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Estimation of total available water in the soil layer by integrating actual evapotranspiration data in a remote sensing-driven soil water balance

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SUMMARY

The total available water (τ) by plants that could be stored in its root soil layer is a key parameter when applying soil water balance models. Since the transpiration rate of a vegetation stand could be the best proxy about the soil water content into the root soil layer, we propose a methodology for estimating τ by using as basic inputs the evapotranspiration rate of the stand and time series of multispectral imagery. This methodology is based on the inverted formulation of the soil water balance model. The inversion of the model was addressed by using an iterative approach, which optimizes the τ parameter to minimize the difference between measured and modeled ET.

This methodology was tested for a Mediterranean holm oak savanna (dehesa) for which eddy covariance measurements of actual ET were available. The optimization procedure was performed by using a continuous dataset (in 2004) of daily ET measurements and 16 sets of 8 daily ET measurements, resulting in τ values of 325 and 305 mm, respectively. The use of these τ values in the RSWB model for the validation period (2005–2008) allowed us to estimate dehesa ET with a RMSE = 0.48 mm/day. The model satisfactorily reproduces the water stress process.

The sensitivity of τ estimates was evaluated regarding two of the more uncertain parameters in the RSWB model. These parameters are the average fraction of τ that can be depleted from the root zone without producing moisture stress (p_τ) and the soil evaporation component. The results of this analysis indicated relatively little influence from the evaporation component and the need for adequate knowledge about p_τ for estimating τ.

1. Introduction

Soil water balance (SWB) has been used traditionally as a basic approach to estimate evapotranspiration (ET) by measuring and balancing the other water budget components. The SWB approach produces robust estimates of average multiyear ET on a regional or global scale (Wang and Dickinson, 2012). SWB is a fundamental model in hydrology (ASCE, 1996) and a physical description of the soil–plant–atmosphere continuum must be based on an understanding of this balance (Hillel et al., 1998). In fact, the soil water balance is at the heart of many hydrologic problems and is of paramount importance in a wide range of issues, such as climate change and desertification and management of water resources (Laio et al., 2001).

In spite of its conceptual relevance, the practical application of the SWB method to estimate ET on finer spatial and temporal scales is subject to important uncertainties. In addition to other water balance components such as precipitation and run-off, the accurate determination of the total available water (τ) by plants limits the accuracy of the SWB estimates (Katerji et al., 2011). τ is defined as the amount of water held in the root soil layer between field capacity and permanent wilting point. Differences in soil properties (texture and structure) affect the water content at field capacity and permanent wilting points because both variables define the water content of the soil at certain matric potentials (Givi et al., 2004) related to the ability of the plants to extract water. The adequate knowledge of these parameters is only possible in very controlled situations, such as pots and lysimeters, in which the amount of water abstraction can be monitored and the soil hydraulic properties are known. Rooting depth and the hydraulic properties which describe the root soil layer are highly variable across space and, for some growing canopies, also over

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time. Moreover, in the case of natural vegetation, spatial variability could be increasing as a consequence of the soil structure (rock, stones, cracks in the soil, etc.) so that field measurements, apart from being cumbersome, may not adequately represent this variability.

The effect of the mismatches in the value of τ is more evident for the ecosystems where the relative importance of water incomes and water demand changes as the case of arid and semiarid environments. Joffre and Rambal (1993) demonstrated that Mediterranean open savannas progress from conditions of water scarcity to water deep percolation in the transition between the dry summer to the rainy fall. As demonstrated by these authors, only a portion of the excess of water is stored in the soil volume explored by the plants and it is latterly used in deficit periods. The rest of the excess of water is percolated to deep layers. The determination of the water percolation requires the precise knowledge of the maximum water content in the soil volume explored by the roots; so that the water percolating out of this layer is considered out of the plants reach. In the other hand, the determination of the water stress conditions is crucial in Mediterranean savanna. Water stress usually limits the ecosystem ET during the dry period, and reductions in ET up to a 20% of potential rate have been reported (Campos et al., 2013). Also the determination of the actual ET and water stress strongly relies on the knowledge of τ.

The actual value of soil moisture influences both the evaporation from bare soil and the transpiration from vegetation. Soil moisture in the surface soil layer mainly determines evaporation and soil moisture in the root soil layer mainly determines transpiration. When soil moisture is high, the transpiration rate depends mainly on vegetation characteristics and climatic conditions. As long as soil moisture content is sufficient to permit the normal course of the plant physiological processes, ET is independent of soil moisture and is assumed to occur at a maximum rate (Laio et al., 2001). When soil moisture content falls below a given point, the plants start reducing transpiration to prevent internal water losses. Below that point water availability becomes a key factor in determining the actual ET which continues at a reduced rate until soil moisture reaches the wilting point. These points depend on the vegetation type and the soil characteristics and are generally determined in terms of soil matric potential of volumetric water content (Laio et al., 2001; Larcher, 1995). The influence of soil moisture on plant transpiration is implicitly included in the Penman–Monteith equation through canopy resistance, r_c, which reveals plant stomatal aperture. For water-stress conditions, r_c is very sensitive to soil moisture, although the value of r_c is also sensitive to vapor pressure deficit for some canopies. Since the 1970s, a practical application of the Penman–Monteith equation has been developed through the so-called "two-step" procedure (Allen et al., 1998; Doorenbos and Pruitt, 1977; Jensen et al., 1970). In this procedure, the influence of soil moisture on plant transpiration is considered by multiplying the plant transpiration rate by the water stress coefficient (K_s). K_s is a dimensionless coefficient depending on the actual water content and maximum water content in the root zone, this is τ. Although this relation could be represented with different notations (Allen et al., 1998; Anderson et al., 2007; Chen et al., 1996; Jensen et al., 1970).

On these conditions, the use of SWB for estimation of surface ET in arid and semiarid areas is seriously constrained by the limited knowledge of τ. But this dependence opens the possibility of an inversion procedure for the determination of τ when actual ET is known or can be estimated. The innovation proposed in this paper is to calibrate the SWB model in terms of τ by using time series of ET measurements as input into the inversion procedure of the water balance formulation. So we could estimate τ without previous knowledge of rooting depth and hydraulic soil properties, solving the difficulty of their determination for natural environments. After the calibration the model is able to predict surface ET, water stress and other SWB components which are important parameters and widely used in many applications.

The inversion of the SWB and K_s formulation has been used in previous papers. This approaches integrates into the soil water balance models either water stress estimates based on canopy temperature (Colaizzi et al., 2003) or ET estimates based on thermal remote sensing signals (Anderson et al., 2007; Crow et al., 2008; Geli, 2012; Neale et al., 2012; Schuurmans et al., 2003). The objective of these previous papers was the estimation of soil moisture or other water balance components. Meanwhile, the value of τ is derived from external sources, such as estimates of water abstraction at different depths from soil moisture measurements, or soil depth maps and a priori knowledge of rooting depth. Regarding to our knowledge and after an in deep analysis of the existing literature, we can say that this is the first time that the methodology is inverted to calibrate the model in terms of τ. The physical basis of the proposed methodology relies in the assumption that the transpiration rate of a vegetation stand is the best proxy of the water content into its root soil layer. The ET over time for a vegetation stand captures the complex relationships between the plants and their environment. As Larcher (1995) pointed out, only the plants itself can show reliably where and when lack of water becomes a stress and this is best revealed by indicators of the state plant́s water balance. We hypothesize that when all SWB components are known and soil water depletion can be estimated, the water stress formulation can be inverted to estimate τ. This approach enables us to first calibrate the soil water balance model and then calculate SWB components, including the key parameters, ET and plant water stress, with the adequate precision.

In this paper we discuss the conditions and constraints of the proposed procedure, which combines a SWB with measurements of actual ET. The methodology was evaluated by using field data obtained from field eddy covariance measurements in a Mediterranean holm oak savanna, traditionally called dehesa, for five consecutive years (2004–2008). Dehesa is an ancient agro-silvopastoral ecosystem traditionally developed on poor or non-agricultural lands and is dedicated to extensive livestock forage. It is widely extended in the Iberian Peninsula with more than $3.5 * 10^6$ ha (Olea and San Miguel-Ayanz, 2006). The Mediterranean climate imposes water shortage during the warm summer period and so vegetation could undergo water stress conditions. These periods of water stress are frequent and recurrent. The water stress determines some important process such as the pasture productivity (Fernández-Ales et al., 1993) and ecosystem disturbances such as damage and even plant mortality (Bréda et al., 2006; Peñuelas et al., 2001) or wild fires (Vidal et al., 1994). It is assumed than an increase of drought severity or frequency could limit the intrinsic productivity and both ecological and economical value of this ecosystem. Thus, the timely and accurate monitoring of vegetation water stress using remote sensing time series, as proposed in this work, may assist early-warning services, helping to assess drought impacts and the design of management actions leading to reduce the economic and environmental vulnerability of these systems.

2. Methodology

2.1. Soil water balance driven by remote sensing data

The model used in this paper is a one-layer water balance performed in the root zone, with additions to simulate surface soil layer evaporation. The methodology is extensively described in the FAO-56 manual (Allen et al., 1998). Therefore, we describe only the most relevant sub-models for the inversion procedure and the necessary integration of remote sensing data in the balance.