Improved simulation of soil water content by the combination of ground and remote sensing data

Lorenzo Gardin1*, Piero Battista1, Lorenzo Bottai2, Marta Chiesi1, Luca Fibbi1, Bernardo Rapi1, Maurizio Romani1, Bernardo Gozzini2 and Fabio Maselli1

1 IBIMET-CNR, Via Madonna del Piano 10, 50019 Sesto Fiorentino (FI), Italy
2 LaMMA Consortium, Via Madonna del Piano 10, 50019 Sesto Fiorentino (FI), Italy
*Corresponding author, e-mail address: lorenzo@studiogardin.it

Abstract
The simulation of site water balance requires the assessment of actual evapotranspiration (\(ET_A\)), which is highly variable both in space and in time depending on several factors (climate, soil, vegetation). In a recent work we proposed a new method based on remotely sensed NDVI data which can estimate daily \(ET_A\) operationally over large areas. The current paper utilizes these \(ET_A\) estimates to drive two crop coefficient models, WinEtro and FAO56, in the prediction of soil water content (SWC). The outputs of the simulations are evaluated versus daily measurements of SWC taken in a Tuscany forest site (Barbialla) during four years. The results obtained indicate the efficiency of the proposed data combination, which improves the SWC simulations of both models examined. Recommendations are finally expressed for the possible extension and enhancement of the method described.

Keywords: MODIS, NDVI, FAO56, WinEtro, crop coefficient.

Introduction
Soil water content (SWC) is an important environmental parameter which affects a great number of ecosystem processes. In most terrestrial ecosystems the amount and seasonal variation in the available water are among the most relevant elements determining local biological functions, such as vegetation growth, development, fructification and species composition. From a practical viewpoint, the assessment of SWC is increasingly used in land use planning, especially at the watershed scale for the estimation of runoff and soil erosion [USDA Soil Conservation Service, 1972; Wischmeier and Smith, 1978]. In agriculture, such assessment allows irrigation scheduling also in view of climate scenarios which imply a shortage of water availability and the need of more rational water management.

Depending on different factors, like climate, soil characteristics, topography and ecosystem composition, the water balance may show excess or shortage of water, either occasionally or continuously [Ilvesniemi et al., 2010]. The modelling of SWC therefore requires information on three components, i.e. site meteorology, terrain/soil and vegetation features. Among the meteorological variables, temperature, rainfall and solar radiation are the most influential
on SWC. Several methods are currently available to inter/extrapolate these meteorological variables from ground stations over the land surface [Haylock et al., 2008]. The accuracy of these methods is generally dependent on the number and quality of the ground stations as well as on the irregularity of the observed terrain [Thornton et al., 1997]. Meteorological products derived from various kinds of remote sensing data are also being increasingly utilized (see for ex. http://oiswww.eumetsat.org/IPPS/html/MSG/PRODUCTS/MPE).

The high variability in soil characters depends both on main pedogenetic factors, such as lithology, physiography, climate, vegetation, etc., and on relevant pedogenetic processes. Soil mapping, based on the soil-landscape paradigm [Hewitt, 1993], identifies and delineates land units similar for factors and pedogenetic processes and thus partly succeeds in addressing soil variability from local to regional scales.

As finally regards vegetation, the plant features which most directly affect SWC are those that regulate actual evapotranspiration ($ET_A$), i.e. plant type and density, rooting system, canopy conductance, etc. These features are also characterized by an extreme spatial variability, which makes the assessment of $ET_A$ over large areas an open issue which has found only partial solutions [Courault et al., 2005].

The simplest operational methods to simulate site water balance utilize the crop coefficient (Kc) concept, defined as the ratio of the $ET_A$ observed for the crop studied over potential evapotranspiration ($ET_0$) [Allen et al., 1998]. This approach, however, presents several drawbacks (see section below), which can be partly overcome by the use of remote sensing estimates of vegetation type and condition [Glenn et al., 2010]. In particular, a new method which combines meteorological and Normalized Difference Vegetation Index (NDVI) data (called NDVI-Cws) has been recently proposed by Maselli et al. [2014] to operationally assess daily $ET_A$ from local to regional scales. The method works without computing a full site water balance and is therefore potentially suited to complement Kc models for the characterization of vegetation functions [Chiesi et al., 2013; Maselli et al., 2014].

The current paper aims at assessing the utility of using the NDVI-Cws $ET_A$ estimates to improve the simulation of SWC obtained by two conventional Kc models. More specifically, these $ET_A$ estimates are used to replace similar estimates obtained from the models in order to homogenize the simulations of below-ground and above-ground ecosystem components (i.e. soil and vegetation). This approach is applied in a Tuscany forest site (Barbialla) evaluating the results against daily measurements of SWC taken during four years.

**Modelling theory**

*Models of soil water balance*

The two crop coefficient models which are currently evaluated are based on the following equation to estimate soil water balance in non-standard conditions:

$$V_t = V_{t-1} + P_t - IF_t - ET_{A,t} - DP_t \quad [1]$$

where:

$V_t$ = volumetric soil water content at time $t$, ranging from the surface to the depth explored by plant roots;

$P_t$ = precipitation at time $t$;
IF\_t = intercepted precipitation by vegetation at time \( t \);
Et\_\( A \),\(_t = actual evapotranspiration at time \( t \);
DP\_t = deep percolation or runoff at time \( t \).

The first model is implemented within the WinEtro software tool [Battista et al., 2003]. WinEtro computes crop water consumption (here assumed equivalent to ET\(_ A \)) through a full site specific water balance which works on a daily basis taking into account rainfall, irrigation intakes, soil texture and plant exigencies characterized through specific Kc, descriptive of the crop phenological stages [Battista et al., 2003]. In this model IF\(_ t \) is approximated to 0, and DP\(_ t \) equals all water which exceeds soil field capacity. To calculate the water available for plants, the model requires the soil water contents at field capacity and wilting point. ET\(_ A \) is computed as the product of ET\(_ 0 \) and time varying Kc [Allen et al., 1998]. The effect of water stress is taken into account by a factor which blocks ET\(_ A \) when wilting point is approached.

The second model, FAO56, is based on the same equation, which is also applied daily using meteorological data, soil characteristics and vegetation parameters. As in WinEtro, the total amount of water which exceeds field capacity is assumed to be lost the same day by deep percolation or runoff. Rainfall interception is computed using the formula proposed by Von Hoyningen-Hüne [1983] and Braden [1985]. Total Available Water (TAW) is defined as the water that plants can extract from the rooting zone and is calculated as the difference of the soil water contents at field capacity and wilting point. ET\(_ A \) is predicted by multiplying the reference evapotranspiration ET\(_ 0 \) for a Kc and a coefficient of water stress (KS). The former is obtained as previously, while KS is calculated using the Readily Available Water (RAW, mm), which is defined as the fraction of TAW that plants can extract without water stress and is expressed as the product of TAW and a coefficient p.

**NDVI-Cws ET\(_ A \) estimation method**

Several methods have been proposed to obtain estimates of ET\(_ A \) using various kinds of remote sensing data [Senay et al., 2012]. Water balance methods are based on the resource optimization theory, which states that plants adjust their foliage density to match the capacity of the environment to support transpiration and photosynthesis [Glenn et al., 2010]. Consequently, remotely sensed indicators of green foliage biomass (i.e. vegetation indices such as NDVI) can be combined with estimates of ET\(_ 0 \) to obtain ET\(_ A \) [Glenn et al., 2010]. Within this approach the use of NDVI data replaces that of time-varying Kc, which would require the knowledge of the crop planted in each area and its calendar [Senay, 2008]. The Kc-NDVI approach overcomes most of these limitations and has been efficiently applied for assessing daily ET\(_ A \) in many agricultural regions [Rocha et al., 2012]. This method, however, still suffers from important drawbacks when extended to the prediction of ET\(_ A \) over natural or mixed landscapes, due to the basic assumption that the observed vegetation is growing under unstressed water conditions [Glenn et al., 2010]. Consequently, the method can simulate ET\(_ A \) in ecosystems where water stress is almost absent (i.e. in humid or irrigated areas), but produces substantial ET\(_ A \) overestimation in water-limited environments [Glenn et al., 2010].

Maselli et al. [2014] have introduced innovations aimed at improving the capability of the Kc-NDVI method to operationally assess ET\(_ A \) in dry areas covered by both agricultural
and natural vegetation types. In synthesis, satellite-derived NDVI data are 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 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:

$$\text{ET}_A = \text{ET}_0 \left( \text{FVC} \ K_{c_{\text{V}} \text{eg}} \text{Cws} + (1 - \text{FVC}) K_{c_{\text{So}}\text{l} \text{ AW}} \right) \tag{2}$$

where $K_{c_{\text{V} \text{eg}}}$ and $K_{c_{\text{So} \text{l}}}$ are maximum $K_c$ values of vegetation and soil and Cws (Coefficient of Water Stress) and AW (Available Water) are the two meteorological factors accounting for short-term water stress, which are obtained as fully explained in Maselli et al. [2009, 2014].

**Study Area and Data**

**Study area**

The current investigation was carried out in the Barbialla study site (Tuscany, Central Italy, lat 43° 35’ 30” N, long 10° 50’ 55” E) (Fig. 1), at an altitude of 135 m a.s.l., in a gently sloped terraced site, dominated by northern aspects. According to Thorntwaite’s classification, the climate of the site is sub-humid, with a mean annual rainfall of 920 mm mostly falling from October to December; the mean annual temperature is 15.1 °C with monthly averages ranging from 6.0 °C (January and February) to 25.1 °C (August).
forest mainly composed of hornbeam (*Ostrya carpinifolia* Scop.), poplar (*Populus alba* L.) and deciduous oaks (*Quercus cerris* L., *Q. pubescens* L., *Q. ilex* L.). The soil surface is covered by native herbaceous vegetation and a few small shrub communities (*Cornus mas*, *C. sanguinea*, *Coronilla emerus*, *Crataegus monogyna*, *Pyracantha coccinea* and *Rubus canescens*).

**Ground measurements**

The soil of the study site was characterized under the MAGNATUM project [Salerni et al., 2013] by collecting and analyzing local soil measurements following standard methodologies [MiPAAF, 1999]; the analytical results are summarized in Table 1. The dominant soil type, developed on Pliocene marine coarse deposits, is deep, lacking in gravels and stones and well drained; its texture is sandy loam. According to Soil Taxonomy [Soil Survey Staff, 2014], this soil is Typic Ustothents coarse loamy, mixed, calcareous, thermic.

Within the same project, four soil moisture capacitive probes were installed at 20 cm soil depth within an area of approximately 1500 m²; hourly data were recorded and stored by a ED50 data-logger from 2009 to 2012.

| Horizon                          | A   | AC  | C   |
|---------------------------------|-----|-----|-----|
| Depth (cm)                      | 8   | 30  | 70  |
| Sand (g/100 g)                  | 60.1| 60.1| 57.5|
| Silt (g/100 g)                  | 30  | 30  | 30.3|
| Clay (g/100 g)                  | 9.9 | 9.9 | 12.2|
| Total calcium carbonate (%)     | 2.6 | 5.1 | 7   |
| pH                              | 7.8 | 8.4 | 8.5 |
| C.E.C. (meq/100 g)              | 20  | 13.7| 14.3|
| EC (dS/m) 1:5                   | 0.1 | 0.09| 0.09|
| Organic carbon (g/100 g)        | 4.2 | 1.25| 0.71|
| Bulk density (g/cm³)            | 1.1 | 1.2 | 1.4 |

**Ancillary and remotely sensed data**

All current simulations of soil water budget and content were driven by environmental data completely independent of the ground measurements at the study site. In particular, the land use was derived from the CORINE 2006 Land Cover map of Italy [ISPRA, 2010]. Information on soil properties was obtained from the regional map and soil database [Gardin and Vinci, 2006].

Daily meteorological data (i.e. minimum and maximum temperature, precipitation and solar radiation) were interpolated at 1 km resolution starting from ground measurements taken in a regional network (see Chiesi et al. [2007] for details). The interpolation was carried out through the sequential application of the DAYMET and MT-CLIM algorithms [Thornton et al., 1997, 2000]. The MODIS NDVI product currently used has a 250 m spatial resolution and it is composited...
over a 16-day period. All NDVI images of the study period covering Central Italy were freely downloaded in a pre-processed format from the USGS database (http://lpdaac.usgs.gov).

**Data Processing**

*Conventional modelling of site water budget*

The water balance of the study site was first calculated by conventionally applying the two crop coefficient models. To this aim, the daily meteorological data (temperature, rainfall and solar radiation) interpolated at the study site were used to predict daily ET$_0$ by the empirical formula of Jensen and Haise [1963]. The soil information required by the models was derived from a polygon of the regional soil map having a size of 300 ha. In particular, the soil parameters in addition to depth (i.e. field capacity and wilting point) were obtained by applying pedotransfer functions to data of particle size (sand, silt and clay content) and bulk density [Schaap et al., 2001]. The resulting soil depth was 143 cm, while the SWC at field capacity and wilting points were 0.29 and 0.08 cm$^3$ cm$^{-3}$, respectively; these values are slightly different from those measured at the site (Tab. 1). The coefficient $p$ required by the FAO56 method was set to 0.4 following tabular data appropriately adjusted according to the soil type, ET$_0$ conditions and root system type [Allen et al., 1998]. Finally, the $K_c$ of the study forest was set following Allen et al. [1998]; its value is 0.2 during winter (December - March) and ramps to 0.5 during the growing season (April - October).

With this parameterization, the two models produced daily SWC estimates whose accuracy was assessed by comparison with the mean daily SWC measurements of the four probes. The results of the comparison were summarised using common accuracy statistics (i.e. correlation coefficient, r, root mean square error, RMSE, and mean bias error, MBE).

*Modelling of site water budget using NDVI-Cws ETA estimates*

The application of the NDVI-Cws ET$_A$ estimation method required the combination of ET$_0$ with rainfall to compute the two water stress factors (AW and Cws). The available MODIS NDVI images were pre-processed as described in Maselli et al. [2009]. The NDVI values of the study site were extracted from the corresponding MODIS pixel and temporally interpolated on a daily basis. From the daily NDVI values, corresponding FVC values were obtained 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. [2014] for details). Finally, daily ET$_A$ was estimated by applying equation 2 for the whole study period.

The availability of these ET$_A$ estimates allowed a modified application of the WinEtro and FAO56 models. Specifically, the daily ET$_A$ estimates obtained from the models were replaced with those produced by the NDVI-Cws method. This led to yield new SWC estimates, whose accuracy was re-assessed by the same comparison with the site measurements described previously.

**Results**

Temperature and precipitation show relevant inter-annual variability during the study period (Fig. 2). In particular, mean annual temperature varies around 15 °C and annual precipitation ranges from 550 mm in 2011 to 1200 mm in 2010. Precipitation has a minimum in summer
which corresponds to the hottest months; as a consequence, the dry season is concentrated around July and August but with variable length.

The seasonal evolution of MODIS NDVI depends both on these meteorological patterns and on the deciduous nature of the study forest (Fig. 2). This evolution is fundamentally bimodal, with a primary maximum in spring, a secondary maximum in autumn and two minima, the first (lower) in winter and the second in summer. The summer minimum is variable depending mainly on spring-summer rainfalls. The bimodal pattern is particularly accentuated in 2012, during which no rainfall occurred from mid-June to end-August.

The combination of solar radiation and average temperature through the formula of Jensen and Haise [1963] determines the ET₀ shown in Figure 3. The average annual total is about 1100 mm, with annual maxima around the summer solstice of 8 mm day⁻¹; deep drops are evident during rainy days both in summer and in spring.

In general the simulated maximum ETₐ is around half of the corresponding ET₀ for all estimation methods (Fig. 3), but some differences are evident due to the simulation logic adopted. WinEtro uses a simplified method which activates the water loss block only when extreme stress condition is approached; consequently, simulated ETₐ has quite regular profiles during all years and does not show clear late summer minima. The total annual average is around 520 mm, which corresponds to less than 50% of total annual rainfall. The corresponding ETₐ simulated by FAO56 is slightly lower (around 460 mm) and has a seasonal evolution more plausible for a typical Mediterranean forest, showing a reduction during the hottest dry months. This pattern is more evident for the NDVI-Cws method, which implicitly considers the phenological evolution of vegetation. In this case the ETₐ peak is in late spring, with a slight decrease in summer due to water shortage; the annual total is on average around 480 mm.

![Figure 2 – Daily values of mean temperature, rainfall and NDVI estimated for the Barbiazza study site during the four years considered (see text for details).](image)
The SWC measurements shown in Figures 4 and 5 indicate a water reduction during summer followed by a recovery dependent on autumn rainfall and ET$_A$ drop. Among the four years considered, 2010 is the most humid and consequently shows higher SWC in summer. WinEtro reproduces the general SWC evolution of all years but shows some problems in the last part of the growing season, likely due to a suboptimal consideration of the effect of water shortage ($r = 0.839$, RMSE = 0.046 $\text{cm}^3 \cdot \text{cm}^{-3}$, MBE = -0.033 $\text{cm}^3 \cdot \text{cm}^{-3}$). This problem is partly overcome by the application of the FAO56 method (Fig. 5), which leads to a slight increase in accuracy and particularly to a reduction of SWC underestimation (MBE = -0.031 $\text{cm}^3 \cdot \text{cm}^{-3}$). The incorporation of NDVI-Cws ET$_A$ estimates enhances the reproduction of the SWC measurements similarly using modified WinEtro (Fig. 4) and FAO56 (Fig. 5).
Discussion and Conclusions

The current simulations of SWC are based on simplified modelling theory which implies several critical issues (see third paragraph of this section and Zhang et al. [2002] for a more extensive review). Other problematic aspects are related to the collection of appropriate information on all involved ecosystem components. The characterization of site meteorology and soil is a necessary prerequisite which, however, is not sufficient without a proper definition of the main vegetation features which regulate water fluxes (plant type, density, structure, etc.). Since these features are extremely variable both in space and in time, conventional methods to simulate soil water balances are based on rough approximations which unavoidably imply relevant drawbacks. This is the case for the widely applied crop coefficient models, which use temporally variable \( K_c \) to predict plant water consumption. Relevant problems are particularly encountered for the operational monitoring of large heterogeneous areas, where the definition of proper multitemporal \( K_c \) values is an almost insurmountable challenge.

As previously noted, the use of the alternative \( K_c \)-NDVI approach only partly addresses these issues in water-limited environments, while a more substantial progress is made through the recently proposed NDVI-Cws method, which can provide ET\( _{\lambda} \) estimates without computing a full site water budget [Maselli et al., 2014]. The current investigation evaluates the possibility of using these ET\( _{\lambda} \) estimates to bring relevant information on actual plant water consumption and improve SWC simulation. From an eco-physiological point of view, the substitution of conventionally obtained ET\( _{\lambda} \) estimates with those of the NDVI-Cws method aims at harmonizing the modelling of below and above ground ecosystem components, thus leading to a more consistent SWC simulation.

The potential of this approach is supported by the results of the current experiment. The conventional crop coefficient models examined (WinEtro and FAO56) reproduce SWC temporal variations with a certain inaccuracy which partly derives from the incompleteness of the applied basic...
theory. These models, in fact, do not consider the multi-layer nature of soil systems and account only roughly for some processes which have variable impact on SWC (i.e. rainfall interception by plants and understory, deep percolation and runoff, etc.). In particular, the models simulate the mean SWC of a single-layer soil having a thickness of 143 cm, while the field measurements refer to a specific depth (20 cm). The possible impact of this factor was simulated by the use of a more complex, multi-layer model, SWAP [Van Dam et al., 2008], driven by the available local soil data (Tab. 1). The SWC errors coming from not considering the real measurement depth were on average quite low (-2%), ranging from -13% in summer to +5% in autumn.

This error source adds to those caused by the different spatial resolutions of the ground measurements and model estimates. The latter is dictated by the interpolated meteorological drivers (temperatures, rainfall, radiation), and by the size of the site polygon from the regional soil map. Moreover, both these datasets contain relevant uncertainty: the local accuracy of the meteorological drivers cannot be assessed due to the lack of corresponding ground data, while the main features drawn from the soil map (depth and SWC at field capacity and wilting point) slightly differ from the site measurements.

In any case, a major error source is due to the previously mentioned inappropriate characterization of the vegetation characteristics which determine the ecosystem resistance to water loss [Maselli et al., 2014]. This issue is partially addressed by the incorporation of the NDVI-Cws ET_A estimates, which provide information of actual daily plant water consumption with a spatial resolution of 250 m. The use of these ET_A estimates to drive the SWC simulation at the experimental site assumes an approximate homogeneity of the main vegetation features (plant type, density, canopy cover, etc.) at this resolution, which has not been experimentally ascertained but is indirectly supported by the improvements obtained using both study models. While the importance of these results is evident, their conclusiveness is limited by the consideration of only one experimental forest site. Other semi-natural and agricultural ecosystems, in fact, can exert different controls on water fluxes and consequently show different responses to the inclusion of NDVI-Cws ET_A estimates. Moreover, the experiment has not addressed the important issue of defining the optimum way to integrate these estimates into SWC modelling. The currently adopted substitution of the ET_A outputs from the crop coefficient models with the NDVI-Cws ET_A estimates, in fact, could give rise to inconsistency in the simulation of the above- and below-ground ecosystem components if the vegetation and soil features are not fully harmonized. For example, high NDVI-Cws ET_A estimates could correspond to an already depleted soil water reserve if the soil is erroneously considered to be too thin.

A similar issue concerns the spatial resolution of the NDVI-Cws ET_A estimates, which could be improved by the use of both data integration methods (see for ex. Maselli [2012]) and of imagery taken by future higher spatial resolution sensors (i.e. those of the Sentinel 2 mission). Consequently, the potential of the approach should be further investigated and confirmed by studies conducted in different areas/periods using more sophisticated data integration methods and/or datasets.

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