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Research Article

A Semiempirical Method to Estimate Actual Evapotranspiration in Mediterranean Environments

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Actual evapotranspiration (ET_A) is a major term of site water balance whose knowledge is essential for numerous purposes. The classical ET_A estimation approach based on the use of multitemporal crop coefficients (Kc) cannot be applied in water-limited environments without proper correction. Such correction can be theoretically obtained by means of soil water content (SWC) measurements, which, however, are affected by several drawbacks, due to both their technical and operational characteristics. The current paper proposes a method to normalize annual SWC datasets and integrate them in an ET_A estimation procedure suitable for monitoring both agricultural and natural Mediterranean ecosystems. Differently from previous approaches, the SWC normalization is obtained using data-specific information, which renders the new method mostly insensitive to the mentioned problems. The method is first described and then applied in three case studies representative of different Mediterranean ecosystems (i.e., grassland, coniferous, and deciduous forests). The results are evaluated versus latent heat measurements taken by eddy covariance flux towers. Satisfactory accuracy is obtained in all three case studies, with advantages and limitations which are discussed in the final concluding sections.

1. Introduction

Arid and semiarid areas are increasingly affected by water scarcity due to the growing request of this resource for several conflicting uses. This is particularly the case for Mediterranean environments, which are characterized by prolonged summer aridity and are very vulnerable to ongoing climatic change [1]. Consequently, numerous initiatives have been promoted for achieving more efficient and sustainable uses of water resources in Mediterranean countries [2].

Actual evapotranspiration (ET_A) is one of the main terms of the water cycle whose monitoring is important for both scientists and practitioners working in different fields, such as meteorologists, agronomists, ecologists, and landscape planners. Numerous methodologies have therefore been developed to measure ET_A, which differ for the basic principles utilized (i.e., energy balance or water balance methods), for the spatial and temporal scales of investigation, and for what is being effectively measured (evapotranspiration itself or one of its components, i.e., evaporation and transpiration) [3].

Among energy balance methods, the eddy covariance technique is widely applied to measure the sensible heat flux over the canopy of vegetation. This technique provides measurements related to the so-called footprint area, whose size and shape can vary during time following wind directions [3]. Additionally, eddy covariance measurements can provide only point observations and are very expensive to collect over long-time periods.

In contrast, water balance methods can be easily applied at different spatial and temporal scales based on a reduced amount of input data. Some of these methods are based on the integration of meteorological data and soil water measurements taken by using a lysimeter [4]. When this instrument is not available, a common alternative is given by probes measuring soil water content (SWC, in $cm^3 \cdot cm^{-3}$) [5, 6]. These methods, however, are particularly susceptible to possible problems arising from the poor representativeness of SWC data, which are often collected only for a single soil layer and can hardly describe the conditions of the whole soil profile [7]. Moreover, the collected SWC datasets are often affected by troubles over medium-long time periods due to maintenance problems and to the high variability of measurement conditions which affects soil sensors [6]. Consequently, SWC measurements are indicative of relative SWC variations in time but can hardly be utilized for the quantitative estimation of the soil water balance and ET_A [8].

An operational alternative is provided by the consolidated Kc approach [9], which corrects potential evapotranspiration (ET_0) by means of multitemporal plant-specific coefficients estimated by different techniques [10]. The original Kc approach, however, assumes that the observed ecosystems are not affected by water limitation and is therefore ineffective for nonirrigated crops or natural vegetation types. A solution to this problem is provided by the consideration of an additional water stress coefficient obtained using SWC as a surrogate of water shortage information [9]. This approach still has to face the mentioned drawbacks of SWC observations, which can seriously deteriorate the quality of the utilized water stress indicators.

The current work addresses this issue by developing and testing a semiempirical method which combines environmental, meteorological, and SWC data for the operational estimation of ET_A in water-limited Mediterranean environments. The next section provides a brief description of the classic Kc approach, followed by the introduction of the proposed method. This method is then applied in three case studies representative of different Mediterranean biome types and environmental conditions. A discussion of the strengths and weaknesses of the methodology is then presented together with the main conclusions of the investigation.

2. Proposed ET_A Modelling Strategy

The classical method to estimate ET_A proposed by FAO is based on the use of time-varying crop coefficients (Kc), defined as the ratio of the ET_A observed for the crop studied over ET_0 [9]. According to this approach, the ET_A on day i is estimated as follows:

$$ET_{Ai} = ET_{0i}\,Kc_i, \tag{1}$$

where Kc_i is the crop coefficient on the same day, which is strictly dependent on the characteristics of the crops/plants considered and is usually determined by semiempirical methods [9]. In general, the annual plant cycle is divided into five distinct periods showing different crop coefficients: (i) Kc_{ini}, which corresponds to a minimum ET_A rate of the crop with respect to a reference coverage (well-watered reference grass); (ii) Kc_{growth}, which is typical during the phase from 10% ground cover to an effective full cover and is obtained by means of a linear ramp function from the predetermined Kc_{ini} to the next Kc_{mid}; (iii) Kc_{mid}, which represents the maximum ET_A rate during the annual plant cycle, from full development to maturity; (iv) Kc_{late}, corresponding to the reduction of plant efficiency during the late season, from maturity to harvest or leaf fall. Similarly to Kc_{growth}, Kc_{late} is computed as a linear function from Kc_{mid} to Kc_{end}; and (v) Kc_{end}, which is detected at the moment of plant harvest or at the end of the season.

This original Kc approach does not consider water limitation and requires the basic assumption that the observed vegetation is growing under unstressed water conditions [9]. The approach is therefore suitable for simulating ET_A in ecosystems where water stress is negligible (i.e., in humid or irrigated areas) but produces substantial ET_A overestimation in water-limited environments [11]. A solution to this problem is provided by using SWC measurements to correct the ET_A estimated by the classical Kc approach in case of water limitation [12]. SWC, in fact, is a direct indicator of the water which is available for both soil evaporation and plant transpiration. Equation (1) is consequently modified into the following equation:

$$ET_{Ai} = ET_{0i}\,Kc_i\,Ks_i, \tag{2}$$

where Ks_i is the water stress coefficient on day i, derivable from SWC data. The relationships between SWC and transpiration, however, are complex and variable depending on a number of environmental factors (mainly soil and vegetation features). A good review of this subject is provided by Verhoef and Egea [13], who report several different functions relating relative transpiration to the fraction of transpirable soil water (FTSW). Similarly, soil evaporation is usually considered to depend on FTSW [13].

An additional problem is related to the numerous sources of uncertainty which affect SWC measurements. These measurements, in fact, can provide only local (point) observations, usually referred to a small soil sample (few cubic centimeters) around the probe [6]. Thus, vertical and horizontal SWC variations out of this area, which are considerable in most real cases, cannot be detected. In particular, SWC measurements are usually taken at limited soil depth (20–50 cm) and cannot be representative of all conditions affecting plant roots, i.e., the so-called "rooting zone," that can be much deeper. SWC probes may also suffer from lack of representativeness for the presence of air gaps in the soil, from poor calibration, and/or from temporal drifting, which further complicate the utilization of the measured data [5, 6].

The semiempirical method currently put forward circumvents these issues by elaborating the available SWC measurements based on data-specific information. In particular, the method utilizes relative SWC (RSWC) to correct the ET_A estimated by the original Kc approach assuming a linear relationship between the two variables. This assumption is theoretically justified by the mentioned complexity and variability of the actual relationships between ET_A and RSWC [13] and is practically necessary to minimize the number of parameters to be identified. As is schematized in Figure 1, in fact, a linear equation relating relative ET_A (RET_A) to SWC can be defined identifying the two extreme points, i.e., the SWC corresponding to full and null evapotranspiration, which can be assumed to correspond to

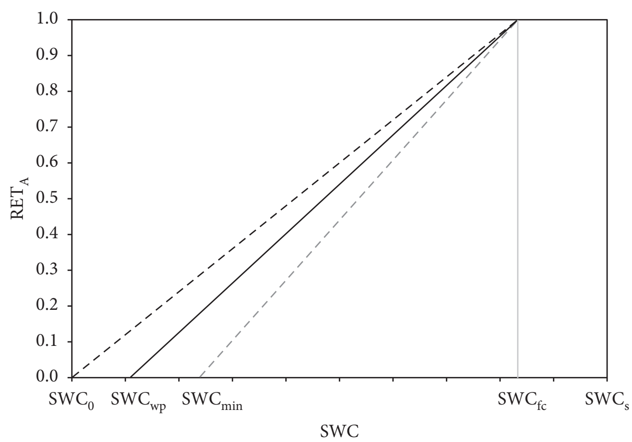


Figure 1: Scheme of the method applied to identify the relationship between SWC and RET_A in each study site; SWC_0 coincides with the measured 0, and SWC_{min}, SWC_{fc}, and SWC_s are readily derivable from the SWC annual evolution, while SWC_{wp} is estimated by optimizing the site soil water balance as described in the text.

field capacity (SWC_{fc}) and permanent wilting point (SWC_{wp}), respectively [8].

The identification of SWC_{wp} and SWC_{fc} allows the computation of the soil water stress coefficient on day i, Ks_i, from the respective SWC, SWC_i, through the following equation:

$$Ks_i = \frac{\left(SWC_i - SWC_{wp}\right)}{\left(SWC_{fc} - SWC_{wp}\right)}. \tag{3}$$

SWC_{fc} and SWC_{wp} could theoretically be identified by applying pedotransfer functions to the site texture data, as is done conventionally [14]. This approach, however, does not take into account the mentioned problems of SWC measurements, which are exacerbated by the uncertainty due to the determination of soil texture features and the application of pedotransfer functions [15]. Consequently, the new method performs the same operation based entirely on the available site datasets, i.e., Kc information plus meteorological and SWC measurements.

As a first step, SWC_{fc} is directly estimated from the annual SWC data series relying on the empirical observation that, in Mediterranean areas, SWC usually approaches field capacity at the beginning and end of the growing season. The SWC_{fc} of each study site is therefore identified by visually examining the annual SWC profile for finding stable values during these two periods.

After this step, the ET_A estimated by equations (2) and (3) can be considered to be mainly regulated by SWC_{wp}, which controls the maximum ecosystem resistance to water loss and can be assumed to range between the measured 0 (SWC_0) and minimum SWC (SWC_{min}) (Figure 1). The identification of SWC_{wp} is performed through the optimization of a classical water balance equation (i.e., an error minimization between SWC measurements and estimates). This approach adopts a simple one-dimensional bucket model and considers precipitation (both rainfall and melted snow) as input to the soil, while the outputs are transpiration, soil evaporation, and outflow due to water exceeding field capacity and saturation, the latter also being derived from the annual SWC profile [16].

Following this modelling approach, the volumetric SWC on day i (V_{swc_i}, in mm) is the product of SWC and the effective soil depth (ESD, in mm) and can be estimated as follows:

$$V_{swc_i} = V_{swc_{i-1}} + P_i - ET_{Ai} - O_i, \tag{4}$$

where P_i is the precipitation, ET_{Ai} is the evapotranspiration, and O_i is the outflow (i.e., percolation plus runoff), all in mm.

In accordance with the described methodological framework, ESD is defined as the soil depth which affects the SWC measurements and should be derived from the available datasets. This condition can be satisfied assuming that all input and output terms of equation (4) are consistent and act similarly in increasing or reducing SWC. In particular, ESD can be estimated relying on the following assumptions:

(1) All SWC increases derive from water supply by precipitation and are directly proportional to this up to saturation (SWC_s)
(2) Such supply corresponds to effective rainfall, i.e., P-ET_0

These assumptions are clearly realistic when other water sources (irrigation, water table, etc.) are not present; in the other cases, which are not currently addressed, the method would require information on the effective water supply.

On this basis, ESD can be estimated as follows:

$$ESD = \frac{\sum_{i=1}^{n1} \left(P_i - ET_{0i}\right)}{\sum_{i=1}^{n1} \left(SWC_J - SWC_{J-1}\right)}, \tag{5}$$

where $n1$ are the days of the year when SWC is below saturation and both effective rainfall and ΔSWC are positive. The ESD estimated in this way is clearly relative to the available datasets and can therefore be seen as a factor which converts SWC (theoretically in $cm^3{\cdot}cm^{-3}$ but actually in any arbitrary unit) into V_{swc} in mm, consistently with all input and output terms of equation (4).

The determination of ESD allows the application of equation (4) to predict daily V_{swc} as a function of the ET_A estimated by equations (2) and (3), which obviously depends on SWC_{wp}. This parameter is therefore varied within the permitted range (from 0 to the minimum measured SWC; Figure 1), and the value most suitable for the observed dataset is found as that which minimizes the root mean square difference between SWC measurements and estimates, the latter being obtained by dividing V_{swc} for ESD. In this way, optimal daily Ks and ET_A estimates are produced which are mostly insensitive to the problems affecting the used SWC observations.

3. Materials and Methods

3.1. Study Areas. The three study sites are representative of different ecosystems (i.e. grassland, coniferous, and deciduous forests) and belong to the European network of eddy covariance flux towers (http://www.europe-fluxdata.eu). The main environmental characteristics of these sites are summarized in Table 1 and described hereinafter.

3.1.1. Amplero. Amplero is located on a plateau in Central Italy, at 884 m a.s.l. (Figure 2). The climate is Alpine-Mediterranean, with the mean annual rainfall of about 1400 mm and mean annual temperature of about 10°C; the climate is therefore characterized by mild and rainy winters and by intense drought during summer [17]. The soil is poorly drained, has a depth of more than 1 m, and is classified as Haplic Phaeozem [18]. The percentage of clay is 56 and pH is 6.5. The site is covered by herbaceous species among which graminoids (*Poa* spp.), legumes (mainly *Trifolium* spp. and *Medicago* spp.), and forbs (*Geranium* spp. and *Cerastium* spp.) are the most abundant [18].

3.1.2. San Rossore. San Rossore is situated in Central Italy within a Regional Park, limited by the Tyrrhenian Sea on the west and the rivers Arno and Serchio on the south and north, respectively (Figure 2). The climate is Mediterranean subhumid, with the mean average temperature of 14.8°C and mean annual rainfall of about 900 mm. The soil is classified as Albic Arenosol with 94% sand and 3% silt [19]. The investigated area is mostly covered by a Mediterranean pine forest (both *Pinus pinaster* Ait. and *Pinus pinea* L.) with a mean tree height of about 20 m and a stand density of 565 ha^{-1} (84% *P. pinaster*, 12% *P. pinea*, and 4% *Q. ilex*) [20].

3.1.3. Collelongo. Collelongo is situated in a mountain area at 1579 m a.s.l. (Figure 2). It has a Mediterranean mountain climate, with a mean annual rainfall of about 1100 mm and mean annual temperature around 7.4°C. The soil is Humic Alisol and has a depth lower than 1 m and a clay loam texture with 30% sand and 40% silt [19]. The area is dominated by a beech forest (*Fagus sylvatica* L.), having a basal area of approximately 32 $m^2 \cdot ha^{-1}$ and a mean height of 22 m [21].

3.2. Data Used. Crop coefficients for grasses, pines, and beeches were derived from a critical review of the available literature [9, 22]. The results of this operation are summarized in Table 2.

Daily meteorological data of the three sites (i.e., minimum and maximum air temperature and precipitation) were derived from a 1 km dataset available for the whole Italian Peninsula [23, 24]. Solar radiation was then obtained by applying the MT-Clim algorithm, which corrects the theoretical top-of-atmosphere radiation on the basis of topography and cloudiness, the latter being estimated from rainfall and the difference between maximum and minimum air temperature [25].

Soil water content measurements were collected at the three study sites by means of a time-domain reflectometry probe, during different periods (i.e., 2002–2008 for Amplero, 1999–2012 for San Rossore, and 1996–2015 for Collelongo) (http://www.europe-fluxdata.eu) [26]. These measurements were taken at soil depths which should be representative of the average conditions of the rooting zone [27].

Continuous water fluxes were measured as latent heat of evaporation (LE) at the same sites by an eddy covariance tower following the conventional protocol in use for FLUXNET [28]; these measurements, converted into mm and summarized on a daily temporal resolution, can be considered to be equivalent to ET_A [29].

3.3. Data Processing. The described ET_A modelling strategy was tested in the three study sites using the available environmental information, daily meteorological data, and SWC measurements of one year. The study years were chosen taking into consideration the completeness of these observations and of the LE measurements and corresponded to 2003 for Amplero, 2005 for San Rossore, and 2007 for Collelongo.

A first trial was performed to assess the accuracy of a classical soil water balance method [5]. Following this method, ET_A was computed by inverting equation (4) for the days when SWC was decreasing and lower than field capacity (i.e., those with no effective water supply or outflow). The ESD needed for this operation was assessed by using equation (5), and the daily ET_A estimates obtained were bounded to the corresponding estimates given by equation (1) (i.e., for fully watered conditions) in order to avoid unrealistically high values. The same equation was used to estimate daily ET_A for all other days (i.e., those with effective water supply or outflow), when fully watered conditions could be presumed.

Next, the new methodology was applied using the same datasets. The daily ET_A estimates produced by the two methods in the three study sites were finally assessed versus the respective LE measurements. The results obtained were summarized by common accuracy statistics, i.e., the determination coefficient (r^2), the root mean square error (RMSE), and the mean bias error (MBE).

4. Results

4.1. Amplero. Figure 3(a) shows the annual evolution of precipitation and potential evapotranspiration for the year 2003, whose summer was particularly hot and dry all over Europe. On an annual basis, the total rainfall is about 1000 mm and is distributed quite regularly during the whole year; spring rainfalls are, however, scarce, while some events occur in summer. The annual ET_0 is higher (1086 mm) and follows a regular evolution with a peak close to the solstice and maxima up to 8 mm; strong reductions are evident in correspondence to rainy days. This annual meteorology leads to the site SWC measurements shown in Figure 3(b); the low spring water recharge joined with the high summer water demand determines a prolonged SWC minimum from May to September.

The effective soil depth identified by equation (5) is 0.74 m (Table 3). The combination of this ESD and the grassland Kc values within the conventional soil water balance algorithm produces poor ET_A estimates (Table 4), due in particular to a clear overestimation during spring-summer.

The visual check of the measured SWC profile leads to identify a SWC_{fc} of 0.42 $cm^3 \cdot cm^{-3}$, which is reached both at

Table 1: Main ecoclimatic characteristics of the selected study sites (see the FLUXNET website for further details).

ID	Position (Lat. N, Long. E)	Altitude (m a.s.l.)	Mean annual temperature (°C)	Mean annual rainfall (mm)	Soil	Ecosystem type
IT-Amp	41.90°, 13.61°	884	10.0	1370	Haplic Phaeozems	Grassland
IT-SRos	43.73°, 10.28°	1	14.8	900	Albic Arenosol	Pine forest
IT-Col	41.87°, 13.58°	1579	7.4	1140	Humic Alisol	Beech forest

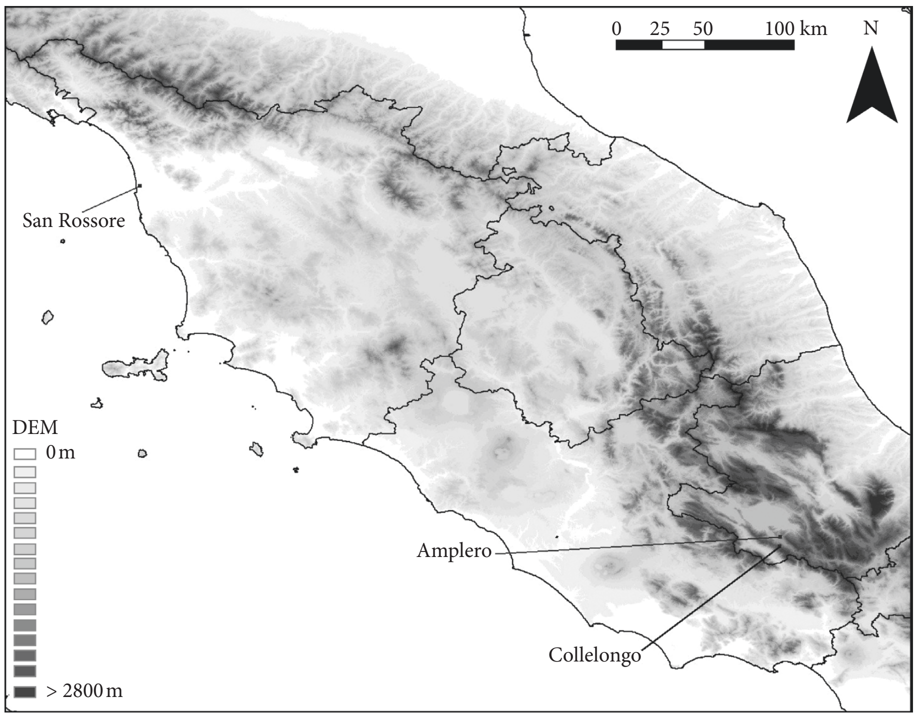


Figure 2: Digital elevation model (DEM) of Central Italy showing the geographical position of the three study sites.

the beginning and at the end of the year (Table 3). Some peaks over this value are evident up to 0.55 $cm^3 \cdot cm^{-3}$, indicating soil saturation. The error minimum in reproducing the pattern of SWC measurements is identified by setting SWC_{wp} to 0.18 $cm^3 \cdot cm^{-3}$. The estimated ET_A values are compared to the LE measurements in Figure 3(c); the accordance is now good (r = 0.838), and both errors are moderate. A slight underestimation is evident during summer (MBE = −0.310 mm), when few drops in predicted evapotranspiration are too strong.

4.2. San Rossore. Figure 4(a) shows the annual precipitation and potential evapotranspiration for 2005. The total rainfall is about 740 mm and is distributed with maxima in spring and autumn. During summer, only few rainy events occur, which contribute to reduction of ET_0 due to the increased cloud cover. The annual ET_0 is much higher (over 1100 mm) with daily peaks up to 8 mm. The annual evolution of measured SWC is shown in Figure 4(b). Two measurement gaps are visible, the first at the beginning and the second at the end of the dry season (May and September, respectively). Some discrepancies are also evident between the plateaus observed at the beginning and at the end of the growing season.

The ESD identified by equation (5) is equal to 1.30 m. Also in this case, the combination of this value and the respective Kc within the conventional soil water balance algorithm produces poor ET_A estimates (Table 4), both in terms of accordance and errors.

For this site, SWC_{fc} is visually identified at 0.19 $cm^3 \cdot cm^{-3}$, while the optimization of the water balance is obtained setting SWC_{wp} to zero. Figure 4(c) shows the estimated ET_A values compared to LE measurements; the annual amount is about 380 mm, the accordance is good (r = 0.790), and both errors are moderate (RMSE = 0.484 mm; MBE = 0.131 mm).

4.3. Collelongo. The 2007 annual precipitation of this mountain site is about 780 mm, distributed with two main peaks in spring and autumn (Figure 5(a)); the occurrence of some rainfalls alleviates summer water stress. The effects of rainy events are clearly reflected into the evolution of ET_0, whose annual total (809 mm) is lower than those obtained for the other sites. The SWC measurements are shown in

Table 2: Initial, middle, and final Kc values utilized in the three case studies.

ID	Initial	Middle	Final
IT-Amp	0.7	1.0	0.7
IT-SRos	0.6	0.7	0.6
IT-Col	0.2	0.7	0.2

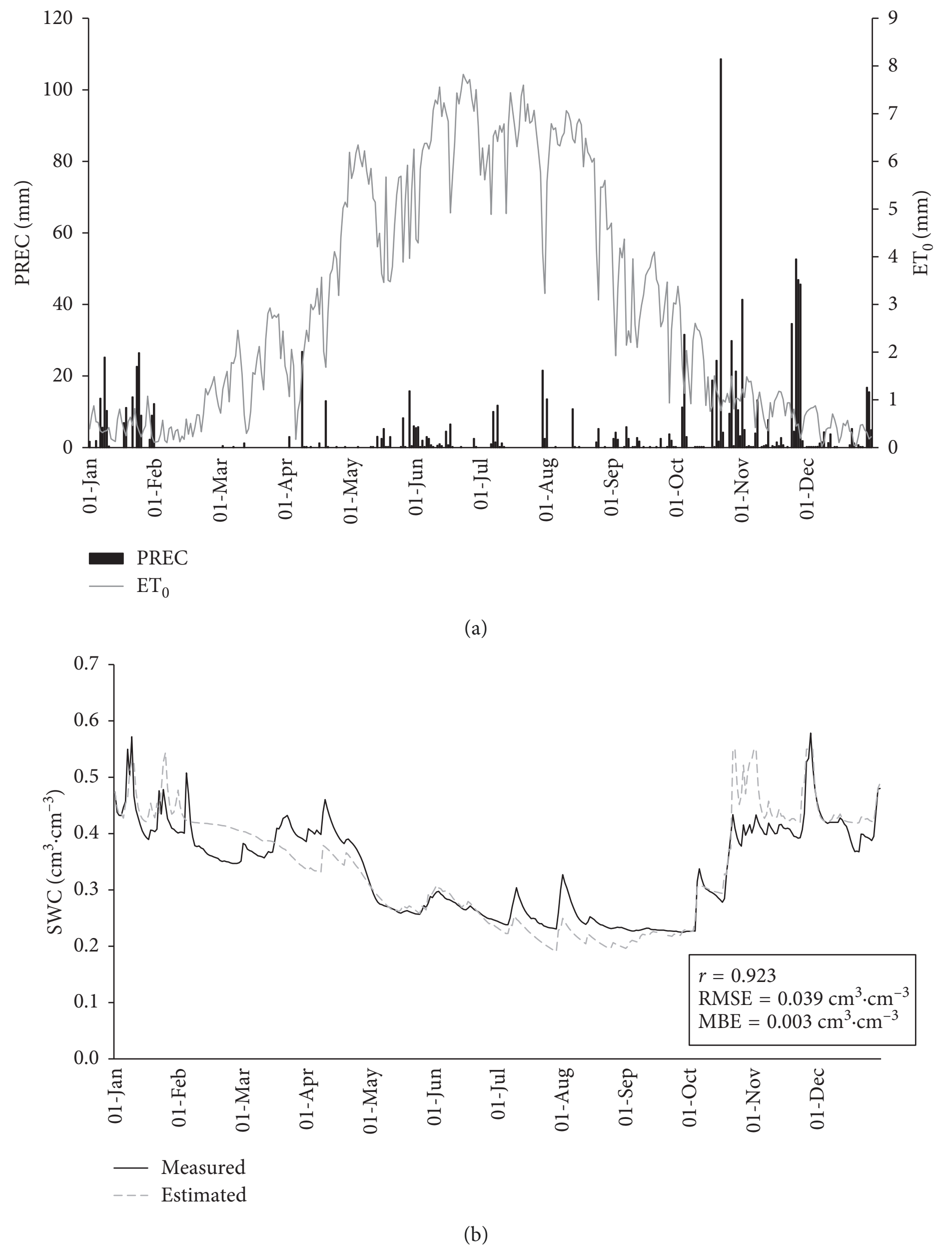
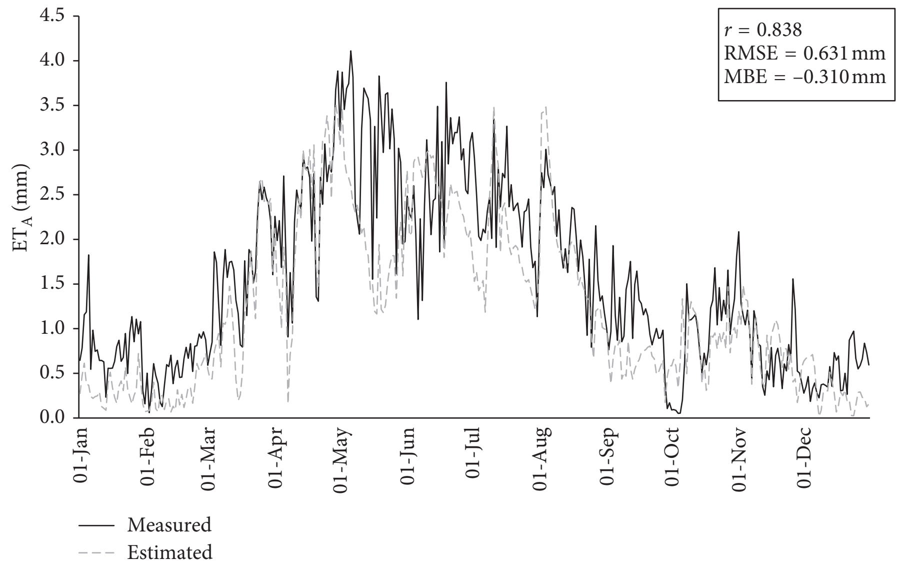


Figure 3: Continued.



(c)

Figure 3: Annual evolutions of daily precipitation (PREC) and potential evapotranspiration (ET_0) (a), measured and calibrated SWC (b), and measured and estimated ET_A (c) for Amplero (all correlations are highly significant, $P < 0.01$).

Table 3: ESD and SWC corresponding to null and full RET_A identified by the described methodology in the three study sites.

ID	Effective soil depth (m)	SWC_{wp} ($cm^3 \cdot cm^{-3}$)	SWC_{fc} ($cm^3 \cdot cm^{-3}$)
IT-Amp	0.74	0.18	0.42
IT-SRos	1.30	0.00	0.19
IT-Col	0.67	0.01	0.45

Figure 5(b). Also in this case, the dataset is incomplete, with about two months of missing measurements before the beginning of the dry season (March-April) and another short gap in September. The summer SWC reduction starts later than in the other two sites, indicating that water scarcity is not so strong, at least for the year examined.

The ESD identified by equation (5) is 0.67 m (Table 3) and is combined with the beech Kc values to drive the conventional soil water balance algorithm. Contrary to the other cases, this algorithm produces satisfactory ET_A estimates (Table 4), both in terms of correlation and errors.

The SWC_{fc} visually identified in this case is $0.45\,cm^3 \cdot cm^{-3}$, while the SWC_{wp} found from the optimized water balance is close to zero (Table 3). The ET_A estimates obtained by the new method well reproduce the available measurements (i.e., more than 85% variance is explained), showing a maximum of about 5 mm at the solstice (Figure 5(c)).

5. Discussion

The classical Kc approach is widely utilized for operationally determining the water demand of irrigated crops [8, 30]. The advantages and limitations of this approach have been investigated in numerous papers and mostly depend on the use of proper Kc values, which can be derived from the existing literature and/or from more modern information sources [31]. In practice, consolidated Kc values are nowadays available to characterize the maximum evapotranspiration of both agricultural and forest ecosystems.

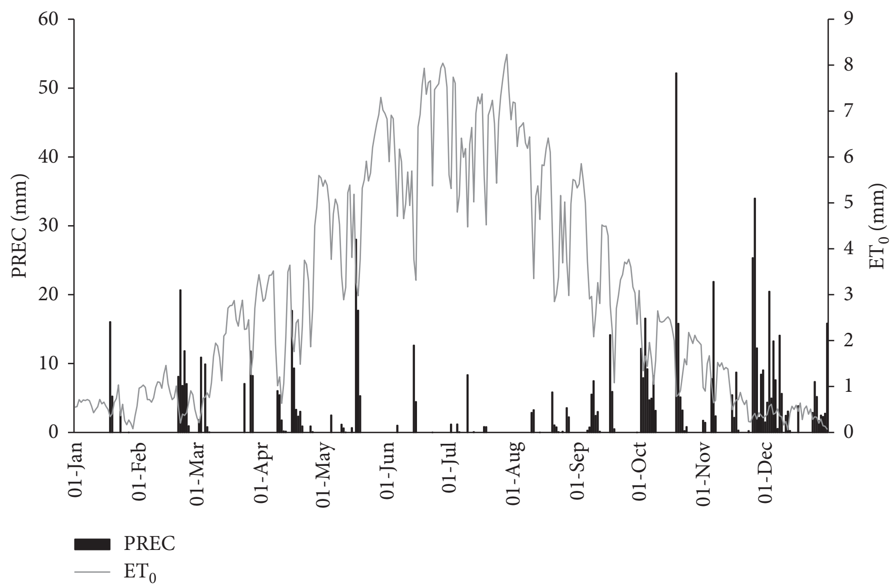
When applied to not fully watered vegetation types, however, the Kc approach must be corrected to account for possible water limitation. This can be done by using SWC measurements, which are related to actual evapotranspiration and are commonly collected in the field [5]. Unfortunately, such measurements give only point information, which is not representative of the entire hydrologically active zone. This also occurs when the measurements of more SWC probes are averaged, which obviously leads to an improved site characterization but is rarely capable of fully accounting for all horizontal and vertical variability in soil features typical of heterogeneous Mediterranean environments [26]. Moreover, SWC measurements are often uncalibrated and affected by temporal drifting [6]. All these factors hamper the application of the classical soil water balance method based on meteorological and SWC data.

The proposed approach circumvents these issues by utilizing relative SWC values, i.e., values normalized between 0 and 1, corresponding to null and full ET_A, respectively. The other meteorological data used, particularly rainfall and ET_0, must instead be quantitative and consistent (i.e., both expressed in mm). The method is applicable to estimate daily ET_A on an annual basis in Mediterranean areas, where SWC is usually high from fall to spring and decreases during the summer dry period.

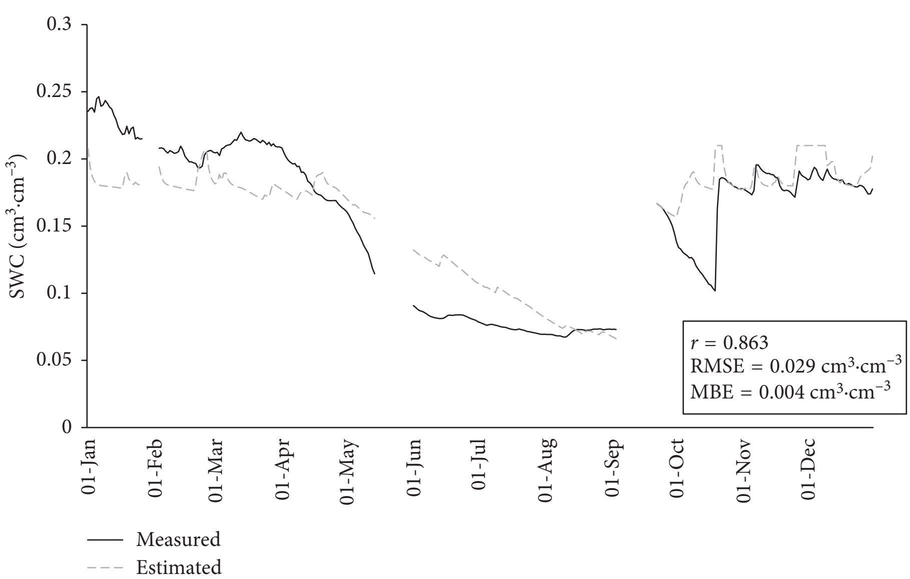
A primary assumption of this approach regards the linear approximation of the $RSWC/RET_A$ relationship; as previously noted, this assumption is necessary to simplify the model application and should imply only minor drawbacks in operational cases where actual soil features are

Table 4: Accuracy statistics of the ET_A estimates obtained by the classical soil water balance method in the three study sites (all correlations are highly significant, $P < 0.01$).

ID	r	RMSE (mm)	MBE (mm)
IT-Amp	0.569	1.449	0.473
IT-SRos	0.513	1.058	0.214
IT-Col	0.917	0.477	0.106

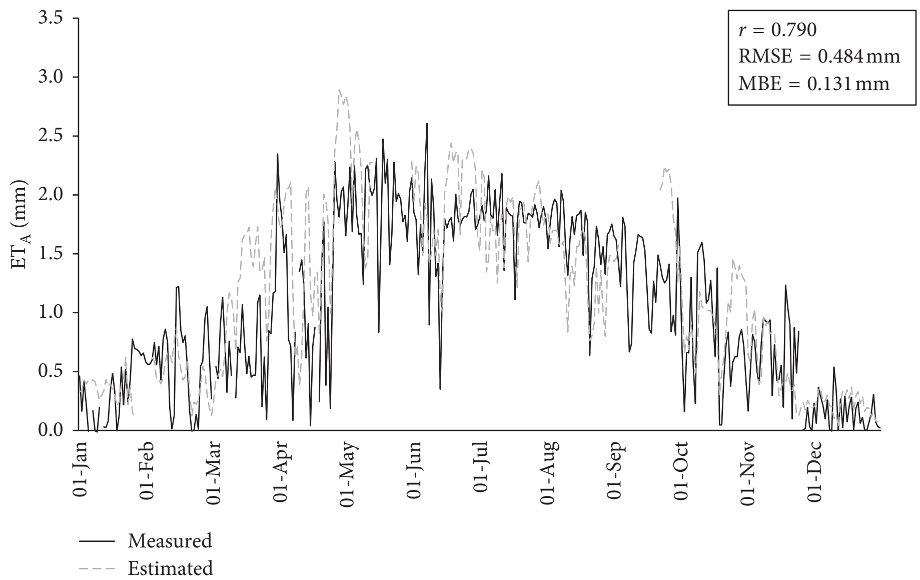


(a)



(b)

Figure 4: Continued.



(c)

Figure 4: Annual evolutions of daily precipitation (PREC) and potential evapotranspiration (ET_0) (a), measured and calibrated SWC (b), and measured and estimated ET_A (c) for San Rossore (all correlations are highly significant, $P < 0.01$).

mostly unknown. The results of the current experiments indicate that this simplification does not deteriorate the final accuracy of the ET_A estimates when compared to different approaches. This is in accordance with what has been found by Lyra et al. [8], who compared different methods to calculate the soil water stress coefficient.

The SWC corresponding to full and null evapotranspiration is assumed to coincide with SWC_{fc} and SWC_{wp}, respectively. This is also a widely used assumption which was found to lead to satisfactory results by Lyra et al. [8]. Several authors, however, state that the SWC corresponding to null ET_A should actually be lower than field capacity [5, 9]. This possibility has been currently explored but has led to decreased ET_A estimation accuracy (data not shown). This finding could be explained by the complexity of the involved relationships and by the vertical heterogeneity in soil water distribution which may reduce the representativeness of SWC measurements for the real conditions affecting plant roots [5].

As mentioned previously, the identification of SWC_{fc} and SWC_{wp} by the application of pedotransfer functions to site texture data may produce variable and inaccurate results. In the current cases, for example, the application of the classical pedotransfer functions of Saxton et al. [14] to the texture information of San Rossore indicates a SWC_{fc} equal to 0.13 and a SWC_{wp} equal to 0.06. When driving the pedotransfer functions of Jabloun and Sahli [32] with the same texture information, a SWC_{fc} equal to 0.24 and a SWC_{wp} equal to 0.18 are obtained. All these values are actually inapplicable to normalize the SWC measurements of this site, and similar results are obtained for the other two sites.

The new method is therefore fully data driven and relies on the previously noted lack of water stress at the beginning and end of the year, which is typical of the Mediterranean climate to visually identify SWC_{fc}. This obviously limits the possibility of extending this operation to different environments and to multiyear measurements, whose feasibility should be evaluated in each single case.

The identification of SWC_{wp} is instead obtained by optimizing a soil water balance based on a one-layer bucket model. The calculation of this water balance requires the preliminary estimation of site ESD, which is carried out assuming the consistency of all input and output terms of the bucket model. Such a property is obviously dependent on the accuracy of the meteorological data used, particularly P and ET_0, which must both be descriptive of actual local conditions. In the current case, the meteorological data used were validated in previous investigations conducted on a national scale by Maselli et al. [23] and Fibbi et al. [24].

The ESD obtained from equation (5) is not a rooting depth but is defined as the zone which is hydrologically active for the specific SWC measurements. This implies that probes placed in the same ecosystem but measuring different SWC variations due to the mentioned factors (vertical and/or horizontal soil heterogeneity, sensor instability, etc.) will produce different ESD estimates. In spite of this, the ESD values currently found are plausible for all three sites, i.e., between 0.5 and 1 m for a temperate hilly grassland, more than 1 m for the Mediterranean plain coniferous forest, and less than 1 m for the mountain broadleaved deciduous forest over the rocky substrate. The same ESD values are also similar to those reported in the literature, i.e., lower than 1 m for Amplero [18], 1–2 m for San Rossore [21], and 0.8 m for Collelongo [21].

This is not the case for the SWC_{fc} and SWC_{wp} currently found, which are only broadly in agreement with those derivable from the application of pedotransfer functions to

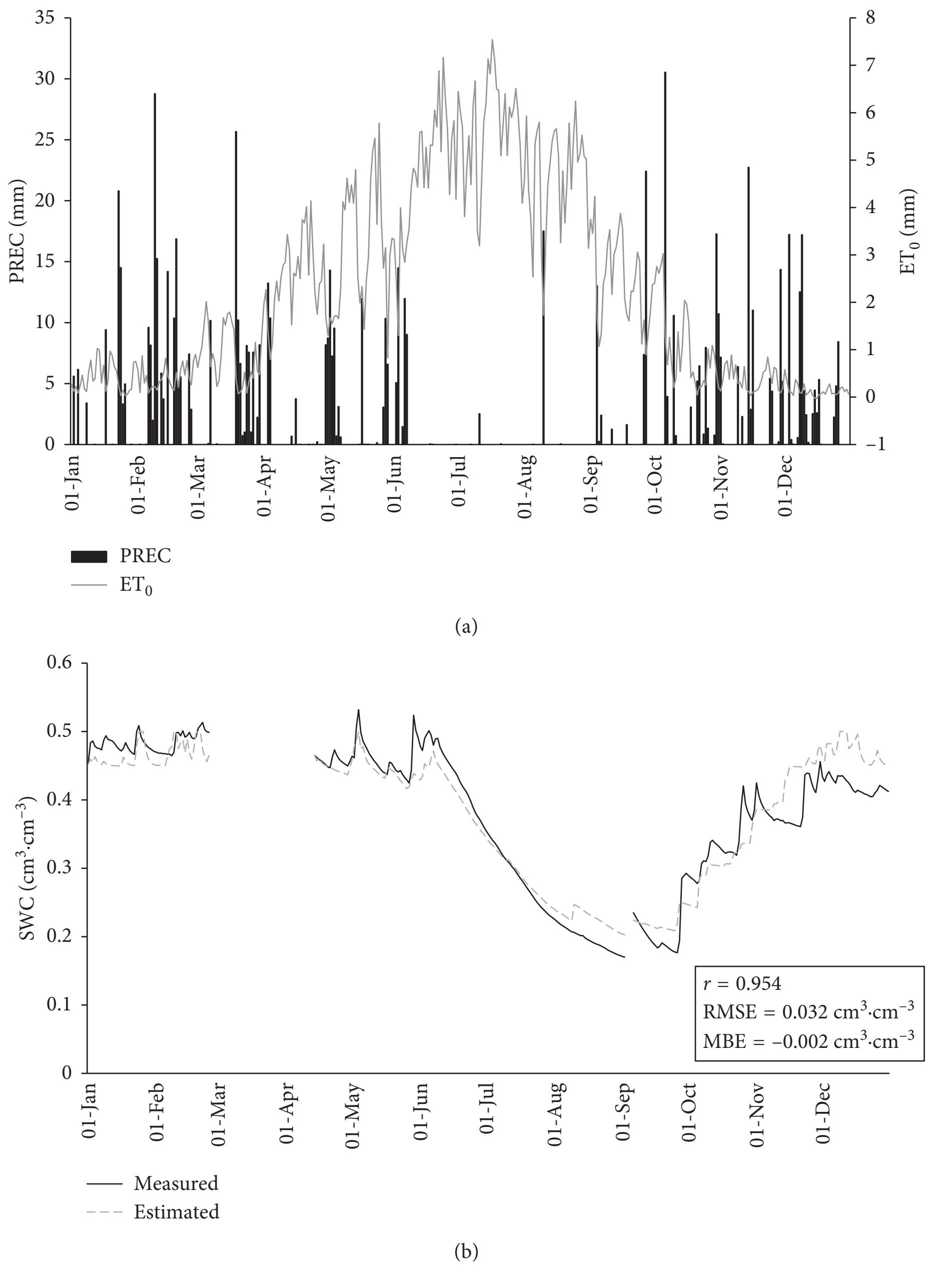
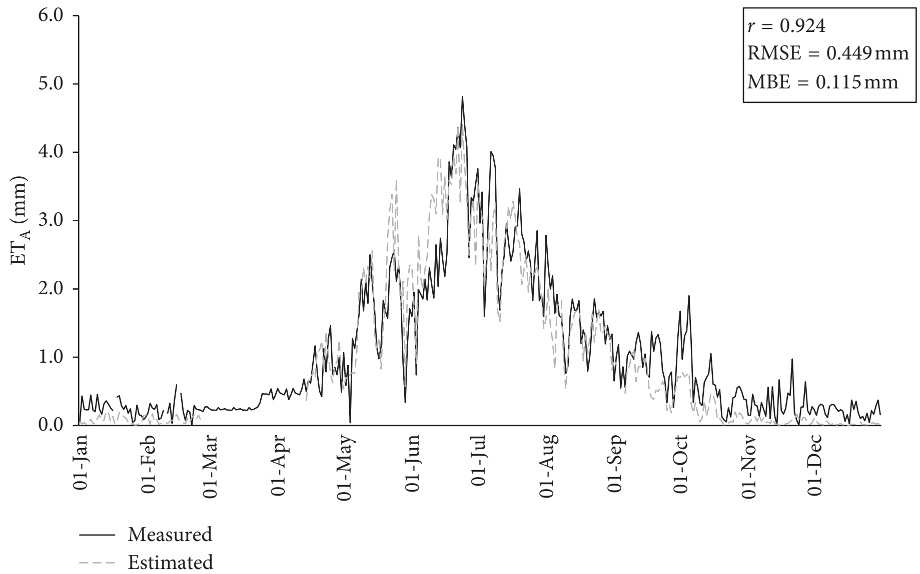


Figure 5: Continued.



(c)

Figure 5: Annual evolutions of daily precipitation (PREC) and potential evapotranspiration (ET_0) (a), measured and calibrated SWC (b), and measured and estimated ET_A (c) for Collelongo (all correlations are highly significant, $P < 0.01$).

the local texture information (i.e., lower for more sandy soils). This confirms the difficulty in deriving appropriate soil hydrological descriptors from conventional texture information but is also ascribable to the relative nature of the current SWC_{fc} and SWC_{wp}, which are intrinsically related to the specific dataset used. As previously noted, this latter property is decisive to allow the normalization of the daily SWC values and the estimation of relevant Ks, which can be combined with a classical Kc approach to predict ET_A.

Overall, the results obtained by the new method are satisfactory and decidedly better than those of a classical soil water balance algorithm for all three study sites (Table 4). The latter algorithm, in fact, provides good results only in the most humid site (Collelongo), where summer water stress is relatively limited. In contrast, this algorithm yields poor estimates in the other two sites, particularly overestimating the day-to-day ET_A variability during the summer dry season. These cases are instead simulated well by the new algorithm, mainly due to the local optimization of SWC_{wp} which guarantees an efficient simulation of ET_A in water stress conditions.

In addition to the aforementioned limitations of the basic theory, the main problems currently found are ascribable to deficiencies in the data used and to spatial mismatches of the measurements/estimates (both horizontal and vertical). In particular, the identification of SWC_{fc} is problematic when the SWC values measured at the beginning of the seasons are not aligned with those at the end of the year. These situations are not rare, as are the cases in which daily meteorological and SWC measurements are missing or unreliable, which obviously prevents the simulation of ET_A.

As regards the validations performed, LE measurements are representative of an area (the so-called "footprint"), which is much wider than that considered by the point SWC observations; consequently, the performed accuracy assessment is necessarily based on assuming a fundamental homogeneity of the soil and vegetation features around the flux towers, which is clearly only approximate. Finally, LE observations can be affected by the incomplete energy balance closure which is typically yielded by the eddy covariance technique [33].

6. Conclusions

The current paper proposes a new semiempirical method which integrates SWC measurements with the conventional Kc approach for the estimation of ET_A in water-limited Mediterranean environments. The method specifically addresses the numerous problems which affect SWC measurements by using a completely data-driven normalization operation. In particular, the new method detects water limitation periods and improves the estimation of ET_A during the dry season. When tested in different environmental situations, the method provided satisfactory results, showing some defects which are mainly related to the representativeness of the SWC data used for the explored ecosystem conditions. The new method is less complex and expensive than other techniques (e.g., those based on energy balance) and, differently from these, can be applied with high spatial and temporal details.

Data Availability

The meteorological data used to support the findings of this study are available from the corresponding author upon request. The flux tower data used to support the findings of this study are available to the public through the FLUXNET website (http://www.europe-fluxdata.eu/).

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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