula:

\[ ET_{A} = ET_{0} f(VI) \]  

where f(VI) is a linear or nonlinear transformation of various vegetation indices, among which the Normalized Difference Vegetation Index (NDVI) is the most commonly used for environmental monitoring [Running and Nemami, 1988; Maselli et al., 2003]. This approach, which is named Kc-NDVI method, is straightforward and is applied for the operational assessment of crop water requirement in many agricultural areas [Rocha et al., 2012]. The Kc-NDVI method, however, is of dubious applicability in natural and semi-natural environments. In particular, the method assumes that vegetation is growing under water unstressed conditions and is consequently unsuited to simulate ET_{A} in ecosystems where water stress may occur for part of the growing season, i.e in non-irrigated, water-limited environments [Glenn et al., 2010]. This issue has been addressed by a recent paper of our research group which has proposed a generalised version of the Kc-NDVI method capable of operationally assessing ET_{A} in these cases [Maselli et al., 2013]. The theoretical bases of this new approach, named NDVI-Cws, are presented in the same paper together with the results of a validation exercise conducted against latent heat eddy covariance measurements. The current paper extends this exercise to three case studies in Tuscany where reference data are obtained by different methods. Two case studies concern fields covered by winter and summer crops, for which reference ET_{A} profiles are produced through a classical Kc method [Battista et al. 2003]. The third experiment is conducted in a forest area covered by Mediterranean deciduous oaks where transpiration measurements were taken during a previous investigation [Chiesi et al., 2002]. After these tests, examples of the operational use of the method for monitoring ET_{A} in Tuscany are shown and commented.

**Materials and Methods**

**Computation of reference ET_{A} data for the agricultural sites**

Reference ET_{A} data for the two agricultural test sites were obtained by a conventional crop coefficient model which is implemented within WinEtro [Battista et al., 2003]. First, two fields covered by winter and summer crops were selected in Tuscany using various types of satellite imagery and provincial agricultural statistics. Specifically, large and homogeneous areas (around 1 km^2) covered by the same crop were searched in order to facilitate the accurate extraction of MODIS NDVI data. The operation was quite complex, since the
mean field size in Central Italy is much smaller than 1 km², and was carried out by visually examining high spatial resolution Landsat TM and Ikonos images of different years. This led to identify two areas of the required size: the first, near Montacchiello, was likely covered by winter crops in 2012 and the second, near Foiano della Chiana, was likely covered by summer crops in 2002 (Fig. 1 and Tab. 1). Both study sites are flat and show a Mediterranean climate with mild winters and hot/dry summers [Rapetti and Vittorini, 1995]. The coverage of these areas with winter and summer crops was confirmed by the analysis of relevant annual NDVI profiles extracted from MODIS imagery (see below). The crop species actually grown in the areas were finally assessed by the examination of local agricultural statistics, which indicated that the former (2012 winter crop) corresponded to non irrigated winter wheat and the latter (2002 summer crop) to irrigated maize.

![Figure 1 - MODIS NDVI image of August 2002 with the position of the three test sites (annual crops, squares, 1 = Montacchiello and 2 = Foiano della Chiana; forest, triangle, 3 = Radicondoli). The image extends over 42.-45° Lat. N, 8-13° Long. E, with a spatial resolution of about 250 m.](image_url)

| ID | Study area               | Position (Lat. N, Long. E) | Altitude (m a.s.l.) | Biome type (crop) | Considered period          |
|----|-------------------------|-----------------------------|---------------------|-------------------|---------------------------|
| 1  | Montacchiello           | 43.65° 10.43°               | 5                   | Winter crop (wheat) | 15/11/2011 - 12/07/2012   |
| 2  | Foiano della Chiana     | 43.25° 11.85°               | 240                 | Summer crop (maize)| 15/04/2002 - 07/09/2002   |
| 3  | Radicondoli             | 43.25° 11.00°               | 600                 | Oak forest (Q. cerris) | 15/05/1998 - 31/10/1998    |
Two meteorological stations adjacent to the two sites (Pisa S. Giusto for Montacchiello, and Bettolle/Cortona for Foiano della Chiana) provided the daily temperature and rainfall data to drive the application of WinEtro in the two study years. This model can compute ET0 through the classical Hargreaves-Samani method. Hargreaves and Samani [1982, 1985] proposed several improvements for the original Hargreaves equation [Hargreaves, 1975] for estimating potential evapotranspiration. One of them provides good estimation of plant water consumption also in the absence of measured global radiation, requiring only daily mean, maximum and minimum air temperatures data [Hargreaves and Samani, 1982, 1985]:

\[
ET_0 = 0.0023 \frac{R_g}{L} (T_{mean} + 17.8) (T_{max} - T_{min})^{0.5} \]  

where \( R_g \) is the extraterrestrial solar radiation (computed on the basis of astronomical formulae), \( L \) is the latent heat of evaporation and \( T_{mean}, T_{max}, \) and \( T_{min} \) are the mean, minimum and maximum temperatures, all referred to examined day. In turn, \( L \) is computed as:

\[
L = (2500.5 - 2.44 T_{mean}) 10^3 \]  

This method is based on the assumption that at least 80% of ET0 can be explained by temperature and solar radiation and \( \Delta T \) is related to humidity and cloudiness [Samani and Pessarakli, 1986]. Thus, although this equation only needs a daily measurement of maximum and minimum temperatures and is presented as a temperature-based method, it effectively uses radiation. For its characteristics, the methodology finds a large range of application in diverse climates around the world [Shahidian et al., 2012].

WinEtro computes crop water consumption (here assumed equivalent to \( \text{ETA} \)) through a full site specific water balance, taking into account rainfall, irrigation intakes, soil texture and plant exigencies, applying specific crop coefficients (\( K_c \)), related to the phenological stage of the crops [Battista et al., 2003]. The information required by the model for the current simulation of winter wheat and maize ET\( \lambda \) was derived from local sources (i.e. regional and provincial agricultural and agro-meteorological reports, soil map of Tuscany, etc., see http://www.arsia.toscana.it/).

Collection of transpiration measurements for the forest site

The transpiration measurements used as reference data for the forest experiment were taken during the 1998 growing season in an area close to Radicondoli (Fig. 1). The terrain of the area is hilly, with elevation of about 600 m; the climate is Mediterranean sub-humid [Rapetti and Vittorini, 1995], with mild winters and long dry summers. The forest areas, which cover about 70% of the landscape, are dominated by diverse deciduous species. Two types of Mediterranean oaks, \textit{Quercus pubescens} Willd. and \textit{Quercus cerris} L., are by far the most common. The understorey layer is generally characterized by the presence of young trees of the main dominant species (especially natural regeneration) and shrubs of different species. Transpiration (actually sap flow) was measured during the 1998 growing season (May-October) in two oak stands of about 1 ha, the first dominated by \textit{Q. cerris} and the second by \textit{Q. pubescens} [Chiesi et al., 2002]. A full description of the technique currently applied to measure sap flow in forest ecosystems is reported in Cermak et al. [1998]. The measurements
were referred only to the trees of the two forest stands, which showed different densities. In the first stand oaks were dense and canopy cover was almost complete (80-90%), while in the second stand canopy closure was notably lower (50-60%). Consequently, only in the *Q. cerris* stand the sap flow measurements could be considered to approximate the total transpiration of the forest, while in the *Q. pubescens* stand the undetected contribution of the understorey was likely significant. Only the sap flow data taken in the first stand were therefore currently used to validate the transpiration estimates obtained by the NDVI-Cws method.

**Application of the NDVI-Cws method**

A full description of the proposed NDVI-Cws method is provided in Maselli et al. [2013]; a functional scheme of the method is shown in Fig. 2. In summary, NDVI is used to estimate fractional vegetation cover (FVC), which indicates the quantity of green transpiring biomass that depends on long-term water stress. The estimation of FVC allows the separate simulation of transpirative and evaporative processes, which are both limited by short term water stress. The effect of this stress is accounted for by two meteorological factors which are applied to vegetated and unvegetated cover fractions according to the formula:

\[
ET_A = ET_0 \left( FVC \times K_{c_{Veg}} \times Cws + (1 - FVC) \times K_{c_{Soil}} \times AW \right) \tag{4}
\]

where \( K_{c_{Veg}} \) and \( K_{c_{Soil}} \) are maximum Kc values of vegetation and soil and \( Cws \) (Coefficient for Water Stress) and \( AW \) (Available Water) are the two meteorological factors which are obtained without computing a full site water balance [Maselli et al., 2009, 2013]. As explained in these articles, in fact, \( Cws \) is calculated as:

\[
Cws = 0.5 + 0.5 \times AW \tag{5}
\]

![Figure 2 - Schematic representation of the new NDVI-Cws ET<sub>A</sub> estimation method (see text and Maselli et al., 2013 for details).](image-url)
where AW is the ratio between precipitation and ET$_0$ cumulated over 2 or 1 months for woody or non woody vegetation types, respectively. Similarly, Kc$_{veg}$ is differentiated for the same vegetation types (0.7 and 1.2, respectively), while Kc$_{soil}$ is fixed to 0.2. The two water stress factors are always activated for the vegetation types which are not irrigated. In the case of irrigated annual crops these factors are activated only when water is not artificially provided, which is indicated by the presence of FVC higher than 0.6 during the summer water-limited period. All current applications of the NDVI-Cws ET$_A$ estimation method were driven by meteorological data (daily minimum and maximum temperature, precipitation and solar radiation) completely independent of those used to produce the reference datasets. These were meteorological data interpolated at 1 km resolution starting from ground measurements taken in a network which did not include the stations of the three study areas. The interpolation was carried out through the sequential application of the DAYMET and MT-CLIM algorithms [Thornton et al., 1997, 2000; Chiesi et al., 2007]. The 1 km daily temperature and solar radiation data were then used to produce ET$_0$ maps through the empirical formula of Jensen and Haise [1963]. These maps were finally combined with relevant rainfall maps to compute maps of AW and Cws. The information on land use needed for activating the two water stress factors was derived from the CORINE land cover map of Tuscany [Maricchiolo et al., 2004].

For the two agricultural study sites the NDVI data required by the NDVI-Cws model were derived from the MODIS Terra and Aqua satellite sensors, which are providing images since spring 2000. The used MODIS NDVI product has a 250 m spatial resolution and is composed over a 16-day time period. All MODIS NDVI images covering Central Italy were freely downloaded in a pre-processed format from the USGS database (http://lpdaac.usgs.gov) for the years from March 2000 to December 2012. These images were processed as described in Maselli et al. [2009] and temporally interpolated on a daily basis. Daily FVC values were then computed by applying the linear equation proposed by Gutman and Ignatov [1998], with NDVI$_{min} = 0.15$ and NDVI$_{max} = 0.9$ [see Maselli et al., 2013 for details]. Finally, the FVC maps were combined through equation [4] with the meteorological maps downscaled to 250 m resolution in order to produce daily ET$_A$ maps for the same period as above (March 2000 to December 2012).

The use of MODIS data was not feasible for the validation experiment in the forest site, whose reference data were collected in 1998. Consequently Spot-Vegetation (VGT) data were used in this case. These data were taken from the archive of VITO (http://free.vgt.vito.be), which freely distributes pre-processed ten-day maximum value composite (MVC) images for the entire globe since April, 1998 [Maisongrande et al., 2004]. These NDVI images, having a pixel size of about 1 km$^2$, were downloaded for the period April-December 1998. The images were pre-processed as described previously, interpolated on a daily basis and transformed into FVC. Since VGT NDVI shows a reduced range with respect to the corresponding MODIS product [Fensholt et al., 2006], the last operation was carried out using slightly different NDVI$_{min}$ and NDVI$_{max}$ values (i.e. 0.25 and 0.85, respectively). Finally, the FVC maps were combined with interpolated meteorological data through a modified version of equation [4] which accounted only for the transpiration component, i.e. excluded the contribution of evaporation (1-FVC).

Quality assessment of the NDVI-Cws estimates
The quality of the NDVI-Cws estimates was finally assessed versus the available reference data. As previously mentioned, for the agricultural sites the daily ET$_A$ estimates were compared to the outputs of WinEtro, while for the forest site the daily transpiration


estimates were compared to the sap flow measurements. In all cases the daily estimates were extracted from the pixel corresponding to each study site for the period of interest. The agreement between the reference and estimated data was summarized using the coefficient of correlations (r), the root mean square error (RMSE) and the mean bias error (MBE).

**Results**

The results of the comparison between \(\text{ET}_A\) estimated by WinEtro and NDVI-Cws method are relatively similar for the two study sites. In the case of winter wheat the \(\text{ET}_A\) simulated by WinEtro shows a peak in May, when leaf development is still maximum and water is not limiting (Fig. 3). Within the simulation no irrigation is required, in spite of the extreme dryness which characterized late winter 2012. The \(\text{ET}_0\) estimates derived from interpolated weather data are similar to those from the meteorological station. This is not the case for Cws, which is clearly underestimated due to a corresponding rainfall underestimation that is particularly evident during the mentioned late winter dry period (data not shown). The MODIS NDVI profile of this field shows a typical peak in April-May (maximum around 0.85) followed by an abrupt decrease in mid-June consequent on wheat maturity and harvesting. Within the complete \(\text{ET}_A\) simulation Cws is always active with the exception of a few days at the end of the wheat growing cycle (early June), when the crop is still green (FVC>0.6).

![Figure 3 - Winter crop (wheat) field close to Montacchiello; daily reference \(\text{ET}_A\) estimated by WinEtro compared to the \(\text{ET}_A\) estimated by the NDVI-Cws method (** = highly significant correlation, \(P < 0.01\)).](image)

The combination of these patterns brings to a certain underestimation of \(\text{ET}_A\) by the NDVI-Cws method in the first part of the season (February-early April), mainly linked to the observed Cws underestimation. In the second part of the season the high \(\text{ET}_0\) variability which is caused by daily global radiation excursion is likely not well simulated by the Hargreaves-Samani method, which takes into account only temperature oscillation. In any case the agreement of the final \(\text{ET}_A\) estimates is good under all statistics considered (\(r=0.912\), RMSE=0.80 mm day\(^{-1}\), MBE=-0.48 mm day\(^{-1}\), Fig. 3).
Concerning the summer crop (maize) field, the ET_{\text{A}} simulated by WinEtro starts to increase at the beginning of April, has a peak at the end of June and then decreases till September (Fig. 4). Simulating the full development of maize by WinEtro requires the application of five irrigation events whose timing (from early June to early August) and intensity (total of 350 mm) are determined automatically by the model on the basis of crop water requirements. The ET_{\text{A}} and Cws estimates derived from the interpolated weather data are similar to those from the meteorological station, with a slight underestimation of Cws due to corresponding rainfall underestimation. The water stress factor, however, is deactivated for the whole summer period (from 1st June to September) due to the high NDVI values which indicate water supply by irrigation. The MODIS NDVI profile of this maize field, in fact, shows a typical evolution for a Mediterranean irrigated summer crop, with a plateau around 0.8 which lasts from early June to late August, followed by an abrupt decrease in early September due to harvest. Consequently, both simulation methods follow the rapid changes in potential evapotranspiration rate related to environmental conditions and particularly to concurrent temperature and radiation variations. A dramatic drop in the evapotranspiration rate is visible at the end of the cycle following crop harvest. Globally the agreement between the two ET_{\text{A}} estimation method is very good ($r=0.928$, RMSE=0.97 mm day\(^{-1}\), MBE=0.29 mm day\(^{-1}\), Fig. 4).

The sap flow profile of the forest study site shows a maximum in June, when potential evapotranspiration is high and water is still available, followed by a decrease due to summer water stress (Fig. 5). No accuracy assessment can concern the interpolated meteorological data due to the lack of local ground measurements. The estimated ET_{\text{0}} shows a maximum of about 8 mm/day at the beginning of July, while Cws is close to the minimum (0.5) from the end of June to the beginning of September. The VGT NDVI profile of this site ranges from 0.74 to 0.83 and is typically bimodal, with a first maximum in late spring and a secondary maximum in early autumn. The accuracy of the NDVI-Cws transpiration estimates is good ($r = 0.840$, RMSE = 0.54 mm day\(^{-1}\), MSE = 0.34 mm day\(^{-1}\)), with a certain tendency to
overestimation which can be partly attributed to the small transpiration contribution of the understorey that is undetected by the sap flow data.

Figure 5 - Forest stand close to Radicondoli; daily oak tree transpiration measured by the sap flow method compared to transpiration estimated by the NDVI-Cws method (** = highly significant correlation, P < 0.01).

Figure 6 - Example daily ET map of Tuscany (1st April 2012) obtained by the NDVI-Cws driven by MODIS data; A and B indicate annual crop and mountain areas, respectively.
Examples of the maps produced by the combination of meteorological and MODIS data are displayed in Figs. 6-7 for two days representative of spring and summer 2012. The former map shows relatively low ET\textsubscript{A} values, which are maximum in plain annual crop areas and decrease with elevation due to ET\textsubscript{0} limitation caused by lowering temperature. The summer map shows very low ET\textsubscript{A} values in bare croplands and intermediate values in most other areas. The highest ET\textsubscript{A} estimates are obtained in humid lowlands, where FVC is higher than 0.6 and the two stress factors are consequently deactivated.

**Discussion and Conclusions**
The modelling approach currently proposed to estimate ET\textsubscript{A} is a straightforward modification of the widely applied Kc-NDVI methods. Relevant innovations are introduced with the aim of improving the operational application of the method in water limited areas covered by mixed vegetation. First, the conversion of NDVI into FVC permits the separate simulation of transpirative and evaporative processes. FVC, in fact, is taken as an indicator of the quantity of transpiring green biomass, which can be transformed into generalized crop coefficients on the basis of accepted literature [Rocha et al., 2012]. This quantity is affected by water availability, since green biomass cannot survive to long water stress period, but is only marginally sensitive to short term dry spells which, however, can limit plant transpiration [Running and Nemani, 1988]. Thus, the effects of short term water stress on plant transpiration and soil evaporation are separately simulated by the use of meteorological water stress factors which do not require the full modelling of soil water...
content. These factors can reduce transpiration to half of its potential value and evaporation to zero. The final ET\textsubscript{A} estimate is therefore obtained by contemporaneously constraining ET\textsubscript{0} for estimated green biomass and meteorological indicators of short term water stress. The current testing of the method was based on reference data obtained from two different sources. The first is a classical simulation model, WinEtro, which combines ET\textsubscript{0} and K\textsubscript{c} estimates with a site specific water balance. The ET\textsubscript{0} estimates are produced by the Hargreaves-Samani method, which is affected by several factors that determine a given degree of approximation, also in optimal working conditions, that is with the availability of reliable local meteorological data. As known, potential evapotranspiration is affected by all meteorological parameters, even if temperature and radiation justify at least 80\% of its variability [Samani, 2000]. Thanks to its general applicability and wide diffusion, the Hargreaves-Samani formula can be used as reference for large scale evaluation and in particular for remote sensing method evaluation and study [Shahidian et al., 2012]. The knowledge of true field data related to decisive agronomic data, like tillage practices, plant phenology and specific cultivar characteristics, can improve the performance of WinEtro in a decisive way, allowing a more reliable and precise evaluation of the remote sensing techniques. The creation of a specific database, containing updated field data and plant characteristics, as well as the use of common and validated meteorological datasets, are strongly recommended. All these conditions were met in the current case, where the model was driven by weather measurements of adjacent stations and locally tuned K\textsubscript{c} profiles. Some uncertainty also affects the forest transpiration data obtained by the sap flow method. A full discussion of the possible errors brought by this measurement technique is reported in Nadezhdina et al. [2002]. As previously noted, the sap flow measurements are referred only to the tree component of the forest and do not include the contribution of understorey, which, however, should be minimal when canopy closure is almost complete as in the examined oak stand.

The NDVI-Cws method is affected by several error sources coming from both the ancillary and remotely sensed data used. This topic is exhaustively discussed in Maselli et al. [2013]. In spite of this problem and of its conceptual simplicity, the method has provided good results in both the agricultural and forest ecosystems analyzed. In the former case the method is inherently capable of considering the effects of spatio-temporal crop variability. The presence of different crops in different study years, in fact, causes varying multitemporal NDVI, and consequently FVC, profiles, which differently constrain the predicted ET\textsubscript{A}. This is a fundamental property of the proposed method, which allows its application on areas covered by annual crops which irregularly alternate from year to year. Similarly good results have been obtained from the parallel testing of the method against eddy covariance latent heat measurements which is described in Maselli et al. [2013]. This test concerned several forest sites representative of different eco-physiological behaviours (conifers and broadleaves, evergreen and deciduous) and environments (from Mediterranean dry to temperate humid) and was completed by the consideration of grassland and annual crop sites. In all cases, the daily ET\textsubscript{A} estimates obtained are significantly correlated with the reference data and show no substantial under or over-estimation patterns. These results, joint to those currently obtained, support the validity of the modelling theory proposed and open the way to the application of the method for operationally monitoring daily ET\textsubscript{A} on regional scale with a spatial resolution which is mostly dictated by the NDVI
data utilized (250 m in the MODIS case). Examples of this application have been currently provided for two days in spring and summer which show contrasting eco-meteorological conditions.

**Acknowledgements**
The authors want to thank Dr. J. Cermak, Dr. N. Nadezhdina, Dr. R. Tognetti and Dr. L. Bonora for their contribution to the collection of the sap flow measurements in the Radicondoli study area. Thanks are also due to two anonymous EJRS reviewers for their helpful comments on the first draft of the manuscript.

**References**
Allen R.G., Pereira L.S., Raes D., Smith M. (1998) - *Crop evapotranspiration - Guidelines for computing crop water requirements* - FAO Irrigation and drainage paper 56. FAO - Food and Agriculture Organization of the United Nations, Rome.
Battista P., Rapi B., Rocchi L. (2003) - *WinEtro: Un logiciel pour l’estimation des besoins en eau des cultures*. In: Manuel technique du Système Agrométéorologique, M.A. El Ouali, G. Maracchi, A. Di Vecchia, L. Bacci (eds.), Project d’Appui à la Direction de la Météorologie Nationale du Maroc. pp. 236-274.
Bolle H.J., Eckardt M., Koslowsky D., Maselli F., Melia-Miralles J., Menenti M., Olesen F.S., Petkov L., Rasool I., Van de Griend A. (2006) - *Mediterranean Landsurface Processes Assessed from Space*. Regional Climate Studies 2006, XXVII. Springer Series, pp. 760. doi: http://dx.doi.org/10.1007/978-3-540-45310-9.
Cermak J., Nadezhdina N., Raschi A., Tognetti R. (1998) - *Transpiration of typical natural plant stands in Tuscany*. Part of the project EC ‘MEGARICH’-ENV4/CT97/0503.
Chiesi M., Maselli F., Moriondo M., Fibbi L., Bindi M., Running S.W. (2007) - *Application of BIOME-BGC to simulate Mediterranean forest processes*. Ecological Modelling, 206: 179-190. doi: http://dx.doi.org/10.1016/j.ecolmodel.2007.03.032.
Fensholt R., Sandholt I., Stisen S. (2006) - *Evaluating MODIS, MERIS, and VEGETATION vegetation indices using in situ measurements in a semiarid environment*. IEEE Transactions on Geoscience and Remote Sensing, 44(7): 1774-1786. doi: http://dx.doi.org/10.1109/TGRS.2006.875940.
Glenn E.P., Nagler P.L. Huete A.R. (2010) - *Vegetation index methods for estimating evapotranspiration by remote sensing*. Surveys in Geophysics, 31: 531-555. doi: http://dx.doi.org/10.1007/s10712-010-9102-2.
Gutman G., Ignatov A. (1998) - *The derivation of the green vegetation fraction from NOAA/AVHRR data for use in numerical weather prediction models*. International Journal of Remote Sensing, 19: 1533-1543. doi: http://dx.doi.org/10.1080/014311698215333.
Hargreaves G.H. (1975) - *Moisture availability and crop production*. Transactions of the American Society of Agricultural and Biological Engineers, 18: 980-984. doi: http://dx.doi.org/10.13031/2013.36722.
Hargreaves G.H., Samani Z.A. (1982) - *Estimating potential evapotranspiration*. Journal of Irrigation and Drainage Division ASCE, 108: 223-230.

Hargreaves G.H., Samani Z.A. (1985) - *Reference crop evapotranspiration from temperature*. Applied Engineering in Agriculture, 1: 96-99. doi: http://dx.doi.org/10.13031/2013.26773.

Jensen M.E., Heise H.R. (1963) - *Estimating evapotranspiration from solar radiation*. Journal of the Irrigation and Drainage Division ASCE, 89: 15-41.

Maisongrande P., Duchemin B., Dedieu G. (2004) - *Vegetation/Spot: an operational mission for the Earth monitoring; presentation of new standard products*. International Journal of Remote Sensing, 25: 9-14. doi: http://dx.doi.org/10.1080/0143116031000115265.

Maricchiolo C., Sambucini V., Pugliese A., Blasi C., Marchetti M., Chirici G., Corona P. (2004) - *La realizzazione in Italia del progetto europeo I&CLC2000: metodologie operative e risultati*. Proceedings, 8th National Conference ASITA, GEOMATICA: Standardizzazione, interoperabilità e nuove tecnologie, Roma, Italy, 1: 113-128.

Maselli F., Romanelli S., Bottai L., Zipoli G. (2003) - *Use of NOAA-AVHRR NDVI images for the estimation of dynamic fire risk in Mediterranean areas*. Remote Sensing of Environment, 86: 187-197. doi: http://dx.doi.org/10.1016/S0034-4257(03)00099-3.

Maselli F., Papale D., Puletti N., Chirici G., Corona P. (2009) - *Combining remote sensing and ancillary data to monitor the gross productivity of water-limited forest ecosystems*. Remote Sensing of Environment, 113: 657-667. doi: http://dx.doi.org/10.1016/j.rse.2008.11.008.

Maselli F., Chiesi L., Angeli L. Papale D., Seufert G. (2013) - *Operational monitoring of daily evapotranspiration by the combination of MODIS NDVI and ground meteorological data*. Submitted to Remote Sensing of Environment.

Mutiibwa D., Irmak S. (2013) - *AVHRR-NDVI-Based crop coefficients for analyzing long-term trends in evapotranspiration in relation to changing climate in the U.S. High Plains*. Water Resources Research, 49: 1-14. doi: http://dx.doi.org/10.1029/2012WR012591.

Nadezhdina N., Cermak J., Ceulemans R. (2002) - *Radial pattern of sap flow in woody stems related to positioning of sensors and scaling errors in dominant and understorey species*. Tree Physiology, 22: 907-918. doi: http://dx.doi.org/10.1093/treephys/22.13.907.

Rapetti F., Vittorini S. (1995) - *Carta climatica della Toscana*. Pacini Editore, Pisa (Italy).

Rocha J., Perdigao A., Melo R., Henriques C. (2012) - *Remote sensing based crop coefficients for water management in agriculture*. In: Sustainable Development - Authoritative and Leading Edge Content for Environmental Management, Sime Curkovic (eds.). Available on line at: http://dx.doi.org/10.5772/48561.

Running S.W., Nemani R.R. (1988) - *Relating seasonal patterns of the AVHRR vegetation index to simulated photosynthesis and transpiration of forests in different climates*. Remote Sensing of Environment, 24: 347–367. doi: http://dx.doi.org/10.1016/0034-4257(88)90034-X.

Samani Z. (2000) - *Estimating solar radiation and evapotranspiration using minimum climatological data*. Journal of Irrigation and Drainage Engineering, 126: 265-267. doi: http://dx.doi.org/10.1061/(ASCE)0733-9437(2000)126:4(265).

Samani Z.A., Pessarakli M. (1986) - *Estimating potential crop evapotranspiration with minimum data in Arizona*. Transactions of the American Society of Agricultural and Biological Engineers, 29: 522-524. doi: http://dx.doi.org/10.13031/2013.30184.

Senay G.B., Bohms S., Verdin J.P. (2012) - *Remote sensing of evapotranspiration for...*
operational drought monitoring using principles of water and energy balance. In: Remote sensing of drought: innovative monitoring approaches, Wardlow B.D., Anderson M.C., Verdin J.P., Taylor and Francis Group (eds.), pp. 123-144. ISBN: 978-1-4398-3557-9.

Shahidian S., Serralheiro R., Serrano J., Teixeira J., Hai N., Santos F. (2012) - Hargreaves and other reduced-set methods for calculating evapotranspiration. Remote Sensing and Modeling, Ayse I. Publisher InTech Eds. Published online 18, January, 2012, Published in print edition January, 2012. ISBN: 978-953-307-808-3.

Thornton P.E., Running S.W., White M.A. (1997) - Generating surfaces of daily meteorological variables over large regions of complex terrain. Journal of Hydrology, 190: 214-251. doi: http://dx.doi.org/10.1016/S0022-1694(96)03128-9.

Thornton P.E., Hasenauer H., White M.A. (2000) - Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: an application over complex terrain in Austria. Agricultural and Forest Meteorology, 104: 255-271. doi: http://dx.doi.org/10.1016/S0168-1923(00)00170-2.

© 2013 by the authors; licensee Italian Society of Remote Sensing (AIT). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/4.0/).