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Remote sensing-based crop biomass with water or light-driven crop growth models in wheat commercial fields

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ABSTRACT

This paper explores the ability of Remote Sensing data from space platforms combined with available meteorological parameters to monitor crop biomass accumulation at satellite scale in a direct, operational way, exploiting the temporal information from time series of multispectral images. We describe a methodology to estimate biomass growth by integrating VI-based biophysical parameter and meteorological input along the growing cycle into the physiologically-based crop growth models, employing water or light use efficiency.

Experimental biomass data of winter and spring wheat (*Triticum aestivum*) growing in commercial plots in Albacete, Spain and Ponca City, OK, USA, under different climates, environment and management, are compared against modeled data. The results exhibit good agreement between measured and modeled biomass data for the calibration and validation datasets. Slopes of the linear relationships provide empirical values of the efficiencies of the whole process of biomass production: light use efficiency (LUE), water use efficiency (WUE) and normalized water productivity (WP*). These values are comparable to the experimental values published in the literature.

1. Introduction

The estimation of biomass production has a prominent role in the strategies to increase crop productivity and improve management efficiency. Monitoring biomass production is a diagnostic tool for the evaluation of crop management because the accumulation of biomass responds to the coupled effects of climate (Fischer, 1993; Garcia et al., 1988; Raes et al., 2008) crop genomics (Calderini et al., 1997; Siddique et al., 1990), and nutrient/water management (Fischer, 1993; Green, 1987; Latiri-souki et al., 1998). The simulation of biomass production during the growing cycle has interesting application for the assessment of the fertilization necessities, essential in the strategies of nitrogen variable doses in coordination with the diagnosis tools for remote estimation of nitrogen concentration (Fitzgerald et al., 2006; Houlès et al., 2007). In addition, biomass accumulation is strongly related to yield production in grain crops although not in an unequivocal way (Aase and Siddoway, 1981; Padilla et al., 2012). The crop yield can be estimated as a variable proportion of total aboveground biomass that goes into the harvestable parts depending on biotic and abiotic stresses, the duration, the severity and the physiological stage of the crop during the stress period (Fischer and Maurer 1978). This proportion is known as harvest index (HI).

The classical approach to the simulation of biomass production is the use of a crop growth model (CGM) based on either light or water use efficiency. This approach relies on the quantitative knowledge of the parameters describing the canopy interaction with solar radiation and the exchange of water transpired by the canopy (Hoogenboom 2000). Simulation of leaf area development is the usual key parameter for the estimation of fraction of incident PAR that is absorbed by the canopy (fAPAR) for those CGMs based on Light Use Efficiency (LUE). This is essentially the background of STICS (Brisson et al., 1998), EPIC (Williams et al., 1990) and CERES (Jones and Kiniry, 1986) as the crop growth module in HybridMAIZE and DSSAT (Jones et al., 2003). The models based on the Water Use Efficiency (WUE) such as AquaCrop (Steduto et al., 2009) or a hybrid approach like CropSyst (Stockle et al., 1994) simulate canopy cover development for the estimation of a transpiration coefficient (K_t), or basal crop coefficient. The ongoing discussion of the WUE dependence on climate has led to the development of normalized WUE by using reference ETo, introducing normalized Water Productivity (WP*). The simulations of the key biophysical parameter in each model must be adapted for each crop, environmental conditions and management.

For an operation description of crop biophysical parameters, remote

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sensing (RS) measurements can provide temporal information on plant responses to dynamic weather conditions and management practices. Thus, RS approaches exhibit a large potential to provide biomass and final yield assessments in addition to variations across fields (Pinter et al., 2003). In the framework of yield/biomass estimates, the use of RS data has followed three main approaches (Sadras et al., 2015): integration/assimilation of RS derived variables into CGM, direct reflectance-based empirical relationships on selected dates, and biomass accumulation models. Empirical relationships have interesting applications for regional yield estimates (Lobell et al., 2003) and yield prediction (Sibley et al., 2014). However, these relationships must be locally calibrated, considering the uncertainties related with the selection of the most representative date for the assessment of biomass production and spatial variability.

The assimilation of RS data has been frequently proposed in the scientific literature in order to initialize, calibrate, or update CGMs (Clevers et al., 1994). On this line Bouman (1992) and Clevers et al. (1994) proposed the initialization (showing date) and re-parametrization (canopy expansion parameters) of the SUCROS model based on radar and canopy reflectance information in sugar beet. Sibley et al. (2014) assimilates RS-based fPAR estimates into the Hybrid-Maize model varying the sowing date, seeding density, and maturity rating of the hybrids (measured as thermal accumulation needed for the crop to reach physiological maturity). Trombetta et al. (2016) proposed the modification of the parameters describing the crop phenology and expansion into AQUACROP based on a relationship between ground cover and leaf area index (LAI) derived from RS data. Jin et al. (2017a,b) assimilated ground cover estimates based on optical and radar into the AQUACROP model. After assimilation, the model is calibrated in terms of canopy expansion and evaluated for the assessment of grain production at regional scale. The calibration of the initial conditions in assimilation methods can be limited by the availability on input data, since the number of parameters to be calibrated depend on the variables actually available. In a simpler approach, Padilla et al. (2012) assimilated RS-based LAI values into the GRAMI model, avoiding the calculation of the most complex processes such as water stress, nitrogen nutrition or plant population density. In the same line, the most recent versions of AQUACROP allows to incorporate canopy cover measurements for a better representation of the crop characteristics. These later assimilation/integration methods suppose a great simplification, but still rely on the aptitudes of the models to reproduce the key variables (PAR absorption or crop transpiration) from related biophysical parameters such as LAI or ground cover.

In this work, we specifically focus on the capability of temporal series of multispectral images combined with available meteorological data to provide, along the entire growing cycle, the key variables into the engine of the models based on LUE and WUE for the estimation of biomass accumulation. We are following the line proposed by Daughtry et al. (1992) working in corn and soybean with models based on LUE, but we are extending this approach to the models based on water use and providing new evidences in a different crop (wheat), monitored in field conditions, and at the scale of commercial farm. This direct approach provides a physically-based agronomic monitoring systems (Daughtry et al., 1992) but it has been hardly explored in the scientific literature. Special mention deserve the work done by Bastiaanssen and Ali, (2003), Zheng et al. (2016) and Zwart and Bastiaanssen, (2007) proposing the integration of RS-based fPAR for the assessment of yield at regional and global scales and some recent experiments (Campos et al., 2017b) demonstrating the feasibility of RS-based K_t for the assessment of biomass and yield in corn and soybeans. Nevertheless, the literature is scarce in comparative studies, analyzing the aptitudes of the models based on water and light use for a common database.

In contrast with previous research, we compared three different approaches for the assessment of biomass, from the most common LUE models to the WUE and WP* approaches. The novelty is the analysis of light use efficiency and water use efficiency approaches using a common base for the estimation of the key variables, fPAR and K_t, and the analysis of the precision of the models under different conditions. The thorough selection of experimental datasets allows us to evaluate and discuss, with empirical evidences, the feasibility of these approaches for wheat under different climatic, management and deficit conditions. The specific objectives are: i) the estimation of the parameters LUE, WUE and WP* for wheat based on the proposed approach; ii) the evaluation of the three models under field conditions and considering the possible effect of nitrogen deficit and climatic conditions. In addition, this paper provides a comprehensive explanation about the foundations of the use of RS data in CGMs and the benefits and constrains of this direct method. Considering that the proposed method represents a considerable simplification with respect to previous approaches, we analyzed and discussed with respect to previous research the model parametrization (LUE, WUE and WP* values) and the exactitude of the models to estimate biomass production.

2. Materials and methodology

2.1. Basis of growth models

Vegetation growth and biomass accumulation occur as consequence of CO2 assimilation and water transpiration flux through plant stomas during the photosynthesis process, in which the required energy is provided by solar radiation (Rosenberg et al., 1983). Attending to the physiological basis of the process, the classical approaches for growth simulation are based in the efficiency of the conversion of the water transpired or the light absorbed into biomass. These two classical models are known as water use efficiency and light (or radiation) use efficiency approaches and both approaches represent the core feature of the "growth-engine" of many crop models (Steduto and Albrizio, 2005).

2.1.1. Biomass production based on radiation/light use efficiency model

Radiation use efficiency was formulated by Monteith (1972) and it focuses on the relationship between the rate on the dry biomass gain (Biomass) and the absorbed solar radiation by the leaves in the wavelengths of the incident photosynthetically active solar radiation (PAR). Thus, the relationship is stablished in terms of the PAR absorbed by the leaves and used in the photosynthesis process (Eq. (1)).

$$Biomass = \int_{t_0}^{t} LUE \cdot APARd(t) \tag{1}$$

where Biomass is the dry biomass per unit of surface gain during the period between t_0 and t in g m^{-2}; LUE is the light use (photochemical) efficiency factor in g MJ^{-1}; APAR, is the PAR absorbed in MJ/m2, represents the photon flux absorbed by the canopy photosynthetic elements.

2.1.2. Biomass production based on water use efficiency models

The models based on the water use efficiency are probably the initial approaches to crop-growth, based on the quantitative statements settled by some pioneers like Briggs and Shantz (1913). These models estimate the rate of Biomass as the integral over the time of the product of crop transpiration multiplied by the term water use efficiency (WUE). Considering that the effect of water stress could reduce the crop transpiration, the relation is stablished in terms of adjusted crop transpiration accounting for water stress conditions ($T_{c,adj}$) as presented in Eq. (2).

$$Biomass = \int_{t_0}^{t} WUE \cdot T_{c,adj} d(t) \tag{2}$$

where $T_{c,adj}$, crop transpiration accounting for water stress conditions in mm; WUE, water use efficiency in g m^{-2} mm^{-1}, is the slope of the relationship between Biomass accumulation and $T_{c,adj}$.