Agricultural Water Management 165 (2016) 141–152

Contents lists available at ScienceDirect

Agricultural Water Management

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

Combining a water balance model with evapotranspiration measurements to estimate total available soil water in irrigated and rainfed vineyards

Isidro Campos[a,*], Claudio Balbontín[b], Jose González-Piqueras[c], Maria P. González-Dugo[d], Christopher M.U. Neale[a], Alfonso Calera[c]

[a] Robert B. Daugherty Water for Food Institute, University of Nebraska, Nebraska Innovation Campus, 2021 Transformation Dr. Ste 3220, Lincoln, NE 68583, USA
[b] Instituto de Investigaciones Agropecuarias, INIA Intihuasi, Colina San Joaquín s/n, La Serena, Coquimbo, Chile
[c] Grupo de Teledetección y SIG, Instituto de Desarrollo Regional, Universidad de Castilla-La Mancha, Campus Universitario, Albacete 02071, Spain
[d] IFAPA—Consejería Agricultura y Pesca de Andalucía, Avda, Menéndez Pidal s/n, Córdoba, Spain

ARTICLE INFO

Article history:
Received 28 March 2015
Received in revised form 7 November 2015
Accepted 28 November 2015
Available online 7 December 2015

Keywords:
NDVI
Water stress
Crop coefficient
Wine-grapes
Total available water
Optimization procedure

ABSTRACT

This research presents an algorithm developed for calibrating the soil water balance model (SWB) in terms of total available water in the soil root zone (TAW) assimilating actual evapotranspiration (ET) data. After calibration, the TAW value is used to estimate the actual ET and water stress processes at canopy scales. This methodology also allows for the estimation of the minimum TAW value that explains the ET rate in the absence of water stress. The model was applied in three vineyards grown under rain-fed, full irrigation and deficit irrigation conditions in La Mancha (southeast Spain) and the Alentejo (southern Portugal). The values of TAW obtained for the analyzed vineyards illustrate the variability of this parameter. TAW values varied from 180 to 390 mm depending on the water availability for growing conditions. The use of these TAW values allowed for a precise estimation of the ET values, water content and water stress process for the validation campaigns. The RMSE values obtained when comparing measured and modelled ET were lower than 0.65 mm/day for each analyzed seasonal campaign. The application of this methodology in operational scenarios will allow for the estimation of TAW for each site in order to optimize the irrigation applied, even in deficit irrigation schemes.

1. Introduction

Soil water balance models (SWB) are theoretical representations of a limited portion of the water cycle, mainly concentrated in the soil–plant–atmosphere interface. These models require a wide number of simplifying assumptions that are needed to represent the extremely large degree of nonlinearity and space-time variability of the water dynamics in the soil (Porporato et al., 2004). Despite these simplifications, SWB models are useful tools for hydrological and agro-ecological analyses. For agricultural water management, SWB models have major use in irrigation scheduling, since they are the most widespread procedure determining the timing and amount of crop irrigation requirements. Also, under rain fed schemes, SWB models are a powerful tool to predict the crop response under different climatic and management scenarios.

One of the core variables, essential for the computation of the water balance, is surface evapotranspiration (ET). An accepted operational methodology for ET estimation is the "Two step" methodology described in the FAO-56 manual (Allen et al., 1998). This methodology consists of estimating crop ET as the product of two parameters. The first parameter is the crop coefficient (K_c), related to the crop characteristics, and the second parameter is the reference crop evapotranspiration, ETo, related with the evaporative power of the atmosphere on the measurement day and location. The methodology can include the dual crop coefficient approach as proposed by Wright (1982), distinguishing between plant transpiration and soil evaporation. This approach has been improved by including a reflectance-based basal crop coefficient (K_{cbrf}) obtained from vegetation indices (VI) derived from remotely sensed surface reflectance. K_{cbf} assessments using VI have been widely evaluated and applied to herbaceous and woody

* Corresponding author.
E-mail address: isidro.campos@unl.edu (I. Campos).

http://dx.doi.org/10.1016/j.agwat.2015.11.018
0378-3774/

crops (Bausch and Neale, 1987; Campos et al., 2010c; Choudhury et al., 1994; Duchemin et al., 2006; Er-Raki et al., 2007; González-Dugo et al., 2013; González-Piqueras, 2006; Hunsaker et al., 2003; Jayanthi et al., 2007; Mateos et al., 2013; Neale et al., 1989). K_{cbrf} estimates track the actual crop growth in the field and can be assimilated into SWB models. These models iteratively correct the K_c estimates by accounting for the water deficit in the root zone and top soil evaporation. The combination of K_{cbrf} and SWB comprises the Remote Sensing-based soil Water Balance (RSWB) (Campos et al., 2010c; Gonzalez-Dugo et al., 2009; Padilla et al., 2011; Sánchez et al., 2012).

The RSWB model can provide a continuous and predictive estimation (Geli, 2012) of water balance components and thus irrigation assessment in irrigated agriculture (Neale et al., 2012). However, for precise estimation of the key component for each application, such as ET and irrigation water requirements, the RSWB requires a precise estimation of the root zone water-holding capacity. Water-holding capacity is represented by the parameter Total Available Water parameter (TAW) in the FAO-56 SWB formulation (Allen et al., 1998). TAW depends on effective root depth and the difference between soil water content at field capacity and wilting point. The importance of this parameter for determining ET or irrigation water requirements will depend on the relative use of the water stored in the soil by the plants. For irrigated vineyards and other perennial crops growing under Mediterranean climatic conditions, the water extraction from the root zone represents up to the 60% of seasonal ET. In contrast applied irrigation represents less than the 30% of ET (Campos et al., 2010c). The impact of the mismatch in the forcing variables and primary inputs in the simulation of water demand in irrigated vineyards has, in general, not been analyzed. However, in the area overlying the Mancha Oriental aquifer (Southeastern Spain), Campos (2012) analyzed the variability in irrigation requirements depending on the value of TAW assimilated in the model for more than 25,000 ha of irrigated vineyards. This study founds that for a range of TAW between 225 mm (root depth of about 1.5 m) and 300 mm (root depth of about 2.0 m), the irrigation requirements could vary between 110 and 160 mm/year. Thus, the proper determination of the TAW parameter is important for accurately estimating ET, irrigation water requirements and other SWB components. The knowledge of TAW is needed for estimating the water reservoir at the beginning of the growing season when establishing the soil water balance. This knowledge allows for managing seasonal irrigation taking into account the available water and actual water requirements. In addition, the proper knowledge of TAW contribute for the estimation of the soil water stress, and this knowledge is essential for planning deficit irrigation management in crops such as wine grapes.

Determining TAW at field scales is difficult because of the variability of soil hydraulic properties, soil limitations to root access and thus the soil volume that is explored by the roots. Another source of uncertainty is the efficiency of the root system to extract water at different depths. The FAO-56 manual (Allen et al., 1998) proposes root zone depths between 1.0 and 2.0 m for irrigated vineyards, which is a large range for the adequate estimation of water requirements. Direct observations of deep roots in vineyards have reported depths upto 6 m (Branas and Vergnes, 1957; Doll, 1954). But certainly the capacity of plants to extract water at these depths can be influenced by the density and functionality of the root system. So the determination of the functional rooting depth in an ecosystem is an important and difficult issue (Jackson et al., 1999). For mature vines, Kozma (1967) reported a uniform three-dimensional distribution of the roots at depths of up to 2 m. Conversely, Smart et al. (2006) concluded that, on average, the distribution of roots of different varieties of vine rootstocks is concentrated in the first 60 cm of soil, with 63% of the total root biomass. Araujo et al. (1995) demonstrated experimentally that the volume of soil explored by vines is influenced by the availability of water, increasing for low application depths and irrigation frequencies. Subsequent studies have reported extraction of soil water at depths greater than 2 m in vineyards (Campos et al., 2010b; Pellegrino et al., 2004). The reported variability in root depths and root distribution make it difficult to establish the actual value of vineyard root depth for a particular plot. Direct observations of soil water extraction through soil water content measurements strictly represent a point measurement, and extrapolation to larger areas or even to plot scales is questionable. Thus the determination of a field representative TAW parameter is needed for estimating ET, irrigation requirements and other SWB components at large scales.

The adequate knowledge of root depth and distribution of cultivated species and varieties, in addition to studies of soil depth in agricultural areas could help to provide adequate values of TAW. However, interesting alternative estimation methodologies can be based on the measurement or estimation of the actual ET of crop canopies. ET is the ultimate result of the interaction between the biotic and abiotic factors operating in crops and other vegetated ecosystems. The effects of atmospheric demand, the canopy density and conductance, soil water availability for the plants and the soil hydraulic properties on ET are generally recognized. Thus, ET values and the temporal evolution of ET provide valuable information about these driving and influencing factors. Some recent research take advance of the possibility to combine estimates of actual ET based on remote sensing energy balance models (RSEB) and SWB models. These approaches are generally named hybrid models. Anderson et al. (2007) and Crow et al. (2008) use the thermal remote sensing data to provide valuable diagnostic information about the sub-surface moisture status. This model obviates the need for precipitation input data and prognostic modeling of the SWB. A similar approach was formulated by Neale et al. (2012). These authors proposed the assimilation of the estimated ET using a remote sensing-based two source energy balance model to correct ET provided by an RSWB model. The corrected ET values are used to update the estimated soil water depletion, and the stress coefficient is recalculated. Along these lines, we propose the inversion of the RSWB formulation by assimilating ground ET measurements for the estimation of TAW. The novelty of this methodology with respect to the hybrid models is that it does need assumptions about the value of TAW. This parameter has a major effect in the application of water budget simulations, also for hybrid models, and as presented before, is rarely known in cultivated vineyards.

The primary objective of this work is to present the theoretical analysis for the inversion of RSWB formulation to estimate TAW, based on the assimilation of ET values into the RSWB formulation. In addition, we present the application of the methodology in three wine grape vineyards monitored during different years in the wine producing areas of La Mancha (Southeast of Spain) and the Alentejo (Southern Portugal). The fields were managed under different conditions of irrigation, crop management and water stress. The results of the methodology are validated by assimilating the value of TAW obtained in each field into the SWB model using independent validation datasets of ET and water depletion.

2. Methodology

2.1. The FAO-56 water balance model driven by remote sensing data

The water balance model used is a one-layer soil water balance (performed in the plant root zone) with additions to simulate soil evaporation from the surface layer. The methodology is extensively described in the FAO-56 manual (Allen et al., 1998). The assimilation of reflectance-based VI in the SWB model is based on the