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Capability of Sentinel-2 data for estimating maximum evapotranspiration and irrigation requirements for tomato crop in Central Italy

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ABSTRACT

The occurrence of water shortages ascribed to projected climate change, especially in the Mediterranean region, fosters the interest in remote sensing (RS) applications to optimize water use in agriculture. Remote sensing evapotranspiration and water demand estimation over large cultivated areas were used to manage irrigation to minimize losses during the crop growing cycle. The research aimed to explore the potential of the MultiSpectral Instrument (MSI) sensor on board Sentinel-2A to estimate crop parameters, mainly surface albedo (α) and Leaf Area Index (LAI) that influence the dynamics of potential evapotranspiration (ET_p) and Irrigation Water Requirements (IWR) of processing tomato crop (*Solanum lycopersicum* L.). Maximum tomato ET_p was calculated according to the FAO Penman-Monteith equation (FAO-56 PM) using appropriate values of canopy parameters derived by processing Sentinel-2A data in combination with daily weather information. For comparison, we used the actual crop evapotranspiration (ET_a) derived from the soil water balance (SWB) module in the Environmental Policy Integrated Climate (EPIC) model and calibrated with in-situ Root Zone Soil Moisture (RZSM). The experiment was set up in a privately-owned farm located in the Tarquinia irrigation district (Central Italy) during two growing seasons, within the framework of the EU Project FATIMA (FArming Tools for external nutrient Inputs and water Management). The results showed that canopy growth, maximum evapotranspiration (ET_p) and IWR were accurately inferred from satellite observations following seasonal rainfall and air temperature patterns. The net estimated IWR from satellite observations for the two-growing seasons was about 272 and 338 mm in 2016 and 2017, respectively. Such estimated requirement was lower compared with the actual amount supplied by the farmer with sprinkler and drip micro-irrigation system in both growing seasons resulting in 364 (276 mm drip micro-irrigation, and 88 mm sprinkler) and 662 (574 mm drip micro-irrigation, and 88 mm sprinkler) mm, respectively. Our findings indicated the suitability of Sentinel-2A to predict tomato water demand at field level, providing useful information for optimizing the irrigation over extended farmland.

1. Introduction

Evidence suggests that human-induced greenhouse gases emissions have altered our climate at a relatively rapid rate (Allen et al., 2009; IPCC, 2013), with the consequence that rising global temperatures and changes in precipitation pattern drastically exposed water-limited environments and agriculture, restricting crop yield, production and food availability (Avramova et al., 2016; McKersie, 2015; Moore and Lobell, 2014). Freshwater scarcity is widely acknowledged as a global systemic risk in terms of potential impact (Mekonnen and Hoekstra, 2016), especially in agricultural production, which uses about 70% of total freshwater withdrawals (WWAP, 2015). In particular, the impacts of climate change on European (EU) agriculture may increase productivity in northern latitudes, while in southern latitude projection indicated reduction in rainfall, and water availability, problems with salinization and increase in pest and disease outbreaks (Falloon and Betts, 2010; Kaley et al., 2017).

All above considered, there is an urgent need to seek out

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technological advancements and scalable solutions in the context of Precision Farming (PF) (Lal and Stewart, 2016; Liaghat and Balasundram, 2010; Moran et al., 1997; Mulla, 2013; Vuolo et al., 2015; Zarco-Tejada et al., 2014) to address management strategies on water inputs in response to seasonal drought.

This objective requires timely and reliable estimation of crop evapotranspiration (ET) and Irrigation Water Requirements (IWR) at field level with high spatial and temporal resolution. Soil water balance (SWB) models present limitations when applied to wide areas due to complexity of input data required, with special concern to soil hydraulic properties, interaction with groundwater, variability of plant development due to different crop varieties and management practices. Diversely, Earth Observation (EO) techniques provide reliable and suitable data to feed PF applications and serve several end-users (i.e. farmers, landowners and decision makers). High temporal and spatial resolution multi-spectral imagery can be used to manage irrigation scheduling based on near real-time actual crop needs (Calera et al., 2017). One advantage is the detection of the actual crop development which influences the entity of evapotranspiration fluxes and hence the irrigation requirements. Although extensive research has been carried out on ET crop estimation for water management using EO data, to date one of the major limitation for their applicability and technological transfer was the limited spatial and temporal resolution of the sensors (Bisquert et al., 2016). In this context, the recent advent of Sentinel-2 mission from European Space Agency (ESA), as part of the programme Copernicus (http://www.copernicus.eu/) (Drusch et al., 2012), has greatly enhanced the possibilities for a routine monitoring of crop parameters, such as LAI. The Multi Spectral Instrument (MSI) on board of Sentinel-2 captures data at 10, 20 and 60-meter spatial resolution over 13 spectral bands and with a very high temporal resolution of five days at the equator. Thanks to the rich information content the application of inversion techniques of radiative transfer models is now possible, providing robust physical basis for describing crop reflectance and estimating crop parameters such as LAI (Herrmann et al., 2011; Laurent et al., 2014; Richter et al., 2012; Verrelst et al., 2015). The combination of freely available satellite imagery, high resolution, novel spectral capabilities, a swath width of 290 km and frequent revisit times is stimulating the development of operational and commercial uses of EO data tailored for PF applications, as well as for scientific projects. The Sentinel-2 mission also provides data to be integrated in a tool for improving the quality of existing Web-GIS Satellite-based Irrigation Advisory Services - IAS (Calera et al., 2017; Richter et al., 2012; Vuolo et al., 2015; D'Urso et al., 2008) or other similar implementations foreseen in the near future (Pereira, 2017).

This study focuses on the determination of the Irrigation Water Requirements in tomato crops by means of Copernicus Sentinel-2A data. It uses Environmental Policy Integrated Climate (EPIC) crop growth model simulations for the comparison of the predicted crop evapotranspiration. The work was developed in the context of the FATIMA project (http://fatima-h2020.eu/), financed by the EU Commission under the HORIZON 2020 programme to develop and adopt innovative farming tools and service capacities that help the intensive farm sector to optimize its external input management (nutrients, energy and water) and productivity. The results of this research can be used for developing operational tools for monitoring water use trends of irrigated crop at commercial farm level in a Mediterranean environment in Central Italy.

2. Methodological approach to estimate potential evapotranspiration from Earth Observation

Over the past two decades, the improvements in the technical capabilities of spaceborne EO sensors allowed different approach for implementing potential evapotranspiration (ET_p) estimation from satellite imagery. Several reviews have attempted to evaluate ET_p EO-based methods and their performances, with special focus on irrigation management in agriculture, considering scales and temporal evolution during the growing season (Allen et al., 2011; Calera et al., 2017; D'Urso, 2010). To date, according to those reviews, two main groups of EO-based methods for ET estimation can be distinguished. The first group considers observations in the thermal range to estimate latent heat flux as a residual of surface energy balance, hence the actual evapotranspiration ET_a, accordingly to different schematizations (Allen et al., 2007; Bastiaanssen et al., 1998; Kalma et al., 2008; Kustas et al., 2016). Surface energy balance methods can detect crop water stress but suffer from the technical limitations of thermal observations from space in terms of spatial and temporal resolution. The second group contemplates visible (VIS) and near-infrared (NIR) wavelengths for characterizing the crop development in the application of the FAO-56 Penman–Monteith (FAO-56 PM) model (Allen et al., 1998); in this case, it is generally assumed that the crop is in "*standard conditions*", i.e. in a disease-free environment with adequate fertilization and sufficient soil water availability (irrigation applied). Often this value of evapotranspiration is referred to as "potential", which might introduce some confusion with the term "reference", for this reason, we prefer to use in this text the complete definition of FAO-56 PM, i.e. evapotranspiration in standard conditions ET_p, which means maximum value of crop evapotranspiration. Thus, we derive the maximum IWR for a crop at a given development stage. Under the hypothesis of a uniform soil cover, the Penman-Monteith approach derives surface resistances to heat and vapour transfer to the atmosphere by using vegetation parameters, namely Leaf Area Index (LAI – key parameter characterizing the structure and functioning of vegetation cover, that influence crop productivity), surface albedo (α-influences the net radiation of the surface, which is the primary source of the energy exchange for the evaporation process), and crop height (h_c - influences the aerodynamic resistance term of the FAO-56 Penman-Monteith equation and the turbulent transfer of vapour from the crop into the atmosphere) (Allen et al., 1998; D'Urso, 2001). Since for a crop in standard conditions, a minimum value of stomatal resistance can be considered for most herbaceous crops ($\approx 100\ s\ m^{-1}$), the surface resistance became a function of LAI only. This is also referred in the FAO-56 paper as the "one-step" or "direct" approach. During recent years, there has been a consistent effort to estimate vegetation parameters (α-LAI) from EO in the VIS and NIR regions (Atzberger and Richter, 2012; Vuolo et al., 2015), allowing to adapt the Penman–Monteith equation to be used directly with EO based LAI and α value (D'Urso, 2010), which can be measured in the field for providing an assessment of accuracy of the ET method, in addition to the below mentioned micro-meteorological techniques, and to derive the maximum IWR. The use of EO-based "one-step" FAO-56 PM method has become more popular recently for assessing ET_p under different hydro-climatic regions and crops such as wheat, cotton, corn, grapes and orchards (Farg et al., 2012; Glenn et al., 2011; Vanino et al., 2015). This approach has the advantage of being easily implemented, especially over homogeneous landscapes represented by irrigated farmland under unstressed conditions (Anderson et al., 2012).

Another category of EO methods for estimating ET_p is based on the traditional concept of the so-called crop coefficient (K_c), defined as the ratio of the unstressed crop evapotranspiration to the reference evapotranspiration (ET_0). K_c is specific to each crop and reflects the canopy development due to agronomic practices (including irrigation) over the course of the growing season. Hence, in this "two-steps" approach, ET_p is estimated as the product of the reference evapotranspiration (ET_0, depending only from atmospheric conditions) and the K_c. Several studies have demonstrated the linear relationship between K_c and different Vegetation Index (VIs), such as the Normalized Difference Vegetation Index (NDVI, Tucker et al., 1979) or the Soil Adjusted Vegetation Index (SAVI, Huete, 1988), derived from spectral observations in the VIS and NIR region (D'Urso and Calera, 2006; Neale et al., 1989). However, the determination of the empirical parameters of the relationship between K_c and VIs would requires measurements of ET over well irrigated crops, by using micro-meteorological methods such as lysimeters,