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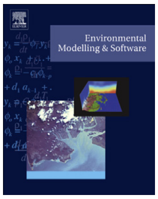

Modelling the impact of drought and heat stress on common bean with two different photosynthesis model approaches

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ABSTRACT

Extreme temperature and drought stress are major environmental factors limiting agriculture worldwide. A comprehensive understanding of plant behavior under different environmental conditions can be gained through experiments and through the application of biophysical crop models. This study presents a field experiment conducted with bean exposed to heat and drought stress. Based on an experimental data collection a crop model was set up, calibrated and validated. Hereby, the two different photosynthesis model approaches already implemented in the model, a simple empirical (the Goudriaan and van Laar or GvL model) and a biochemical photosynthesis model approach (the Farquhar-Ball-Collatz or FBC model), were tested. Both photosynthesis model approaches performed adequately under no stress conditions. Under heat stress conditions, yield was underestimated by both models. However, the FBC model performed better than the simpler photosynthesis model approach of the GvL model. The FBC crop model was able to predict the soil water dynamics, the plant growth and the stomatal conductance.

1. Introduction

Abiotic stress conditions such as extreme air or soil temperatures and drought cause extensive losses to agricultural production worldwide (Mittler, 2006). This is true not only for climatic regions with fluctuating temperature (i.e. arid areas with high midday temperatures and cold nights) but also for temperate climatic areas (i.e. regions where cold soil temperatures in spring hamper the emergence of seeds). Moreover, the effect of temperature on plants is a key factor considering the impact of climate change on agricultural production.

Individually, temperature and drought stress conditions have been the subject of intense research. Drought and heat stress have antagonistic effects on leaf stomata when occurring separately. In general, stomata close rapidly under drought conditions and open under warm and moist conditions. However, in the field, crops are routinely subjected to a combination of different abiotic stresses (Hasanuzzaman et al., 2013). The response of plants to a combination of two different abiotic stresses cannot be directly extrapolated from the response of plants to each of the different stresses applied individually (Mittler, 2006). Physiological characterization of plants subjected to either drought, heat stress or a combination of drought and heat stress revealed that the stress combination has several unique aspects, combining high respiration with low photosynthesis, closed stomata and high leaf temperature (Mittler, 2006). According to Porch et al. (2009), high temperature stress can interact with and increase the effects of drought stress.

In common bean (*Phaseolus vulgaris* L.), a very important food legume adapted to moderate climates, drought and heat stress result in significant yield reductions (Porch et al., 2009; Reynolds-Henne et al., 2010). Beans, characterized by a rather limited and shallow root system, are particularly susceptible to drought stress during flowering (Graham and Ranalli, 1997). Gross and Kigel (1994) studied the effects of high temperature on different stages of reproductive development in common bean. The authors found that elevated temperatures during flower development markedly reduced fruit set. The lowest pod set was observed when flower buds were exposed to heat one to six days prior to anthesis, and sensitivity to heat tended to increase as anthesis approached. Graham and Ranalli (1997) found that the bean reproductive

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development is very sensitive to temperature. Under moderate stress conditions, legumes close their stomata or respond with irregular conductance, whereas under high temperature stress conditions, they further open their stomata even under drought conditions (Reynolds-Henne et al., 2010). Bean yield is also influenced by the duration of the vegetative and reproductive stages (Rosales-Serna et al., 2004) and the redistribution of assimilates into economically important organs, factors that are both highly dependent on temperature. Due to its high drought susceptibility, 70% of the study area (Saxony, Germany) cultivated with common bean was irrigated in 2011 (Jäkel, 2013). According to the Land Statistical Office, the average fresh matter yield of common bean in Saxony was 11.5 t ha^{-1} in 2014.

Crop growth modelling is a widely accepted tool for process understanding but also for supporting an efficient and sustainable crop production. Accurate model predictions under drought stress, temperature stress or both stresses combined are especially important for climate change scenario analyses when the effect of changing environmental conditions on yield is analysed. Temperature plays a major role in modelling the crop development and leaf photosynthesis. Many crop models simulate plant development based on temperature and photoperiod. Most crop models consider the air temperature via the prediction of the leaf photosynthesis which is closely associated with above-ground dry matter production. Many models lump transpiration and carbon assimilation into a single process based on the observation that the relative transpiration ratio is proportional to relative biomass at the end of the growing season (Timlin et al., 2008). The daily above-ground dry matter production is often estimated as a function of estimated light interception, light intensity, and a radiation-use efficiency coefficient (Prasad et al., 2008).

The plant response to environmental stress is regularly modelled using empirical relationships based on the observed behavior (Timlin et al., 2008). Hereby, drought stress is often simulated by multiplying the potential new daily dry matter by a stress multiplier that mostly ranges between 0 and 1. The relationships used to quantify the stress are typically a ratio of the amount of the plant water demand and the amount of water available in the soil for root uptake (Prasad et al., 2008). Thus to accurately simulate timing and severity of drought stress, precise predictions of the soil water and the plant water demand are necessary. According to Prasad et al. (2008), species and growth-stage-specific temperature stress multipliers are often even more empirically based on observed plant responses to temperatures than drought stress multipliers. Temperature stress multipliers often have a region where no stress is predicted (multiplier of 1) with temperature extremes that limit this region. When both stresses are combined, many models simulate these stresses separately and apply the minimum of the two to quantify the effects of growth and developmental processes. Sometimes, adaptive or multiplicative approaches to combine stress factors are applied (Dudley and Shani, 2003).

Moreover, biochemical models can be used to estimate leaf photosynthesis. A number of mechanistic models of photosynthesis and stomatal conductance at the leaf level that are derived from the photosynthesis model of Farquhar et al. (1980) and the empirical stomatal conductance model of Ball et al. (1987) have been developed and are widely used. Collatz et al. (1991) has implemented these two models and combined them with leaf energy balances. Probably the most important recent advance in modelling photosynthesis and transpiration is related to the availability of the mechanistically based biochemical photosynthesis model Farquhar et al. (1980) and Timlin et al. (2008). Timlin et al. (2008) suggest that the implementation of such mechanistically based biochemical approaches can improve crop model predictions of transpiration and photosynthesis under drought stress. The Farquhar photosynthesis model has been implemented in some agricultural and forestry field-scale models (Engel and Priesack, 1993; Jansson, 2012; Yin and van Laar, 2005; Plauborg et al., 2010).

Field-scale application studies using mechanistic models of photosynthesis and stomatal conductance are rare. Ahmadi et al. (2009) and Plauborg et al. (2010) compared the experimental data of a partial root-zone drying (PRD) irrigation experiment to simulated results using the Daisy model which included modelling 2D soil water flow, and abscisic acid (ABA) signalling and its effect on stomatal conductance and potato production. Wöhling et al. (2013) assessed the performances of five crop models and one land-surface model in which two of them used the Farquhar model. The models were tested to reproduce the dynamics of soil water contents, evapotranspiration, and leaf area index during a growing season of winter wheat at two contrasting field plots in Germany. Bonan et al. (2014) implemented a stomatal model in a multi-layer plant canopy model and evaluated the simulations using leaf analyses, eddy covariance fluxes at forest sites, and parameter sensitivity analyses. Karlberg et al. (2006) predicted photosynthesis, transpiration and plant growth of salinity-stressed tomato using an integrated ecosystems model (the CoupModel). The model was calibrated and tested using two experimental data sets of two different seasons from lysimeter trials conducted in Israel. Fleisher et al. (2015) implemented four water-stress factors in a potato model in order to assess the contribution each factor to improve the modelling accuracy and compared the simulation results to experimental data consisting of six irrigation treatments. However, no scientific article is know to the authors in which the whole water transport along the soil-plant-atmosphere continuum including soil water dynamic and stomatal opening is predicted and verified based on a comprehensive experimental data set.

In this study, the collected data of a two-year common bean irrigation experiment were used to test the ability of the soil-atmosphere-vegetation transfer (SVAT) model Daisy (Abrahamsen and Hansen, 2000; Plauborg et al., 2010) to predict the effects of drought and high temperature stress on plants. Hereby, the two different photosynthesis model approaches that are implemented in Daisy, a simple one based on the calculation of light distribution within the canopy and single light response curves (Goudriaan and van Laar, 1978), and a biochemical photosynthesis model based on Farquhar et al. (1980) coupled with an empirical stomata conductance model (Ball et al., 1987) were tested and compared. The comparison of the two photosynthesis model approaches included multiple model runs with 300 years of synthetic weather data with several growth and climate conditions. Moreover, the prediction of the water transport along the soil-plant-atmosphere continuum including the leaf stomatal conductance using the biochemical model approach was evaluated.

2. Material and methods

In this study, a field irrigation experiment conducted in Germany is presented. Common bean was cultivated in two growth periods, one growth period under normal climatic conditions and one growth period under warm to hot climatic conditions. In both growth periods, some treatments were not irrigated (drought stress) while others were irrigated.

2.1. Experimental site and experimental design

In a two-year field trial, common bean (*Phaseolus vulgaris* L., cultivar Stanley) was cultivated to estimate the crop irrigation water requirements. The experimental site described in this study is located in Pillnitz near Dresden, Germany (51°N, 13.9°E and