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Estimation of Actual Evapotranspiration in Fragmented Mediterranean Areas by the Spatio-Temporal Fusion of NDVI Data

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***Abstract*—Actual evapotranspiration (ET_A) is a fundamental component of the land water cycle that can be predicted by the combination of meteorological data and remotely sensed normalized difference vegetation index (NDVI) observations. The proficient application of this approach to the retrospective study of fragmented areas, however, depends on the preliminary use of spatio-temporal fusion (STF) methods capable of integrating different satellite datasets. One of these methods is the Spatial Enhancer of Vegetation Index image Series (SEVIS), which has been recently developed to improve the annual NDVI datasets based on one or a few high spatial resolution images. This STF method is currently applied to moderate resolution imaging spectroradiometer (MODIS) and TM/ETM+/OLI imagery taken over three fragmented areas in Tuscany (Central Italy), representative of different Mediterranean ecosystems, i.e., an urban grassland, a tomato field, and an olive grove. The performance of SEVIS is evaluated by comparing the ET_A estimates obtained from the original (MODIS) and synthetic (MODIS plus TM/ETM+/OLI) NDVI datasets to ground ET_A observations. The experimental results indicate that the original MODIS NDVI data cannot properly characterize the seasonal vegetation evolutions of the three study sites, which negatively affects the performance of ET_A simulation. In contrast, such evolutions are reasonably reproduced by the synthetic NDVI datasets, which improves the accuracy of the ET_A estimates both in terms of correlation and errors. The improvements are particularly evident during the summer dry period when the MODIS images are incapable of characterizing the actual vegetation response to water stress.**

***Index Terms*—Moderate Resolution Imaging Spectroradiometer (MODIS), Normalized Difference Vegetation Index (NDVI), Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), Operational Land Imager (OLI).**

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I. Introduction

Actual evapotranspiration (ET_A), defined as the sum of evaporation (from soil and plant surface) and transpiration (from vegetation), is a major component of the land water cycle, which should be strongly impacted by the increase in drought frequency and intensity associated to global warming [1].

Such a phenomenon is expected to be particularly effective in water-limited Mediterranean regions, which are also characterized by a high fragmentation of the vegetation cover [2]. This enhances the importance and complexity of estimating the ET_A of Mediterranean ecosystems at various spatial and temporal scales [3].

Among the techniques that have been developed for the estimation of ET_A, those that are based on ground measurements present relevant theoretical or practical drawbacks [3]. Eddy covariance observations, for example, are representative of the so-called "footprint" area, whose size and shape can change in time depending on the measurement instrument height, site micrometeorological conditions, and vegetation characteristics [4]. The use of lysimeters is generally complex, expensive, and anyway limited to the areas covered by herbaceous vegetation [5].

This is a major reason for the wide popularity of the semiempirical crop coefficient (*Kc*) method promoted by FAO [6], which predicts ET_A by combining multitemporal crop-specific coefficients with meteorological estimates of potential evapotranspiration (ET_0). While the original *Kc* method was efficient only in well-watered ecosystems, its applicability has been extended to the other cases by the consideration of soil water content (SWC) observations, which are indicative of water stress effect [7]. Unfortunately, the accuracy of such a method is affected by the numerous technical and operational drawbacks, which characterize SWC measurements [8]. This issue has been addressed by Chiesi *et al.* [9], who proposed a simple and efficient methodology to assess daily ET_A based on standard meteorological and SWC datasets. The ET_A obtained by this and similar methods, however, is still referred to the areas actually observed by the SWC measurements, which can be very small (few meters) in regions having spatially heterogeneous environmental features.

Remote sensing data have been widely applied for estimating ET_A on larger areas, thanks to their capability of providing precious information on these features at various spatial and temporal scales [10]. The estimation of ET_A through remote sensing techniques is generally carried out by energy balance and water balance methods, both presenting advantages and limitations (e.g., [11]). A popular variant of the latter approach utilizes multitemporal *Kc* values derived from remotely sensed vegetation indices (VI) to quantify the biomass amount that would be transpiring in well-watered conditions [12]. This strategy has been recently extended by Maselli *et al.* [13], who proposed the combination of meteorological data and satellite normalized difference vegetation index (NDVI) observations to estimate ET_A in water limited cases. The method, named NDVI-Cws, has been tested versus various types of ground data (i.e., eddy covariance latent heat observations, sap flow transpiration measurements, etc.), in both agricultural and seminatural ecosystems [13], [14].

The application of this simulation approach is generally constrained by the spatial and temporal features of the available NDVI datasets, which should be descriptive of the actual variability of the observed ecosystems. As previously mentioned, in Mediterranean regions, most of the agricultural fields and forest plots have a small size and are covered by vegetation whose quantity and status can vary in few days [15]. Such vegetation patches can be currently characterized by using the images of the new satellite systems (i.e., those of the Sentinel 2 mission), while the success of this operation in retrospective cases depends on the application of efficient spatio-temporal fusion (STF) methods capable of blending data from different sensors [16], [17].

This has promoted the development of numerous STF methods, which have reached various levels of complexity and applicability [18]. Most of these methods estimate reflectance or VI changes based on the definition of similarities between high spatial resolution (HR) pixels [16] and are suboptimal to apply for long-term projections in areas where the main vegetation types show diverging phenologies. The STF method proposed by Maselli *et al.* [19] overcomes this drawback through the statistical decomposition of low spatial resolution (LR) NDVI multitemporal data series. This method, refined and definitively named Spatial Enhancer of VI image Series (SEVIS) in [20], is suitable to predict the annual NDVI evolutions of ecosystems characterized by high spatio-temporal variability and complexity. SEVIS could, therefore, be particularly useful to drive the estimation of seasonal ET_A in fragmented and heterogeneous Mediterranean areas.

The current article aims at assessing this hypothesis in three case studies representative of different Mediterranean ecosystems, i.e., a grassland within an urban park, a field grown with a summer crop (tomato), and an olive orchard. The investigation utilizes images taken by Aqua/Terra Moderate Resolution Imaging Spectroradiometer (MODIS) and by Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) as LR and HR data, respectively, to produce synthetic, spatially enhanced NDVI data series. The NDVI-Cws method is then driven by both the MODIS and the synthetic NDVI data, obtaining ET_A estimates that are evaluated versus relevant ground observations.

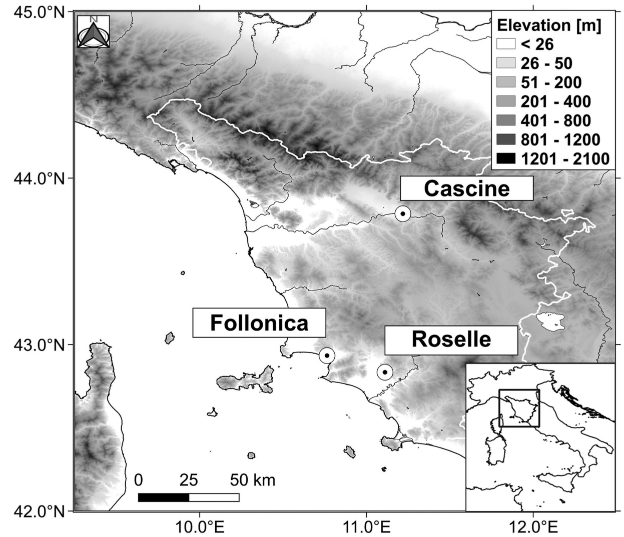

Fig. 1. Digital elevation model of Central Italy showing the location of the three study areas in Tuscany (the position of the region is indicated in the bottom-right box).

II. Materials and Methods

A. Study Areas

The current investigation concerns three spatially heterogeneous areas in Central Italy for which the land cover information, meteorological data, and SWC measurements are available. The main characteristics of each site are summarized in the following.

1) Cascine: The first test site is located within the largest green area in Florence, the urban park of Cascine (43.7854° N, 11.2183° E, Central Italy) (see Fig. 1). This park lies in an alluvial plain along the Arno River, at an altitude of 40 m above sea level. The climate is Mediterranean subhumid, with a mean annual temperature of 15.7 °C and mean annual rainfall of about 800 mm concentrated in autumn and spring. The park, which is used for recreational purposes, is characterized by the presence of broadleaves and conifers, meadows, and some buildings interspersed with small agricultural areas.

The agricultural areas are highly fragmented and are mostly grown with grasses, annual crops (mainly vegetables), vineyards and olive groves. The study site corresponds to a field of about 30 m × 50 m where the soil is sandy-clay-loam and has a depth over 2 m; the field is usually covered by seminatural grassland, and this was actually the case in the study year (2009).

2) Roselle: The second test site is located in the South of Tuscany, Central Italy (42.8446° N, 11.1126° E, Fig. 1), in an almost flat area at an altitude of about 35 m above sea level. The area is covered by fields having a size of few hectares, which are grown with differentiated and alternated winter and summer crops. The climate is Mediterranean subarid, with mild winter and hot and dry summer. The mean annual temperature is about 15.8 °C and rainfall, which is mostly concentrated in spring and autumn, is about 660 mm.

The study field extends over about 250 m × 250 m, where the soil is clay-loam. During the 2009 growing season, tomatoes

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were transplanted at the end of April and fruits were collected at the mid of August. A drip irrigation system was installed in the field to support water needs during the driest periods. The study field is surrounded by other fields of variable size, which in 2009 were grown with diversified winter and summer crops (mainly wheat, corn, and vegetables) and permanent plantations (mostly olive groves).

3) Follonica: The third test site is located near the town of Follonica, Tuscany (42.9328° N, 10.7642° E; 17 m above sea level) (see Fig. 1). The climate is Mediterranean subarid, with a mean annual air temperature of 16 °C. January is the coldest (9 °C) and July the warmest month (24 °C). The mean annual precipitation is 650 mm, mostly concentrated in autumn and spring, while summer rainfall is very scarce. The soil has a total depth of about 3 m; its surface layer (about 0.5 m) is silty-loam, with a low amount of organic matter.

The experimental olive orchard (*Olea europaea* L., cv. Leccino) extends over an area of about 0.1 ha, which was planted in 2003 with a 4 m × 4 m spacing. In 2013, the olive trees had a mean height of around 3 m and a canopy fractional cover around 0.25 [14]. The intertree areas are covered by several herbaceous native species that, being the olive orchard usually managed in rainfed condition, are almost completely dried during the summer period. The orchard is surrounded by other fields covered with different annual and permanent crops and by urban and residential areas.

B. Study Data

A fully equipped agrometeorological station was installed at each experimental site to collect standard daily meteorological data (i.e., minimum and maximum air temperature, precipitation, and solar radiation) in the respective study years (2009 for Cascine and Roselle, and 2013 for Follonica). In case of missing data, daily values were retrieved from the archive of the LaMMA Consortium, having a 250 m spatial resolution, which was produced by the application of the DAYMET algorithm to the air temperature and precipitation measurements collected at all regional ground stations [21].

The SWC measurements were collected at the same three sites during the respective years by means of capacitive probes; these probes were placed at 0.2 m depth for Cascine (Theta Probe ML2X), and 0.3 m for Roselle (Decagon EC-20) and Follonica (Decagon 10HS).

The low spatial resolution NDVI images of 2009 and 2013 were collected by the Aqua/Terra MODIS satellite sensor. In particular, 23 maximum value composites (MVC) over 16-day periods with a 250-m spatial resolution (MODIS13Q1 Vegetation Indices 16-Day L3 Global 250 m Grid SIN) were freely downloaded from the USGS website in a preprocessed format (https://modis.gsfc.nasa.gov/data). These NDVI MVC images were corrected for residual radiometric and atmospheric disturbances, as described in [13].

The high spatial resolution data were obtained from the cloud-free Landsat acquisitions taken in the same two years. For the first year (2009) a Landsat 7 ETM+ scene of 10th April and a Landsat 5 TM scene of 29th July were selected. The ETM+ scene over Roselle, however, was heavily affected by the scan line correction failure and was therefore unusable. This was not the case for the scene over the Cascine site, which was near the center of the ETM+ frame. For the third area, two Landsat 8 OLI scenes were used, acquired on 13th April and 3rd August 2013. All Landsat scenes were freely downloaded from the USGS website (https://earthexplorer.usgs.gov) in a geometrically and atmospherically corrected format. False-color composites of these scenes are shown in Fig. 2 for the three study areas.

III. Data Processing

The current experiment consisted of two main methodological steps, whose main features are summarized in the following sections. Full descriptions of the algorithms applied are reported in the mentioned papers together with justifications of all choices and assumptions made. The two steps were independently applied to the Cascine, Roselle, and Follonica study areas.

A. Ground-Based ET_A Assessment

The daily $\mathrm{ET_A}$ values, currently used as a ground reference, were obtained relying on the classical method proposed by the FAO. This method is based on the use of time-varying crop coefficients (*Kc*), defined as the ratio of the $\mathrm{ET_A}$ observable for a fully watered crop over $\mathrm{ET_0}$ [7]. The method allows the consideration of the water limitation, which is typical of arid and semiarid ecosystems through a water stress factor.

Thus, the daily $\mathrm{ET_A}$ is estimated as follows:

$$\mathrm{ET_A} = \mathrm{ET_0} Kc Ks \tag{1}$$

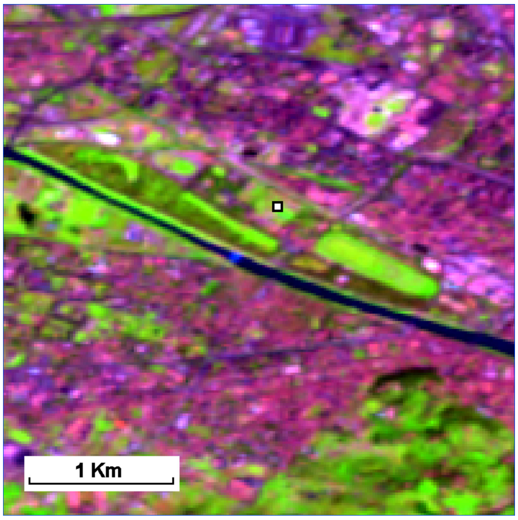
where *Kc* is the crop coefficient of the day, which is strictly dependent on the characteristics of the plants considered, and *Ks* is the coefficient that accounts for water stress [7].

The proper *Kc* values are available for most vegetation types, while the computation of *Ks* is generally a nontrivial issue. Such a coefficient, in fact, can be derived from SWC measurements, but the relationships that link SWC to evapotranspiration are usually complex and variable depending on several environmental factors (see [22] for a review). An additional problem is related to the numerous sources of uncertainty, which affect the SWC measurements [8], [23]. The semiempirical method proposed by Chiesi *et al.* [9] addresses these issues by processing the local SWC measurements based on site-specific information. According to this method, *Ks* is computed as

$$Ks = (\mathrm{SWC} - \mathrm{SWC_{wp}}) \,/\, (\mathrm{SWC_{fc}} - \mathrm{SWC_{wp}}) \tag{2}$$

where $\mathrm{SWC_{wp}}$ and $\mathrm{SWC_{fc}}$ are the SWC at wilting point and field capacity, respectively. The two SWC values are defined for each site together with the effective soil depth (ESD), as fully described in [9].

This method was applied to the available daily meteorological and SWC data for the entire 2009 in the first case study (Cascine) and only for the 2009 tomato growing season (April–August) in the second case study (Roselle); in the case of Follonica, it was applied to the entire 2013. The site meteorological data were first checked for consistency and quality, and data gaps were



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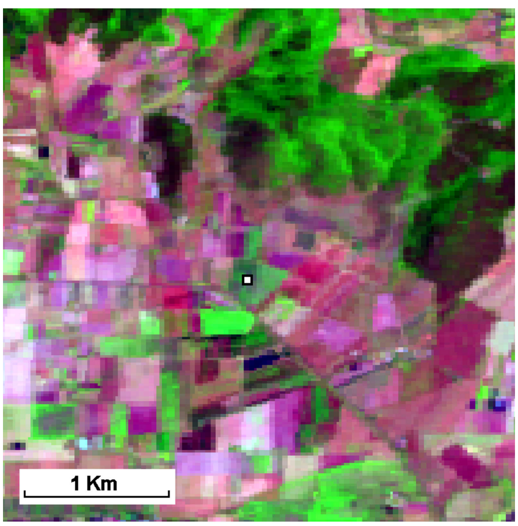

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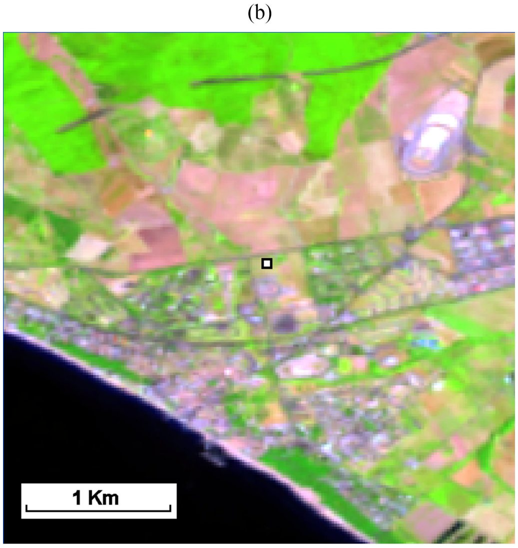

(c)

Fig. 2. False-color composites (RGB = red, near-infrared and middle-infrared bands) obtained from (a) Landsat scenes of Cascine (10th April 2009), (b) Roselle (29th July 2009), and (c) Follonica (3rd August 2013); the black squares near the center of the images indicate the position of the three study sites.

filled as described above. Solar radiation was then estimated through the MT-Clim algorithm [24]. On the basis of the daily air temperature and solar radiation, ET_0 was estimated using the Jensen and Haise equation [25], while classical crop coefficients for grassland, tomato, and olive grove were derived from the existing literature [6]. The site specific daily *Ks* values were finally obtained by the use of (2).

B. Remote Sensing ET_A Estimation

The remote-sensing-based method that was currently applied, named NDVI-Cws, uses meteorological data (i.e., daily air temperature, precipitation, and solar radiation) and NDVI images that must be descriptive of the actual vegetation conditions and relevant seasonal evolutions at the study site [13]. Based on these assumptions, the method uses the fractional vegetation cover (FVC) to account for the contribution of site transpiration and evaporation by means of the following equation:

$$\mathrm{ET_A} = \mathrm{ET_0}\,[\mathrm{FVC}\;\; Kc_{\mathrm{Veg}}\;\mathrm{Cws} + (1-\mathrm{FVC})\;\; Kc_{\mathrm{Soil}}\;\mathrm{AW}] \tag{3}$$

where FVC is the fractional vegetation cover, while Cws and AW are the two short-term water stress scalars. Kc_{Veg} and Kc_{Soil} correspond to the maximum crop coefficient for vegetation and soil, respectively. FVC is linearly derived from NDVI, while the two water stress scalars are computed through the combination of precipitation and ET_0 [13].

The NDVI-Cws method was first fed with NDVI values directly extracted from the 250-m MODIS pixels corresponding to the study sites. Next, the spatial detail of the MODIS images was improved by applying SEVIS to the same and to the available HR images.

As previously mentioned, SEVIS had been specifically conceived to cope with the diverging phenologies of spatially heterogeneous Mediterranean vegetation types. Thus, this STF method should be particularly suitable for the estimation of the annual NDVI evolutions in small urban and agricultural areas where diversified artificial and seminatural land cover types coexist. SEVIS consists of the following five steps:

1) Application of the sequential maximum angle convex cone (SMACC) algorithm [26] to the LR multitemporal dataset for identifying NDVI endmembers (EMs) of vegetation types having uniform phenological evolutions and respective abundance images.
2) Use of this information to drive a fuzzy maximum likelihood (ML) classification of the HR imagery.
3) Spatial enhancement of the SMACC abundance images based on the HR ML membership grade images.
4) Modification of the LR multitemporal NDVI endmembers to account for the intraclass variability of vegetation features that can be found in relatively large areas.
5) Recomposition of the multitemporal NDVI endmembers and the spatially enhanced abundance images to produce synthetic HR imagery.

SEVIS was applied to the LR NDVI images of the whole study year in the case of Cascine and Follonica (i.e., 23 MODIS NDVI MVC images) and only to the LR NDVI images of the

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tomato growing season in the case of Roselle (i.e., 9 MODIS NDVI MVC images from April to August). In the former cases, two Landsat scenes were used as HR data taken in spring and summer, while in the case of Roselle only the summer scene was utilized. SEVIS, thus produced 23 and 9 spatially enhanced images, respectively, from which new multitemporal NDVI profiles of the three study sites were extracted.

The NDVI profiles derived from both the MODIS and the synthetic HR images were interpolated on a daily basis and converted into FVC using a linear equation [13]. Equation (3) was then applied using the same meteorological data as above to compute both ET_0 and the water stress scalars (Cws and AW).

In the case of Roselle, the computation of the water stress scalars also considered the amount of water provided by drip irrigation, while for the olive grove of Follonica, a lower limit was set to the same scalars to account for the possible rescue irrigation. In all case studies, Kc_{Soil} was set to 0.2, while the maximum crop coefficient (Kc_{Veg}) was set to 1.2 for Cascine and Roselle (grassland and tomato field, respectively) and to 0.9 for Follonica (olive grove) [13]. Following the same publication, the accumulation period to compute the water stress scalars was 30 days for the grassland and tomato field, and 45 days for the olive grove.

The daily ET_A estimates obtained using both the MODIS and the synthetic NDVI profiles were finally assessed versus the respective ground observations, summarizing the results by means of common accuracy statistics [i.e., the coefficient of determination r^2, the root-mean-square error (RMSE), and the mean bias error (MBE)].

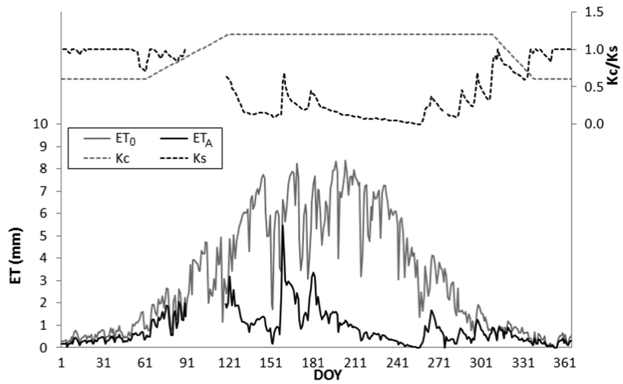
IV. Results

Out of the three study sites, the Cascine grassland is the most fragmented and surrounded by the most diversified land cover types (forest, annual and perennial crops, urban, and residential areas) (see Figs. 2 and 3). This case study is, therefore, used for fully illustrating the results obtained, while only the most relevant findings are provided for the Roselle and Follonica experiments.

A. Cascine

The meteorology of Cascine during 2009 is typical of a Mediterranean climate, with moderate rainfall (total about 790 mm) and dry summer. The annual ET_0 follows this meteorological pattern, i.e., it is maximum just after the summer solstice and decreases during the rainy days; the annual total is much higher than rainfall (about 1140 mm), suggesting the existence of a marked water stress summer period [see Fig. 4(a)]. This is clearly detected by the evolution of the water stress coefficient (Ks) obtained from the ground SWC probe using the soil parameters reported in Table I; the missing values are due to the absence of SWC measurements. The grassland Kc varies between 0.6 at the beginning (January and February) and end of the season (mostly December) and 1.2 at fully developed conditions (from May to November). The combination of this

Fig. 3. Cascine area. (a) Examples of MODIS, (b) Landsat, and (c) synthetic NDVI images of July 2009, with superimposed park boundary (white line); NDVI ranges from 0, black, to 1, white.



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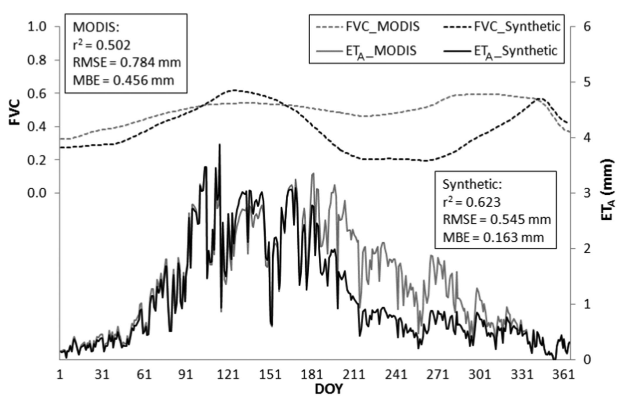

(b)

Fig. 4. Cascine. (a) Annual evolution of ET_0, *Kc*, *Ks*, and ET_A obtained from the ground measurements. (b) Annual evolution of MODIS and synthetic FVC, and corresponding ET_A estimates (the accuracy statistics refer to the comparison between the ground and remote sensing ET_A observations; both correlations are highly significant, $P < 0.01$).

TABLE I
SOIL PARAMETERS USED TO COMPUTE THE REFERENCE ET_A IN THE THREE CASE STUDIES (SEE TEXT FOR DETAILS)

Study site	ESD (m)	SWC_{fc}	SWC_{wp}
Cascine	0.47	0.32	0.09
Roselle	0.51	0.30	0.15
Follonica	0.69	0.29	0.15

information yields the ET_A evolution shown in the same figure; daily ET_A is generally lower than 4 mm, with only a few exceptions, with a strong reduction during the spring and summer periods affected by water shortage.

Both the OLI and MODIS images of the study area are characterized by the marked spatio-temporal variations related to the different NDVI evolutions of the main land cover types [urban areas, croplands, grasslands, and forests, Figs. 2(a) and 3]. In particular, different vegetation types show diversified responses to summer dryness, with NDVI decreases that are minimum for the urban forest and maximum for the grassland.

This is confirmed by the results of the SMACC algorithm, which identifies five main NDVI endmembers associable to the deciduous forest, urban, residential and riparian areas, and grassland, the last showing the most clear spring peak and a strong reduction during summer [27]. Based on this information and on the two HR images considered, SEVIS produces synthetic NDVI images of which an example is shown in Fig. 3(c). The spatial detail of these images is highly improved with respect to MODIS, particularly within the Cascine park, where all mentioned vegetation types are intermingled.

The MODIS FVC evolution of the study site used to estimate ET_A is shown in Fig. 4(b); only minor variations are visible during the year, being the range approximately between 0.33 and 0.60. This results from the mixed nature of the corresponding MODIS pixel, which is covered by all the five SMACC classes, with a prevalence of riparian vegetation.

The same figure reports the FVC evolution of the study site derived from the synthetic images; this shows a greater annual variability (between 0.20 and 0.62), a higher spring peak and, above all, a higher effect of summer dryness.

These patterns are clearly reflected in the ET_A estimates obtained using the MODIS and the synthetic data; the ET_A obtained from the spatially enhanced NDVI dataset shows a more marked peak at the beginning of April and a stronger reduction during summer, which more faithfully reproduces the pattern of the ground-based ET_A [see Fig. 4(a)]. The accuracy statistics confirm the improvement obtained, being the determination coefficient increased from 0.502 to 0.623 and the RMSE and the MBE reduced from 0.784 to 0.545 mm and from 0.456 to 0.163 mm, respectively.

B. Roselle

Fig. 5(a) shows the evolution of ET_0 and of the two coefficients, *Kc* and *Ks*, relative to the tomato field of Roselle. All data series are referred only to the growing cycle of the crop, i.e., from middle April (day of the year, DOY = 110), when the field was prepared for transplanting, to middle August (DOY = 230), when the fruits were harvested. *Kc* varies from 0.2 (i.e., bare soil) to 0.3 at the transplanting date (30th April, DOY = 120), then it rapidly reaches a maximum of 1.15 after 55 days and, finally, tends to decrease toward 0.3 at the date of fruit harvesting.

Ks, obtained using the parameters of Table I, shows a high day-to-day variability, mainly due to the irrigation events, and a decreasing trend, indicating that the crop is not fully watered. The combination of ET_0 and the two coefficients provides the ET_A values shown in the same figure: the total amount is about 400 mm with daily values of approximately 4 mm during summer and great day-to-day variations.

The visual examination of the available OLI images [see Fig. 2(b)] confirms the existence of a quite fragmented land cover due to the presence of relatively small forest patches and fields, the latter grown with diversified winter and summer crops. This results in the SMACC identification of six NDVI endmembers, which, however, are only partially differentiated (data not shown). The FVC profiles of the study site obtained from the MODIS and synthetic images are shown in Fig. 5(b). The MODIS profile has a constant tendency to decrease, which seems not appropriate to reproduce tomato vegetation activity.

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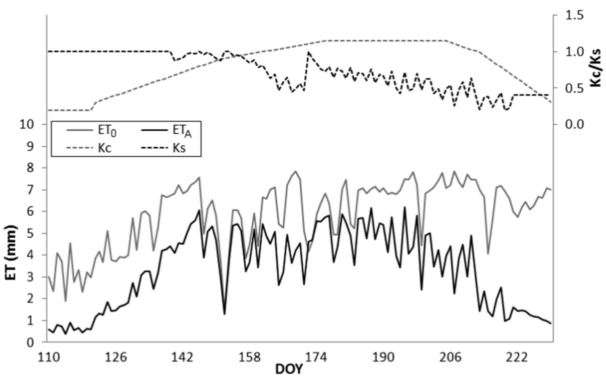

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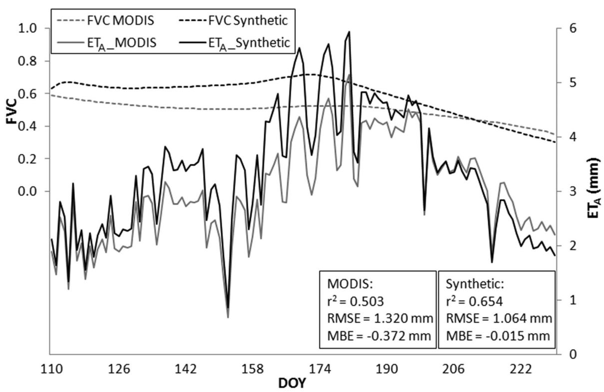
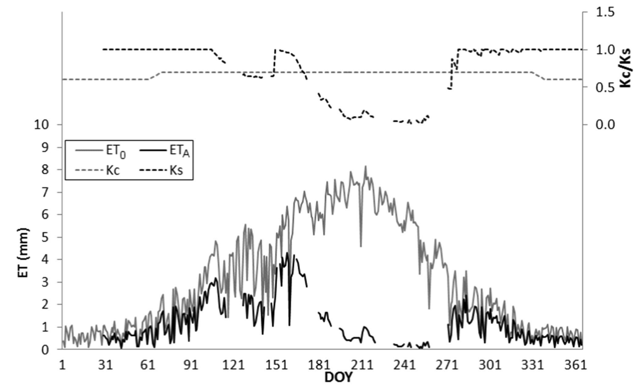


(b)

Fig. 5. Roselle. (a) Annual evolution of ET_0, *Kc*, *Ks*, and ET_A obtained from the ground measurements. (b) Annual evolution of the MODIS and the synthetic FVC, and corresponding ET_A estimates (the accuracy statistics refer to the comparison between the ground and remote sensing ET_A observations; both correlations are highly significant, $P < 0.01$).



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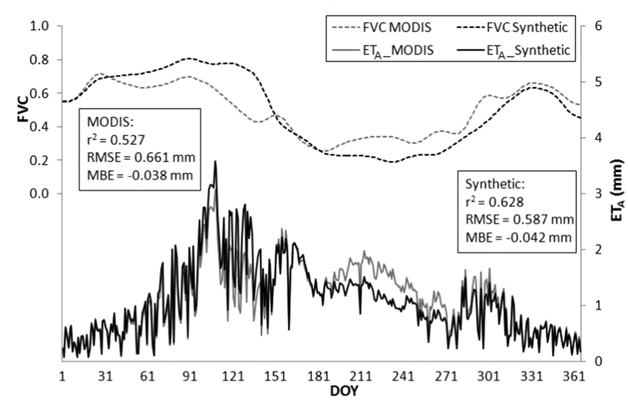

(b)

Fig. 6. Follonica. (a) Annual evolution of ET_0, *Kc*, *Ks*, and ET_A obtained from the ground measurements. (b) Annual evolution of the MODIS and synthetic FVC, and corresponding ET_A estimates (the accuracy statistics refer to the comparison between the ground and remote sensing ET_A observations; both correlations are highly significant, $P < 0.01$).

In contrast, the spatially enhanced FVC profile shows a peak of about 0.7 at the end of June (DOY = 177), when plants are fully developed, and decrease toward the harvest date.

These different FVC evolutions determine the two ET_A series shown in the same figure; also in this case, the use of the synthetic data leads to an increase of the determination coefficient (from 0.503 to 0.654), and to a reduction of the RMSE and of the MBE (from 1.320 to 1.064 mm and from −0.372 to −0.015 mm, respectively).

C. Follonica

The annual ET_0 evolution of the Follonica site is shown in Fig. 6(a) together with that of the two coefficients, *Kc* and *Ks*, utilized to yield ET_A. The second coefficient, obtained as in the previous cases (see Table I), clearly reduces the observed ET_A from July to September.

Also in this case, the high spatial heterogeneity of the vegetation cover around the study site is clearly visible from the OLI images [see Fig. 2(c)]. The MODIS FVC evolution of the study site utilized to estimate ET_A is shown in Fig. 6(b); the spring peak, as well as the summer minimum, are not very clear. The SMACC identifies seven main NDVI endmembers, four of which can be attributed to the different spring crops (data not shown). The HR study pixel is mostly covered by these crops, which leads to a synthetic FVC evolution more characterized by a spring maximum (up to 0.8) and a summer decline (minimum at 0.2).

The different behavior of these datasets determines the two ET_A series still shown in Fig. 6(b); the use of the synthetic NDVI data yields an increase of the determination coefficient from 0.527 to 0.628, with a corresponding reduction of the RMSE from 0.661 to 0.587 mm, while the MBE remains around −0.04 mm.

V. Discussion and Conclusion

The assessment of ET_A is of great importance for the correct simulation of the land water cycle at different spatial and temporal scales [11]. The ET_A estimation methods based on the use of ground data have difficulty in accounting for the spatial variability of the major factors that affect water fluxes, i.e., terrain, soil, and vegetation features.

This is also the case for the classical *Kc* method, which rescales the potential crop evapotranspiration by means of the normalized SWC observations [7]. This method, in fact, is affected by the numerous uncertainties and by the scarce spatial representativeness of the SWC measurements [8]. While the impact of the former problem can be mitigated by the use of "ad hoc" algorithms to transform SWC into *Ks* [7], the obtained ET_A

observations are still representative only of the small area sensed by the SWC probes. This can be particularly problematic in spatially heterogeneous and fragmented urban and agricultural areas, which are common in Mediterranean regions.

These considerations suggest that optimal use of the crop coefficient methods would be to produce reference ET_A datasets for relatively small and homogeneous land areas. This is the case for the method currently applied, which was recently assessed versus eddy covariance flux tower observations taken in three Italian sites representative of different Mediterranean ecosystems [9]. This experiment demonstrated that the proper elaboration of the ground meteorological and SWC data can reasonably reproduce the site daily ET_A measured by the flux towers within sufficiently homogeneous footprints. The accuracy attainable is obviously dependent on the choice of appropriate multitemporal *Kc* values, which, in general, are well known for the main agricultural vegetation types. Similarly, the performance of the method is sensitive to the use of representative daily *Ks*, at a degree proportional to the site aridity level. The transformation of SWC into *Ks* in water-limited environments is, therefore, a critical issue, which has been fully treated in [9]. In all cases, the method remains affected by the spatial heterogeneity of the ecosystem characteristics around the SWC measurement site and is, therefore, preferentially suitable for local ET_A simulation.

On the other hand, remote-sensing-based techniques are potentially capable of providing ET_A estimates over wider areas with spatio-temporal resolutions, which are constrained by the datasets used. Among these methods, the NDVI-Cws has been successfully tested in the homogeneous agricultural and forest areas, which can be efficiently characterized by the used 250-m resolution MODIS NDVI imagery [13], [28]. The same datasets, however, cannot be directly used to obtain ET_A estimates in the spatially fragmented environments, where higher spatial resolution imagery becomes necessary. As previously noted, such imagery can only be obtained through the STF methods while performing retrospective, long-term studies [18].

This is the case of SEVIS that was specifically aimed at producing seasonal or annual synthetic NDVI image series with improved spatial detail based on one or few HR images [20]. Differently from other STF methods, SEVIS uses the multitemporal LR dataset not to estimate NDVI changes from the base to the prediction dates, but to identify the typical NDVI evolutions of the main vegetation types for the entire study period. This information is then integrated with the single-date HR images, improving the prediction of medium-long term NDVI developments [20]. The same paper reports on the intercomparison of this STF method with other, more conventional algorithms. The experimental results confirmed that SEVIS is particularly efficient to cope with the spatially fragmented nature and diverging phenological evolutions, which are typical of Mediterranean vegetation types.

The current investigation has, therefore, concerned the applicability of SEVIS to produce spatially enhanced ET_A estimates in the relatively small urban and agricultural areas grown with both nonirrigated and irrigated crop types. The estimates have been assessed versus similar observations obtained by the mentioned elaboration of ground data, which were the only available for the study sites. Such validation approach presents a drawback due to the use of the same daily ET_0 values to produce both reference and remotely sensed ET_A data series. This obviously implies only partial independence of the compared ground and remote sensing ET_A, which renders the accordance obtained statistically spurious and, consequently, artificially inflated. This problem, however, only marginally affects the validity of the comparative study performed, which is focused on assessing the possible improvements obtainable by combining the same ground observations with different NDVI data series.

The experimental results of all case studies support this consideration, being the NDVI multitemporal profiles derived from the original MODIS images clearly inadequate to describe the expected vegetation evolutions. This is particularly true for the examined urban grassland and olive orchard, whose size is much smaller than the MODIS pixel resolution (250 m $\times$ 250 m). In these cases, the MODIS NDVI values do not clearly show the spring peak and the summer drop, which is typical of water-limited Mediterranean grasslands and tree plantations, mostly due to the interference of other vegetation types having different phenology [29]. The problem is also evident for the tomato field, which is larger but surrounded by other cropped fields with extremely diversified growing cycles. Consequently, the seasonal NDVI evolution obtained from the MODIS data does not show the June maximum that follows the full growth of this irrigated summer crop. In general, the three experiments performed, support the expectation that the MODIS NDVI values are altered with an intensity that is inversely proportional to both the extent of the observed land area and the synchronicity of the surrounding vegetation growing cycles.

Such problems are notably alleviated by the use of the synthetic NDVI dataset produced by SEVIS, which more reasonably reproduces the expected seasonal developments of both the nonirrigated and irrigated vegetation types, particularly during the summer dry period. This is confirmed by the quantitative analysis versus ground ET_A observations, which are more accurately simulated by using the synthetic NDVI product.

Most of the previous studies on the estimation of ET_A by the spatio-temporal fusion of the satellite data concerned energy balance methods and, therefore, focused on improving the features of the thermal infrared imagery [30], [31]. More recently, He *et al.* [32] used a spatio-temporally fused enhanced vegetation index dataset to enhance the spatial detail of the MOD16 ET algorithm. In these cases, the accuracy assessment of the spatially enhanced ET_A product was performed against eddy covariance ET_A observations, which are representative of relatively large footprints (typically around 0.2–1.0 km^2). In contrast, the ET_A estimates currently obtained are validated versus ground observations representative of small areas, which is logically a more appropriate approach. All these factors, joined to the different environmental characteristics of the investigated areas, hinder the direct comparison of our experimental findings with those of the previous investigations.

The current findings, however, demonstrate that SEVIS is capable of improving the prediction of ET_A in the ecologically complex areas examined. Similar results can be expected when applying the method in other spatially fragmented areas covered by the vegetation types showing diverging seasonal NDVI evolutions. These cases are common in Mediterranean and other intensively populated regions, where vegetation development is constrained by contrasting natural and human-induced factors that can be efficiently accounted for by the proposed data integration methodology.

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