Estimate of evapotranspiration using surface energy fluxes from Landsat TM

Barbagallo S., Consoli S., Russo A.

in

Santini A. (ed.), Lamaddalena N. (ed.), Severino G. (ed.), Palladino M. (ed.).
Irrigation in Mediterranean agriculture: challenges and innovation for the next decades

Bari : CIHEAM
Options Méditerranéennes : Série A. Séminaires Méditerranéens; n. 84

2008
pages 105-114

Estimate of evapotranspiration using surface energy fluxes from Landsat TM

S. Barbagallo, S. Consoli, A. Russo

University of Catania, Italy - Department of Agricultural Engineering

Abstract. Daily evapotranspiration fluxes over the semi-arid Catania Plain area (Eastern Sicily, Italy) were evaluated using remotely sensed data from Landsat Thematic Mapper TM5 images. A one-source parameterization of the surface sensible heat flux exchange using satellite surface temperature has been used. The transfer of sensible and latent heat is described by aerodynamic resistance and surface resistance. Remote sensing-based assessments of crop water stress (CWSI) were made in order to identify local irrigation requirements. Evapotranspiration data and crop coefficient values obtained from the approach were compared with: (i) data from the semi-empirical approach "Kc reflectance-based", which integrates satellite data in the visible and NIR regions of the electromagnetic spectrum with ground-based measurements and (ii) surface energy flux measurements collected from a micrometeorological tower located in the experiment area.

Keywords. Evapotranspiration – Remote sensing – Surface energy balance – Water stress.

Estimation de l'évapotranspiration à partir des flux énergétiques superficiels du Landsat TM

Résumé. *Les flux journaliers de l'évapotranspiration dans la Plaine de Catania (Sicile de l'Est, Italie), à climat semi-aride, ont été évalués à l'aide des données de télédétection obtenues des images du Landsat Thematic Mapper TM5. La paramétrisation de l'échange des flux de chaleur sensible superficielle a été effectuée, utilisant la température superficielle mesurée par satellite. Le transfert de la chaleur sensible et latente est décrit par la résistance aérodynamique et superficielle. L'évaluation des données satellitaires de l'indice du stress hydrique de la culture « Crop Water Stress Index » (CWSI) a servi à identifier les besoins locaux en irrigation. Les données de l'évapotranspiration ont été confrontées avec : i) les données résultantes utilisant les coefficients culturaux calculés par l'approche semi-empirique basée sur la réflectance et ii) les mesures des flux de l'énergie de surface collectées sur une tour micrométéorologique située dans la zone d'expérimentation.*

Mots-clés. *Evapotranspiration – Télédétection – Bilan d'énergie de surface – Stress hydrique.*

I – Introduction

Generally, two main satellite-based approaches were applied over irrigated agricultural areas to estimate crop water needs in terms of evapotranspiration flux: (1) the reflectance-based crop coefficient method (D'Urso, 2001) and (2) the energy balance method (Bastiaansen *et al.*, 1998). In the reflectance-based crop coefficient method, spectral inputs in the red and near-infrared bands from ground-based radiometers, airborne sensors or satellite images are used to obtain vegetative indices related to the basal crop coefficient (Neale *et al.*, 1989). One of the main advantages of using crop coefficients is that they provide an underlying model for interpolation between satellite images over time. In the energy balance method, remotely sensed data in the thermal infrared spectrum are used to model different components of the energy balance equation, such as net radiation, soil heat flux, sensible heat flux and latent heat flux. The method is more complex to apply, requiring calibrated satellite imagery and the use of an atmospherically corrected thermal infrared band, which for most satellite instruments translates into lower spatial resolution. Modeling evapotranspiration on a large scale with heterogeneous surface conditions requires a great deal of simplification, while preserving the key surface elements which control energy balance. For example, in the absence of vegetation, the surface characteristics can be described by surface albedo, emissivity, roughness length, and soil moisture content. When vegetation is present, the surface parameterization becomes more complex because vegetation transpiration is affected by the morphological and physiological characteristics of vegetation. When surface temperature is measured by a satellite (or an aircraft), the complex surface status can be lumped together, the remotely-sensed surface temperature representing a spatially integrated thermal status of the surface (Zhang *et al.*, 1995). Based on these considerations, actual evapotranspiration from a heterogeneous surface can be conceptualized as a one-layer process from an average surface transferring sensible and latent heat. In the paper, a one-layer resistance model was applied to estimate evapotranspiration fluxes over a semi-arid agricultural area in Eastern Sicily (Italy). Remotely sensed data of spatially integrated surface characteristics were combined with ground-based agro-meteorological measurements. Satellite data was provided by the Landsat Thematic Mapper TM5 sensor during June-September 2007. The objectives of the study were (i) to compare satellite-based energy balance surface fluxes with micrometeorological data from a flux tower that could be used to scale ET over orange orchards; (ii) to apply a reflectance-based approach to derive relationships between Landsat-based vegetation indices and crop coefficients (K_c) and (iii) to recognize plant water stress by satellite-based estimates of the crop water stress index (CWSI).

II – Modeling approach

1. The surface energy balance approach

The complex relationships between surface temperature, vegetation features and energy flux have been analyzed by several authors (Monteith, 1991; Zhang *et al.*, 1995) and numerous studies have proposed the use of one-dimensional (1-D) models to describe radiation conduction and turbulent transport mechanisms which influence energy balance and surface temperature (Friedl, 2002) (Figure 1). Generally, all such models are based on energy conservation principles which dictate that net radiation R_N is balanced by the soil heat flux G, sensible heat flux (H) and latent heat flux (LE) at the surface

$$R_N = G + H + LE \tag{1}$$

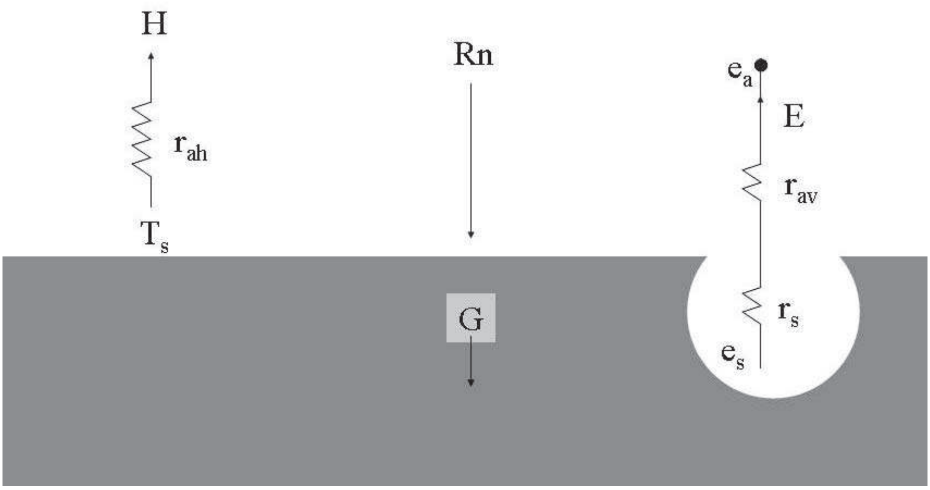


Figure 1. Schematic diagram of one-source thermal-based model for energy balance terms.

Generally, it is assumed that R_N may be easily computed, and G is parameterized in a straightforward fashion (as a simple proportion of R_N). The two remaining terms, H and LE, are turbulent flux quantities and are the most difficult to estimate. In the study, net radiation was estimated as:

$$R_N = R_S(1-r) + \varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4 \tag{2}$$

where R_s is the incoming short wave radiation (Wm^{-2}), σ is the Stefan-Boltzman constant, ε is emissivity and T is the temperature (K) with the subscripts 'a' and 's' for air and surface respectively; the surface albedo (r) is computed as in Menenti (1984). Soil heat flux was calculated by assuming that the ratio G/R_N is related to the fractional vegetation cover (Boegh *et al.*, 2002)

$$(G/R_N) = f_v (G/R_N)_{veg} + (1-f_v)\cdot(G/R_N)_{soil} \tag{3}$$

with $(G/R_N)_{veg}$=0.05, $(G/RN)_{soil}$=0.315, and f_v estimated from LAI. The terms of Eq. (1) are modelled using a 1-D flux-gradient expression based on a convection analogue to Ohm's law

$$H = \rho C_p \frac{T_s - T_a}{r_{ah}} \tag{4}$$

where ρ is air density (Kg m^{-3}), C_p is the specific heat of air at a constant pressure (J kg^{-1} K^{-1}) and r_{ah} is the aerodynamic resistance for sensible heat (s m^{-1}). Eq. 4 is a one-layer bulk transfer equation based on the assumption that the radiometric temperature measured by a thermal infrared radiometer is identical to the aerodynamic temperature. In fact, in the case of full canopy cover, there is near-equivalence between these two temperatures and it is found that estimates of evapotraspiration using radiometric temperatures are in good agreement with observed values (Zhang *et al.*, 1995). In the study surface temperature T_s was derived from band 6 TIR of Landsat TM5 using the model developed by Sobrino *et al.* (2004)

$$T_s = \frac{T_B}{1 + \left(\lambda \cdot {T_B}/{r}\right) \ln(\varepsilon)} \tag{5}$$

where λ is the wavelength of emitted radiance, $r=h\cdot c\cdot\sigma$ equaling 1.438 10^{-2} mK, where h is Planck's constant, c the velocity of light and σ the Boltzman constant; emissivity ε was estimated through (Sobrino *et al.*, 2001)

$$\varepsilon = f_v \varepsilon_v + (1-f_v)\cdot \varepsilon_s \tag{6}$$

where ε_v and ε_s denote emissivity of vegetation (0.985) and soil (0.960). The fractional vegetation cover fv is related to leaf area index (LAI), $f_v = 1 - e^{-0.5\cdot LAI}$ (Norman *et al.*, 1995). By applying the inverse of Plank's radiation equation, spectral radiance in the thermal band was converted to brightness temperature T_B

$$T_B = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda + 1}\right)} \tag{7}$$

where K_1 and K_2 are calibration constants defined for Landsat 5 TM sensor (Chander and Markham, 2003): L_λ is the pixel value as radiance (W m^{-2} sr^{-1} μm^{-1}). The inverse of Planck's law, used to derive T_s, can be interpreted as a correction of the atmospheric and emissivity effects on the data measured by the sensor (Sobrino *et al.*, 2004). Latent heat transfer is expressed as

$$LE = \frac{\rho C_p}{\gamma} \frac{e_s(T_s) - e_a}{r_{av} + r_s} \tag{8}$$

where γ is the psychometric constant, $e_s(T_s)$ is the saturated vapour pressure at the surface temperature (kPa), e_a is the vapour pressure at the reference height (kPa), r_{av} is the physiological resistance (s m^{-1}) to moisture transport at the surface. The surface resistance r_s (s m^{-1}) to vapour transfer exerts strong control on the partitioning of available energy (R_N-G) between H and LE. The aerodynamic resistance r_{ah} of eq. 4 was calculated on the basis of the Monin-Obukhov surface layer similarity theory (Brutsaert, 1982)

$$r_{ah} = \frac{\left[\ln\left(\frac{z-d}{z_{oh}}\right) - \Psi_{sh}\right] \times \left[\ln\left(\frac{z-d}{z_{om}}\right) - \Psi_{sm}\right]}{k^2 \cdot u} \tag{9}$$

where z_{oh} e z_{om} are roughness lengths for sensible heat and for momentum (m), respectively; $z_{om}=0.13 \cdot h_c$ (with h_c the mean height of the crop in meters); $z_{oh}=0.1 \cdot z_{om}$ (Chodhury *et al.*, 1987); $d=0.66 \cdot h_c$ is the zero-plane displacement height (m); Ψ_{sh} e Ψ_{sm} are the stability correction functions for momentum and sensible heat; k is von Karman's constant; u (m s^{-1}) is the wind speed at level z (10 meters). The stability correction functions were determined with the Businger-Dyer formulations (Sugita and Brutsaert, 1990) for unstable conditions (Businger, 1988). Surface resistance was determined by substituting eqs. (4) and (8) into eq. (1), without making a distinction between soil evaporation and plant transpiration

$$r_s = \frac{(e_s(T_s) - e_a)}{\gamma\left[(R_N - G)/\rho C_p - (T_s - T_a)/r_{ah}\right]} r_{av} \tag{10}$$

in which the physiological resistance r_{av} was considered equal to r_{ah} (Zhang *et al.*, 1995). The extrapolation of LE into daily estimates, which most interests agricultural water management, was based on evaporative fraction (EF) (Bastiaanssen, 1995)

$$EF = \frac{LE}{R_n - G} \tag{11}$$

Daily evapotranspiration ET_{24} (mm d^{-1}) values were then calculated by the following equation

$$ET_{24} = EF \frac{R_{N,24}}{L} \tag{12}$$

where L (MJ m^{-2} mm^{-1}) is the latent heat of vaporization and $R_{N,24}$ is the daily net radiation measured by a micrometeorological flux tower.

2. The crop water stress index

The CWSI was computed as (Idso *et al.*, 1981)

$$CWSI = \frac{(T_s - T_a) - (T_s - T_a)_{lower}}{(T_s - T_a)_{upper} - (T_s - T_a)_{lower}} \tag{13}$$

where $(T_s\text{-}T_a)$ is the measurement, $(T_s\text{-}T_a)_{lower}$ is the theoretical minimum value for $(T_s\text{-}T_a)$ and $(T_s\text{-}T_a)_{upper}$ is the theoretical maximum value for $(T_s\text{-}T_a)$. Jackson *et al.* (1988), using a steady state energy balance of a crop canopy, developed a theoretical CSWI where

$$T_s - T_a = \frac{r_{ah}(R_n - G)}{\rho C_p} \times \frac{\gamma(1 + r_s/r_{ah})}{\Delta + \gamma(1 + r_s/r_{ah})} - \frac{VPD}{\Delta + \gamma(1 + r_s/r_{ah})} \quad (14)$$

in which VPD is the vapor pressure deficit (kPa); the other variables of Eq. 14 are satellite-based estimates and were introduced in the previous paragraph. The maximum theoretical value for (T_s-T_a) was evaluated assuming r_s approaches infinity and the minimum theoretical value for (T_s-T_a) was defined by setting r_s equal to zero in Eq. 14.

3. The K_c reflectance-based approach

The reflectance-based crop coefficient method (D'Urso, 2001) consists of the direct application of a theoretical ET equation to define K_c (Doorenbos and Pruitt, 1977; Allen *et al.*, 1998)

$$K_c = \frac{ET_c}{ET_0} \quad (15)$$

While reference evapotranspiration (ET_0) accounts for variations in weather and offers a measure of the 'evaporative' demand of the atmosphere, crop coefficients (K_c) account for the difference between reference (ET_0) and potential (ET_c) crop evapotranspiration. Crop coefficient values (K_c) were expressed as follows (Stanghellini *et al.*, 1990):

$$K_c = \sum_{i=0}^{4} C_i LAI^i \quad \text{with} \quad C_i = a_i + b_i r \qquad i = 0,.1,2,.3,.4 \quad (16)$$

where the coefficients a and b of the polynomial equation were determined as functions of climatic data (net radiation R_N, air temperature T, air humidity RH, and wind speed u) measured by the automatic stations located in the study-area, and canopy properties (LAI, albedo r) determined using remote sensed data.

III – Application of the proposed approaches

1. Experimental site and micrometeorological energy fluxes

The Catania Plain area is the largest agricultural district in Sicily (Italy), with an area of about 50,000 ha. It is characterized by citrus orchards for more than 90% of the irrigated area (about 18,000 ha). The climate is semi-arid and the annual potential ET exceeds by about 30% the mean annual rainfall (about 500 mm) (Consoli *et al.*, 2006). During June-September 2007, surface energy fluxes, meteorological data and radiometric temperatures were measured by a micrometeorological flux tower located in a experimental orchard with a fetch of more than 200 m in all directions. Net radiation R_N was measured using a net radiometer mounted above the orchard canopy. Soil heat flux density G was measured using soil heat flux plates and soil averaging temperature sensors. High frequency temperature data was collected at 4 Hz using two 76.2 µm diameter fine-wire thermocouples mounted at 0.5 meters above the canopy top. When plotted against time the temperature traces show ramp-like characteristics, which are used to estimate heat fluxes using a conservation of energy equation (Gao *et al.* 1989; Paw U *et al.* 1995). The temperature data was analyzed to determine the mean ramp amplitude (a) and the inverse ramp frequency (d+s) using a structure function (Van Atta, 1977) and time lags of 0.25 and 0.50 seconds for each of the two thermocouples. Sensible heat flux was calculated, using the Surface Renewal technique, as

$$H = \alpha \rho C_p \left(\frac{a}{d + s}\right) z \quad (17)$$

Factor α is a correction term for unequal heating below the sensors. In combination, half-hourly data on H, R_N and G were used to calculate latent heat flux density (LE) as the residual of the energy balance equation. Soil moisture was monitored continuously using the Time Domain Reflectrometry (TDR) technique in different fields within the experimental area, at soil depths of 15, 30 and 60 cm. Leaf area index (LAI) values were measured with a Licor LAI-2000 digital analyzer at regular intervals during the satellite acquisitions.

2. Processing satellite-based data

The satellite data consisted of Landsat Thematic Mapper TM5 images acquired on June 14th, July 22nd, August 17th and September 8th 2007. The images were geometrically rectified to a UTM projection system (Jensen, 1986). The reflectance values in the VIS/NIR region were calculated from the images, or at the top of atmosphere or by applying a correction for the atmospheric effects. Thermal band 6 needs no calibration, since the derived surface temperature data accords well with the surface temperature data from the infrared thermometers mounted at a height of 4 m above ground and pointing 45° towards the surface. Landsat TM pixels encompassing the tower site were used to establish relationships between flux tower ET and the satellite data for energy flux and vegetation indices.

IV – Results and discussion

1. Comparing the model estimates of energy flux with micrometeorological measurements

Sensible heat flux (H) from the micrometeorological tower was between zero and 3.4 MJ m^{-2} d^{-1} with an average of 2.5 MJ m^{-2} d^{-1}. Latent heat flux (LE) average was 11.6 MJ m^{-2}d^{-1}, varying between 4.2 and 16.2 MJ m^{-2}d^{-1}. Net radiation (R_N) values were between a maximum of 18.9 and a minimum of 2.7 MJ m^{-2} d^{-1}, with an average of 13.3 MJ m^{-2}d^{-1}. On a daily basis the G term was generally close to zero. Micrometeorological tower fluxes during the satellite overpass (10:00 a.m. local time) were plotted in Figure 2. In general, agreement between the modeled and observed fluxes was good. The observed mean energy fluxes were respectively 521.5, 42.5, 31.7 and 447.3 W m^{-2} for R_N, G, H and LE flux densities. The energy fluxes obtained by processing TM bands during the satellite acquisition dates had a relatively narrow spatial distribution (maximum time variation of about 24%) at the tower site, with average values of 570, 40.4, 45.6 and 408.3 W m^{-2} respectively for R_N, G, H and LE flux densities.

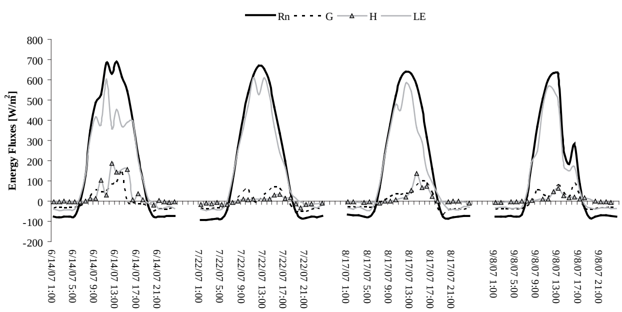


Figure 2. Hourly energy flux at the micrometeorological station.

The spatial variability of surface energy fluxes from Landsat scenes of about 850 mixed pixels was depicted in Figure 3. The study revealed that the amount of energy available for physical and biological processes over the crop (R_N) varied from a maximum of 638 to a minimum of 361 W m^{-2}. The main variation of LE occurred due to variations of R_s, T_s, LAI and soil moisture. The LE variation was from 127to 564 W m^{-2}. The G range was 28.8-48.5 W m^{-2}, with a maximum spatial variation of 10%. H flux from the surface to the atmosphere varied from 74.7 to 17.5 W m^{-2}, with a mean of 45.6 W m^{-2} and spatial variation of 24%. Daily satellite ET_{24} (mm d^{-1}) values strongly (R^2=0.8) correlated with NDVI and LAI. ET correlated more weakly (R^2=0.37) with R_N across the period, showing that the plants were not radiation-limited most of the time. Hence, ET was mainly determined by the amount of green vegetation or functioning vegetation in the agricultural field which is typical for semi-arid landscapes (Nagler *et al.*, 2007). The calculated ET_{24} values compare fairly well to the tower flux estimates of ET using Surface Renewal technique.

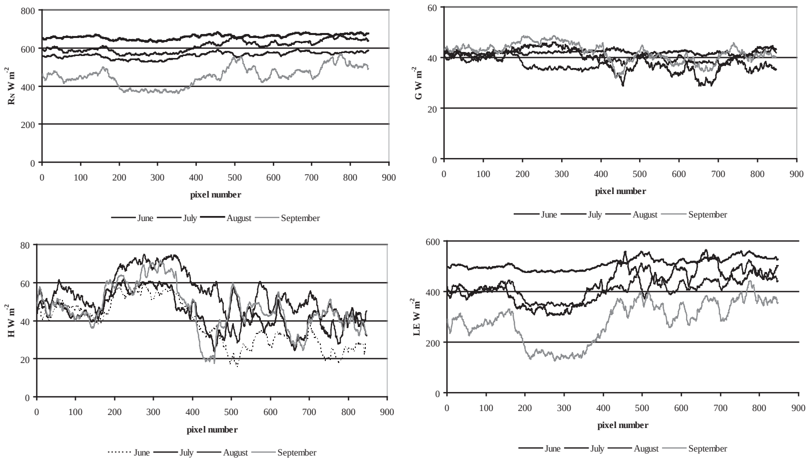


Figure 3. Spatial distribution of remote sensed energy fluxes.

Mean ET_{24} values across June-September 2007 were 4.98 and 5.08 mm d^{-1}, respectively, from the satellite energy balance approach and from tower flux measurements with a temporal variability of about 15%. In Figure 4, the satellite-based crop coefficients (K_c) were compared with tower flux K_c and the results of the reflectance-based approach. K_c during June-September 2007 were in the ranges 0.75-0.92, 0.76-0.89 and 0.5-1.14 from respectively, satellite energy balance, reflectance-based approach and tower flux data. Maximum variability occurred with K_c tower flux data whereas the satellite-based K_c estimates were more uniform. On average (about 0.8), K_c were slightly higher than those reported in the widely used FAO publications for orchards with about 70% ground cover. Linear correlations express the increase in K_c from the reflectance-based approach with NDVI (Rouse, 1974). The linear trend presents a determination coefficients (R^2) higher than 0.90, with minimal scatter around the regression lines. Figure 5 depicts the surface resistance (r_s) as functions of the fractional vegetation cover (fv). In the Figure, r_s tends to change logarithmically with vegetation density variation. Dense vegetation (fv=0.88; r_s 145-160 s m^{-1}) has been found for stressed canopies in semi-arid areas (Soegaard, 1999). High surface resistances reflect dry soil surfaces and, generally, correspond to low soil moisture content at the irrigated site. This was confirmed by soil water content at selected control sites reaching minimums of 27% when the T_s-T_a difference was maximum. As expected, both T_s-T_a and r_s are lower when LAI (and fv) is high. Generally, a rather small range of r_{ah} values represents each fv.

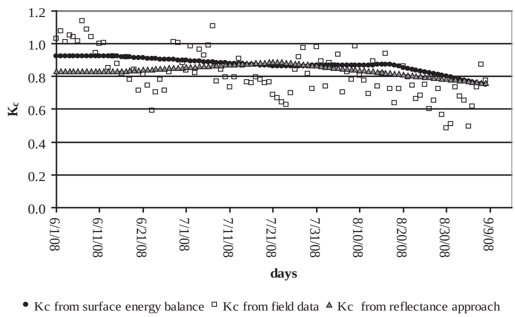


Figure 4. K_c from field data compared with K_c from the satellite approach.

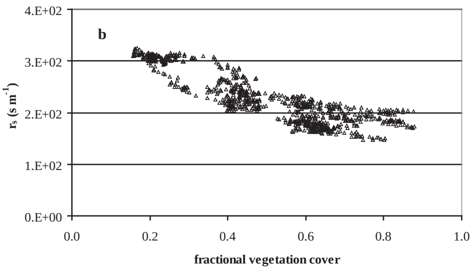
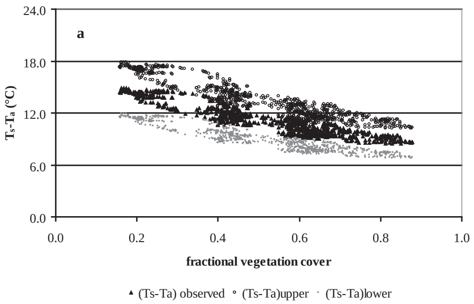


Figure 5. Satellite-based surface resistance (rs) as a function of fv.

In order to examine satellite observations for plant water stress, the theoretical upper and lower limits for T_s-T_a are plotted against fv, together with the T_s-T_a observations in Fig. 6a. The T_s-T_a range is fairly small for a given fv which represents homogeneous surface conditions. Generally, observed T_s-T_a exceeded the theoretical lower limit, symbolizing the increase of surface control on LE probably caused by a reduction in the soil water availability and increased plant water stress (Fig. 6b). The study revealed a mean CWSI from satellite data of 0.6 with a low variation (9%) for each value of fv. Energy flux data from the micrometeorological tower determined a mean CWSI of 0.67 during satellite acquisitions. Previous studies on CWSI for many crops in different parts of the world highlighted that $CWSI_s$ higher than 0.6 indicate soil moisture depletion requiring irrigation.



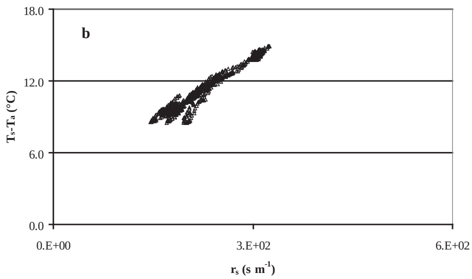


Figure 6. (a) (T_s-T_a) as a function of f_v; (b) (T_s and T_a) as a function of r_s (b).

V – Conclusion

In this study, a one-layer resistance model was used for the spatial estimation of evapotranspiration rates, vegetation indices and features using Landsat TM and local agro-meteorological data. The model formulates the transfer of sensible and latent heat fluxes between the surface and atmosphere using the concept of aerodynamic resistance and surface resistance. Maps of atmospheric resistance, surface resistance, surface energy flux, evapotranspiration rates and CWSI were produced. The satellite-based estimates of ET rates compare well with the micrometeorological tower-based ET flux. However, the method should be tested thoroughly using an extended spatially distributed dataset. Reflectance-based crop coefficient values K_c had about the same range of variation of data on K_c derived by the one-layer energy balance method, with a mean of 0.8, slightly higher than the widely used FAO 56 data. The satellite-based estimate of surface resistance r_s tended to be lowest for dense vegetation (fv≈0.88) and highest for bare soil or canopies with intermediate vegetation cover. The surface resistance approaches 145-160 s m^{-1} for dense vegetation highlighting water stressed canopy conditions. A tendency to quite steady atmospheric resistance is partially due to the effect of fully vegetated pixels and the low spatial resolution of surface temperature T_s. The results of the satellite surface energy balance were further used to compute the upper and lower theoretical limits of T_s-T_a for each image's pixels. In particular, the dependency of T_s-T_a lower and upper limits on the fractional vegetation cover and surface resistance was demonstrated. Derived and measured $CWSI_s$ were in good accordance and had a mean of about 0.6 which indicates a certain soil moisture depletion. Finally, estimating ET within wide spatial scales by one-layer models and integrating ground-based meteorological data with satellite observations is a useful tool for quantifying and controlling water consumption especially in areas of limited water supply.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. *Crop evapotranspiration: Guidelines for computing crop water requirements*. Rome: FAO. (Irrigation and drainage paper, 56).

Atta, C.W. van, 1977. Effect of coherent structures on structure functions of temperature in the atmopheric boundary layer. *Arch of Mech,* 29, 161-171.

Bastiaanssen, W.G.M., 1995. *Regionalization of surface flux densities and moisture indicators in compasite terrain: A remote sensing approach under clear skies in Mediterranean climates*. Ph.D. Diss., CIP Data Koninklijke Bibliotheek, Den Haag, the Netherlands. 273 p.

Boegh, E., Soegaard, H., Thomsen, A., 2002. Evaluating evapotranspiration rates and surface conditions using Landsat TM to estimate atmospheric resistance and surface resistance. *Remote Sens Environ*,79. pp. 329-343.

Brutsaert, W., 1982. *Evaporation into the atmosphere*. *Theory, History and Applications*. Boston, MA: Reidel.

Businger, J.A., 1988. A note on the Businger-Dyer profiles. *Boundary-Layer Meteorol*, 42. pp. 145-151.

Chander, C., Markham, B., 2003. Revised Landsat-5 TM radiometric calibration procedures and postcalibration dynamic ranges. *IEEE Trans. On Geosci and Remote Sens*, 41, 11. pp. 2674-2677.

Chodhury, B.J., Idso, S.B., Reginato, R.J., 1987. Analysis of an empirical model for soil heat flux under a growing wheat crop for estimating evaporation by an infrared-temperature based energy balance equation. *Agr Forest Meteorol*, 39. pp. 283-297.

Consoli, S., D'urso, G., Toscano, A., 2006. Remote sensing to estimate ET-fluxes and the performance of an irrigation district in southern Italy. *Agric Water Manage*, 81. pp. 295-314.

D'Urso, G. 2001. Simulation and Management of On-Demand Irrigation Systems: a combined agro-hydrological approach Ph.D. Thesis, Wageningen University. 174p.

Doorenbos, J., Pruitt, W.O., 1977. *Crop water requirements*. Rome: FAO. (Irrigation and drainage paper, 24 rev.).

Friedl, M.A., 2002. Forward and inverse modelling of land surface energy balance using surface temperature measurements. *Remote Sens Environ,* 79. pp. 344-354.

Gao, W., Shaw, R.H., Paw, U K.T., 1989. Observation of organized structure in turbulent flow within and above a forest canopy. *Boundary-Layer Meteorol*, 47. pp. 349-377.

Idso, S.B., Jackson, R.D., Pinter, P.J., Hatfield, J.L., 1981. Normalizing the stress-degree-day parameter for environmental variability. *Agr Meteorol*, 24. pp. 45-55.

Jackson, R.D., Kustas, W.P., Choudhury, B.J., 1988. A reexamination of the Crop Water Stress Index. *Irrig Sci*, 9. pp. 309-317.

Jensen, J.R., 1986. *Introductory digital image processing. A remote sensing perspective*. Englewood Cliff, N.J., USA: Prentice-Hall.

Menenti, M., 1984. *Physical aspect and determination of evaporation in desert applying remote sensing techniques*. ICW Report , 10. Special issue.

Monteith, J.L., Ong, C.K., Corlett, J.E., 1991. Microclimatic interactions in agroforestry systems. *For Ec Manag*, 45. pp. 31-44.

Nagler, P.L., Glenn, E.P., Kim, H., Emmerich, W., Scott, R.L., Huxman, T.E., Huete, A.R., 2007. Relationship between evapotranspiration and precipitation pulse in a semiarid rangeland estimated by moisture flux towers and MODIS vegetation indices. *J Arid Env*, 70, 443-462.

Neale, C.M.U., Bausch, W., Heermann, D., 1989. Development of reflectance based crop coefficients for corn. *Transaction of the ASAE*, 30, 3. 703-709.

Norman, J.M., Kustas, W.P., Humes, K.S., 1995. A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature. *Agr Forest Meteorol*, 80. pp. 87-109.

Paw, U.K.T., Qiu, J., Su, H.B., Watanabe, T., Brunet Y.,1995. Surface renewal analysis: a new method to obtain scalar fluxes without velocity data. *Agr Forest Meteorol*, 74. pp. 119-137.

Rouse, J.M., R.H. Haas, J.A. Schell, D.W. Deering, J.C. Harlan., 1974. *Monitoring the vernal advancement of retrogradation of natural vegetation*. Greenbelt, MD: NASA/GSFC, 371p.

Sobrino, J.A., Raissouni, N., Li Z., 2001. A comparative study of land surface emissivity retrieval from NOAA data. *Remote Sens Environ*, 75. pp. 256-266.

Sobrino, J.A., Jiménez-Muñoz, J.C., El-Kharraz, J., Gómez, M., Romaguera, M., Sòria G., 2004. Single-channel and two channel methods for land surface temperature retrieval from DAIS data and its application to the Barrax site. *Int J Remote Sens*, 25. pp. 215–230.

Soegaard, H., 1999. Fluxes of carbon dioxide, water vapour and sensible heat in a boreal agricultural area of Sweden - scaled from canopy to landscape level. *Agric Forest Meteorol*, 98-99. pp. 463-478.

Stanghellini, C., Bosma, A.H., Gabriels, P.C.J., Werkhoven C., 1990. The water consumption of agricultural crops: how crop coefficients are affected by crop geometry and microclimate. *Acta Hort*, 278. pp. 509-515.

Sugita, M., Brutsaert, W., 1990. Regional surface fluxes from remote sensed surface skin temperature and lower boundary layer measurements. *Water Resour Res,* 26. pp. 2937-2944.

Zhang, Lu, Lemeue, R., Goutorbe J.P., 1995. A one-layer resistance model for estimating regional evapotranspiration using remote sensing data. *Agr Forest Meteorol*, 77. pp. 241-261.