Agricultural Water Management 164 (2016) 304–316

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Calibration of the AquaCrop model for winter wheat using MODIS LAI images

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ARTICLE INFO

Article history:
Received 7 May 2015
Received in revised form
19 September 2015
Accepted 14 October 2015
Available online 2 November 2015

Keywords:
AquaCrop
Canopy cover
LAI
MODIS images
Model assessment

ABSTRACT

In semi-arid environments vegetation density and distribution is of considerable importance for the hydrological water balance. A number of hydrological models exploit Leaf Area Index (LAI) maps retrieved by remote sensing as a measure of the vegetation cover, in order to enhance the evaluation of evapotranspiration and interception losses.

On the other hand, actual evapotranspiration and vegetation development can be derived through crop growth models, such as AquaCrop, developed by FAO (Food and Agricultural Organization), which allows the simulation of the canopy development of the main field crops. We used MODIS LAI images to calibrate AquaCrop according to the canopy cover development of winter wheat. With this aim we exploited an empirical relationship between LAI and canopy cover. In detail Aquacrop was calibrated with MODIS LAI maps collected between 2008 and 2011, and validated with reference to MODIS LAI maps of 2013–2014 in Rocchetta Sant'Antonio and Sant'Agata, two test sites in the Carapelle watershed, Southern Italy. Results, in terms of evaluation of canopy cover, provided improvements. For example, for Rocchetta Sant'Antonio, the statistical indexes varyfrom $r = 0.40$, ER = 0.22, RMSE = 17.28 and KGE = 0.31 (using the model without calibration), to r = 0.86, ER = 0.08, RMSE = 6.01 and KGE 0.85 (after calibration).

1. Introduction

Hydrological processes within the Mediterranean area are highly variable both in space and time due to rainy regime, topography, soil conditions and land use (Moussa et al., 2007). In this context, hydrologic distributed models play a key role due to the increasing use of physical information provided by remote sensed data (e.g., Iacobellis et al., 2013). Particularly variables that quantify the development of vegetation cover are useful to estimate evapotranspiration and interception losses as well as in the assessment of soil erosion (van der Knijff et al., 2000; Kamaludin et al., 2013).

In this field, the use of crop growth models is crucial in order to optimize agricultural practices and, even more important, in order to model the vegetal cover variations at a yearly scale. Nevertheless their use at regional scale is limited by the need of intensive ground-based datasets that are necessary for calibration and testing. Among many growth models available in literature, that present a large number of variables not easily to compute (Raes et al., 2012), in this study we used the FAO AquaCrop model. With its reduced number of parameters AquaCrop is characterized by a better balance between simplicity, accuracy and robustness, than other crop models (Steduto et al., 2008). AquaCrop has been extensively tested across different regions in the world and different crops (e.g., Ahmadi et al., 2015). Nevertheless, without specific calibration of main parameters it still shows large uncertainties in the evaluation of important outputs such as actual evapotranspiration, soil moisture and crop yield. In this work we try to enhance the use of AquaCrop at regional scale exploiting the availability of a well established remote sensing product such as the MODIS-LAI images.

Remote or proximal sensing techniques that use spectral approaches can provide a rapid identification of water stress through many vegetation indices (Rinaldi et al., 2015). Particularly, Leaf Area Index (LAI) and canopy cover (CC) assume considerable relevance in the definition of crop development models and ecological processes analysis (Griffin et.al., 2008).

LAI is a dimensionless variable defined as the ratio between the total leaf surface and the leaf surface projected on the ground (Ross, 1981). This dynamic index is related to photosynthesis, transpiration surface of forest cover (Jonckheere et al., 2004), rainfall interception and energy exchange between vegetation and the atmosphere (Leuschner et al., 2006). Accordingly, LAI was also implemented in hydrological modelling, e.g., DREAM model

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http://dx.doi.org/10.1016/j.agwat.2015.10.013
0378-3774/

(Manfreda et al., 2005). Remote sensing provides the only reliable option for mapping LAI continuously over the globe (Tarantino et al., 2015a,b). LAI retrieval from passive remotely sensed data has been evaluated through semi empirical-statistical approach or with radiative transfer model (RTM) inversion of leaf canopy reflected energy (Zheng and Moskal, 2009). In the first mentioned approach LAI is estimated through vegetation indices (e.g., Clevers, 1989; Rouse et al., 1974; Stenberg et al., 2004) while the second one require an inversion of physical based models (e.g., Darvishzadeh et al., 2008; Fei et al., 2012; Houborg et al., 2015).

In this study LAI maps derived from the Moderate Resolution Imaging Spectroradiometer (MODIS), particularly the MCD15A2 level-4 product were used. The MODIS instrument was designed and developed following the science community objective to collect high temporal resolution global data useful for short/long term environmental studies (Xiong and Barnes, 2006). Modis is part of the payload of the National Aeronautics and Space Administration (NASA) Terra and Aqua satellites respectively known also as Earth Observation System (EOS) AM-1 and EOS PM-1. The MCD15A2 level-4 product is available at 1 km spatial resolution and at time-steps of 8–16 days. The algorithm implements a land cover classification where six biome types (respectively grasslands and cereals, shrubs, arable broadleaf, wooded meadows, broadleaf forest and coniferous woodland) are distinguished (Altobelli et al., 2007). Each biome represents a pattern of the architecture of an individual tree and the entire canopy as well as patterns of spectral reflectance and transmittance of vegetation elements (Knyazikhin et al., 1998; Weiss et al., 2000).

CC is defined as the ground fraction covered by the vertical projection of the trees (Nilson and Kuusk, 2004), and is commonly expressed in percentage terms (canopy cover percentage, or its inverse, canopy openness percentage). CC is a parameter useful in forest ecology and is used to study the potential risk of fire, watershed, erosion and illegal logging (Chopping et al., 2008; Ozdemir, 2014). Both the United Nation of Food and Agriculture (FAO) and the National Land Cover Database (NLCD) used CC to identify tree covered areas (FAO, 2010; Homer et al., 2007).

LAI and CC are estimated also by growth models. Particularly interesting is the integration of remote sensing data into crop growth models with the aim of improving the accuracy of model simulation (Dente et al., 2008; Huang et al., 2015; Jongschaap, 2006; Mo et al., 2005). Maas (1993) compared the results of calibrating a crop simulation model on winter wheat using LAI observation from field and remote sensing. Moulin et al. (1998) in a review paper described the relations between crop state variables and satellite observations. Weiss et al. (2001) described the process of coupling the STICS model (Brisson et al., 1998) with the SAIL RTM (Verhoef, 1984) and then performed a sensitivity analysis to select crop model parameters that mostly influenced the radiometric signal. Bach et al. (2001) combined the PROMET-V (Schneider and Mauser, 2001) and the SAIL with good results in the estimation of LAI, canopy ehight and dry biomass. Doraiswamy et al., (2004) investigasted the usefulness of MODIS data both to assess crop condition and in crop simulation model. LAI maps derived both from active and passive sensor were assimilated in Dente et al. (2008) in order to improve the wheat yield prediction accuracy using the CERES–Wheat model. Fang et al., 2008 developed a procedure to predict regional crop yield estimation from MODIS data. Xu et al., 2011 implemeted the phenology information derived from the MODIS LAI product in the SWAP model (Van Dam et al., 1997) for winter wheat estimation at regional scale. The MODIS LAI product was also used by Fang et al., 2011 to estimate the corn yeld with the CSM–CERES–Maize model model coupled with the MCRM model (Kuusk, 1998). Huang et al., 2015 implemented whithin the WOFOST model LAI derived from MODIS and LANDSAT^{TM} data to predict winter wheat yield at regional scale.

Table 1
Main characteristics of the Carapelle watershed.

Watershed area	982.6 km^2
Maximum altitude	1075 m a.s.l
Average altitude	540 m a.s.l.
Mean watershed slope	4.4%
Mean annual rainfall (Rocchetta Sant'Antonio)	1.94 mm
Mean annual rainfall (Sant'Agata di Puglia)	2.00 mm
Mean annual temperature (Rocchetta Sant'Antonio)	13.67 °C
Mean annual temperature (Sant'Agata di Puglia)	13.84 °C

The aim of this paper is to assess the AquaCrop model performances by exploiting the LAI–CC variability of winter durum wheat, which is the predominant type of vegetation in a study area within the Carapelle's catchment, in Southern Italy, using the MODIS images for model calibration and validation. For this purpose, the LAI–CC empirical relationship found by Nielsen et al. (2012) was used.

Calibration and validation were carried out separately using MODIS low-resolution images: the calibration was developed in 2009–2010 in Rocchetta and between 2008 and 2010 in Sant'Agata, while the validation was carried out in 2013–2014 for both sites.

2. Materials and methods

2.1. Study area

The test sites are close to the towns of Rocchetta Sant'Antonio and Sant'Agata di Puglia respectively, both in the Carapelle riverbasin. Furthermore the Lacedonia weather station, located close to the previous ones, was considered in case of missing data. The main stream of Carapelle originates in the Campanian Apennine, from La Forma Mountain, and flows into the Adriatic Sea. The catchment has a watershed area of 982.6 km^2 (Table 1, Figs. 1 and 2).

The river regime is torrential, with streamflow generally high in November and December, dry in July and August. The climate is typically Mediterranean with moderately rainy winters, warm and dry summers. The rainfall range is from 477 to 815 mm/year and the average temperatures range from 10 to 16 °C/year. The main cultivations are durum wheat (85% of total basin area), different types of vegetables and olives groves, localized in low hilly and plain areas, while forests and pasture are present in the higher slopes (Milella et al., 2012). The size of the two study sites is approximately 1 km^2 (Fig. 2).

2.2. Model description

AquaCrop (http://www.fao.org/nr/water/aquacrop.html) is a software system developed by the Land and Water Division of FAO in order to increase water efficiency practices in agricultural production (Araya et al., 2010). AquaCrop uses the first Doorenbos and Kassam (1979) equation for the biomass calculation and, finally, the crop yield, proportional to the biomass according to a "harvestable part". The software simulates Biomass (B) and Yields (Y) production of agricultural crops, focusing on water stress conditions (Steduto et al., 2009). The model is based on the water resource used in transpiration, which results in biomass using a crop-specific conservative parameter (Geerts et al., 2009).

The stress coefficients play a key role in the model. They describe the different stress conditions, detected in the crop biomass production (wheat, vegetables). These coefficients "continuously adjust" the computed quantities in each calculation step. They vary between 1 (no stress) and 0 (max stress) (Fig. 3).

The stress coefficients account for soil water, air temperature, soil fertility and salinity. They affect the canopy expansion pro-