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Water productivity and crop yield: A simplified remote sensing driven operational approach

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ABSTRACT

This paper develops and proposes a simplified operational remote sensing approach to assist crop growth models in reproducing actual processes in the field by relating satellite based remote sensing data and key canopy biophysical parameters. While relationships between spectral vegetation indices (VI) and biomass production have been conducted in the past, we specifically pursue the relationship between crop transpiration and biomass production as described in the FAO-66 Aquacrop manual. The authors point to a possible general relationship between a transpiration coefficient (herein we propose the basal crop coefficient, K_{cb}, as a proxy) and biomass production. In parallel, many studies have demonstrated the well-established relationship between K_{cb} and remote sensing based VI. Thus, the relationship between both parameters has a strong basis but must be demonstrated. We analyze the relationship between biomass production and the reflectance based K_{cb} using field data obtained during 11 years in irrigated and rainfed soybeans and maize in eastern Nebraska. The analysis confirms that the relationship is strong and paves the way for the use of remote sensing data for a quantitative analysis of crop biomass production and yield.

1. Introduction

Crop growth models can be powerful tools for assessing the impacts of environmental conditions and genetic potential on crop production. At the scale of a management unit, modeling approaches also allow for the evaluation of agronomic management strategies in crop productivity (Villalobos et al., 1996). In addition, interesting conclusions can be obtained when comparing actual yield records with potential or attainable yield derived from these models at larger scales as proposed in the framework of yield gap analysis studies (Van Ittersum et al., 2013). The application of these models is only possible if the state-of-the-art allows for a precise estimation of site to site variations in potential yield, capturing the dynamic components of technology and environment (Sadras et al., 2014). But their use in real/operational scenarios is generally limited by data availability, i.e: crop initial conditions, planting date and application of inputs. Under this scenario, a possible alternative for assisting the models in reproducing the actual processes in the field is the use of algorithms relating remote sensing (RS) data and key canopy biophysical parameters in the crop growth models.

The up-to-date methodologies developed for yield forecasting based on RS are generally distinguished as regression and mechanistic crop growth models (Rembold et al., 2013). In addition, Sadras et al. (2014) proposed the differentiation of mechanistic approaches into assimilation and biomass production and partitioning models. Regression models are data-driven approaches developed on the basis of the strong relationships between biophysical parameters derived from RS and yield data (e.g., Shanahan et al. (2001), Cicek et al. (2010), Panda et al. (2010)). Assimilation models are based on the optimization of one or more crop characteristics or initial conditions to better fit the behavior of the biophysical parameters derived from RS data (e.g., Sibley et al. (2014), Bouman (1992), Clevers et al. (1994)). The biomass production and partitioning models use remote sensing methods for assessing crop evapotranspiration and/or light absorption. The accumulated values of these variables over the growing cycle are converted into biomass by using the factors Light Use Efficiency or Water Use Efficiency and to yield using the harvest index (the ratio between yield production and total biomass). Some examples of these approaches are described by Padilla et al. (2011) who estimated harvested yield for wheat and González-Dugo and Mateos (2008) who quantified water productivity

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for cotton and sugar beet.

Biomass and partitioning models could be improved by considering the most recent advances in this subject compiled in the FAO-66 manual by Steduto et al. (2012). The improvement described in FAO-66, already included in the AQUACROP model, is the consideration of the dependence of the water use efficiency on atmospheric conditions. In a complete analysis of the relationship between carbon assimilation and water transpiration at leaf and canopy scales, Steduto et al. (2007) established the need to normalize the water productivity for local climate, specifically for the evaporative demand of the atmosphere, in order to extrapolate water productivity values between climatic zones. This consideration is not entirely new and the necessity to normalize the water use efficiency for atmospheric demand and CO_2 concentration was described as early as Tanner and Sinclair (1983). The innovation of the AQUACROP model is the use of the reference evapotranspiration (ETo) against alternative normalization procedures such as the vapor pressure deficit approach as originally proposed by Tanner and Sinclair (1983). The normalization procedure based on vapor pressure deficits is difficulty applied because we need to know the vapor pressure deficit between the plant canopy and the air, determined through the temperature of each component. The difficulty comes in the estimation of vapor pressure deficit for plant canopy, where we need to know the plant canopy temperature which is mostly determined by the leaf temperatures in the canopy. Without doing a detailed canopy energy balance, leaf temperatures are difficult to predict. The proposed solution is the use of the Penman-Monteith equation for ETo estimation as presented in the FAO-56 manual (Allen et al., 1998). The difficulty in measuring or estimating canopy temperature was solved by Penman (Penman, 1947) who noted that the canopy temperature can be assessed with air temperature values and the approximate slope of saturated vapor pressure versus temperature relationship. This approach raises other issues like the need for a canopy conductance terms and the value of the VPD at the reference height. Nevertheless, the empirical evidences published by Steduto et al. (2007) and Steduto and Albrizio (2005) point to the relative advantage of this normalization procedure.

However, the operational application of this methodology is still limited by our capability of estimating the crop transpiration (T) or in an alternative approach, the ratio T/ETo. The ratio T/ETo approximates the definition of basal crop coefficient (K_{cb}) as proposed by Wright (1982) and further described by Allen et al. (1998). The estimation of K_{cb}, reflecting the heterogeneity of plant development in the field is feasible using vegetation indices (VI) based on canopy reflectance as demonstrated in multiple studies (i.e. Bausch and Neale, 1987; Campos et al., 2016; Duchemin et al., 2006; Er-Raki et al., 2007; Hunsaker et al., 2005; Jayanthi et al., 2007; Neale et al., 2012, 1989). The K_{cb}-VI relationships are generally established in terms of a K_{cb} value greater than 0 for bare soil conditions and K_{cb} max for VI max or the LAI threshold at effective full cover, the point in time when the actual ET reaches a maximum. The presence of a K_{cb} value greater than 0 for bare soil conditions has been recurrently analyzed in the literature and as early as Wright (1982) and Allen et al. (1998). Torres and Calera (2010) demonstrated empirically that this residual K_{cb} can be expected for bare soil conditions when the accumulated water use does not depend on plant activity but on bare soil evaporation. Taking this into account, a relationship with a minimum K_{cb} value equal to 0 for bare soil conditions and K_{cb} maximum for effective cover conditions is necessary to reproduce those processes exclusively related to plant transpiration, such as biomass production. These relationships were recently investigated by Campos et al. (2017) for maize and soybean.

These developments point to the possibility of estimating biomass production based on optical RS data in a robust and standardized methodology that can be applied in different climatic zones. However, little research has explored the possibility of an operational assessment of biomass production using optical RS data, based on plant transpiration as the driving variable. The primary objective of this paper is to use optical RS to estimate crop biomass production based on the normalization of water productivity. This paper analyzes the basis for this relationship and discusses possible constraints related to effects of abiotic stresses in the operational use. A second objective is the estimation of crop yield based on biomass production. For such, the harvest index of the maize and soybean crops used in objective one was analyzed.

2. Materials and methods

2.1. AQUACROP and FAO-66 approach to crop productivity in terms of biomass and yield

Eq. (1) predicts a linear relationship between biomass production on a ground area basis (in g m^{-2}) and the accumulated value of the ratio between adjusted transpiration (T_{adj}, in mm), considering the eventual presence of water stress, and ETo in mm. Notice the difference between the most common definition of water productivity to the innovative concept of normalized water use efficiency for biomass production (WUE_B*, in g m^{-2}). The WUE_B* approach considers the normalization of ET_{adj} by ETo which is conceptually equivalent to the basal crop coefficient accounting for water stress ($K_{cb,adj}$).

$$WUE_B^* = \frac{Biomass}{\sum_{i=1}^{n}\frac{T_{adj}}{ETo}} = \frac{Biomass}{\sum_{i=1}^{n}K_{cb,adj}} \tag{1}$$

The value of WUE_B* is slightly affected by plant nutrition and the effect of plant water stress reducing the crop transpiration and biomass production is already included in the term $K_{cb,adj}$. $K_{cb,adj}$ can be estimated through the product of the basal crop coefficient already defined (K_{cb}) and a water stress coefficient (K_{sw}). In addition, temperature (cold) stress in the production of biomass is represented by a temperature stress coefficient (K_{st}). The relationship between the factors affecting biomass production is presented in Eq. (2), where all the terms and units have been previously described.

$$Biomass = WUE_B^* \times \sum_{i=1}^{n} K_{cb} \times K_{ST} \times K_{SW} \tag{2}$$

At the leaf scale the relationship between biomass and water use only varies between C3 and C4 species because of the different concentration between that of the atmosphere and that in the leaf intercellular air space for both plant types (Steduto et al., 2007). So different values of WUE_B* must be expected for different plant types, as is the case for maize (C4) and soybean (C3). In addition, the upscaling from leaf assimilation to canopy biomass production requires additional assumptions. Plant tissue composition and the ratio of net assimilation over respiration may vary during the growing season thus affecting the efficiency of biomass accumulation (as discussed later in the results section). A controversial point, not considered in the FAO-66 methodology, is the reduction in biomass production resulting from the limitation in the photosynthetic radiation (PAR) absorbed by the canopy. The original formulation does not totally overlook this factor and its effect, because this adjustment could already be included in the correction for cold stress, considering the fact that both processes (low incoming radiation and cold temperature) are intrinsically linked in most environments. Thus, in our simplified approach we are not considering the effect of PAR limitation for biomass production, and this research focuses on the water use efficiency portion. Nevertheless, the possible effect of reduced PAR is analyzed in the discussion section. The FAO-66 methodology considers other abiotic stresses like soil salinity and fertility, but these stresses were neglected in this analysis considering the fertilization applied, availability of nutrients in the soil and that salinity is not the most imperative agronomical restriction in the area. The method to solve Eq. (2) is to calculate biomass as the summation of the product in each time step. According with the FAO-66 methodology the best time step to reproduce the factors affecting the biomass production is daily. Thus the VI used to estimate K_t must be interpolated from the time-discrete data derived from RS data. In