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Canopy temperature for simulation of heat stress in irrigated wheat in a semi-arid environment: A multi-model comparison

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ABSTRACT

Even brief periods of high temperatures occurring around flowering and during grain filling can severely reduce grain yield in cereals. Recently, ecophysiological and crop models have begun to represent such phenomena. Most models use air temperature (T_{air}) in their heat stress responses despite evidence that crop canopy temperature (T_c) better explains grain yield losses. T_c can deviate significantly from T_{air} based on climatic factors and the crop water status. The broad objective of this study was to evaluate whether simulation of T_c improves the ability of crop models to simulate heat stress impacts on wheat under irrigated conditions. Nine process-based models, each using one of three broad approaches (empirical, EMP; energy balance assuming neutral atmospheric stability, EBN; and energy balance correcting for the atmospheric stability conditions, EBSC) to simulate T_c, simulated grain yield under a range of temperature conditions. The models varied widely in their ability to reproduce the measured T_c with the commonly used EBN models performing much worse than either EMP or EBSC. Use of T_c to account for heat stress effects did improve simulations compared to using only T_{air} to a relatively minor extent, but the models that additionally use T_c on various other processes as well did not have better yield simulations. Models that simulated yield well under heat stress had varying skill in simulating T_c. For example, the EBN models had very poor simulations of T_c but performed very well in simulating grain yield. These results highlight the need to more systematically understand and model heat stress events in wheat.

1. Introduction

The rising temperatures expected with climate change are likely to reduce wheat yields (Asseng et al., 2015), although the impact may be moderated by positive CO_2 fertilization effects. Without consideration of adaptations in crop variety, the dominant effect of warming is to accelerate crop development. Evidence suggests that heat stress consisting of even brief periods of high temperatures above crop specific critical thresholds (Ferris et al., 1998; Porter and Gawith, 1999; Wheeler et al., 2000; Jagadish et al., 2007; Vignjevic et al., 2015) are already causing large reductions in cereal yield (Schlenker and Roberts, 2009; Hawkins et al., 2013; Lobell et al., 2013; Fontana et al., 2015). It is expected that negative impacts of high temperature on crop yields will become more frequent with increased climate variability and higher mean temperatures (Field

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et al., 2012). To date, few climate change impact studies using crop models have considered such heat stress effects (Teixeira et al., 2013; Deryng et al., 2014).

High temperatures affect a number of crop growth and development processes that together result in the heat stress impacts observed in the field (Rezaei et al., 2015). Photosynthesis rates in wheat decrease when temperature exceeds optimum values (Sage and Kubien, 2007) due to reduction in the efficacy of photosystem II (Nash et al., 1985), thykaloid membrane instability (Bukhov et al., 1999) and reduced RUBISCO activity (Crafts-Brandner and Law, 2000). Reduced photosynthesis rates, together with increased respiration at high temperature (Brooks and Farquhar, 1985), result in reduced net assimilation. The reduction in net assimilation is reversible, though if coinciding with anthesis may result in large reductions in grain number and yield (Porter and Gawith, 1999). However, as compensation for the negative effects of heat stress on net assimilation, remobilization of non-structural carbohydrates (NSC) to grains during grain filling increases and is considered vital to ensuring yield during high temperatures (Tahir and Nakata, 2005). The tradeoff is that high temperature accelerates leaf senescence due to oxidative damage (Harding et al., 1990). Development rates are accelerated with temperature (Roberts and Summerfield, 1987) resulting in lower yields due to the shorter grain filling period. Finally, reproductive failure, including pollen infertility, flowering and fertilization failure and grain abortion are significant and irreversible sources of yield loss under high temperatures associated primarily with a reduction in grain number (Porter and Gawith, 1999; Barnabás et al., 2008).

While many crop models account for the temperature effects on net assimilation and development rate, it is only recently that crop models have attempted to explicitly simulate heat stress effects such as accelerated senescence or the reduction of grain number due to the failure of reproductive processes (Asseng et al., 2011; Moriondo et al., 2011; Eitzinger et al., 2013). The later heat stress responses can be considered, and are represented in crop models, as discontinuities in the regular temperature responses driving grain yield formation. Further, much evidence supports that genotypes that maintain relatively higher yield levels under heat or drought stress have cooler canopies than genotypes with the greatest yield reductions (Pinto et al., 2010; Pinto and Reynolds, 2015). These authors hypothesize that the genotypic differences conferring cooler canopies are related to the ability of the roots to extract more water from the soil profile. As such, it is important to accurately estimate the absolute temperature of the affected plant tissue. As an example, consider that yield loss due to irreversible grain sterility begins at 31 °C (Wheeler et al., 1996a,b; Porter and Gawith, 1999), but no grain abortion occurs at 30 °C. In this case, being off by 1 °C could result in large errors of either under or overestimation of heat stress effects. This may not be true for the temperature dependence of net assimilation and radiation use efficiency (RUE) functions, for example, as both types of functions are continuous and being a few degrees off with the crop temperature implies a relative error proportional to the ratio of the error in temperature to the range of temperatures over which the function is defined. In spite of the need to correctly specify the crop temperature, most crop modelling attempts to account for heat stress have used air temperature (T_{air}), which can differ by several degrees from actual crop canopy temperature (T_c). Siebert et al. (2014) found that stress thermal time, an index of heat stress that sums temperatures greater than a high temperature threshold during a period in which crops are sensitive to heat stress (Blumenthal et al., 1991), computed with T_c and not T_{air}, is a more appropriate predictor of heat stress impacts on grain yield. Herein we hypothesize that T_c and not T_{air} must be used to simulate yield reductions under high temperature (Siebert et al., 2014) and the related progression of crop senescence (Kimball et al., 2012).

Critically, T_c can deviate significantly from T_{air} (Siebert et al., 2014; Rezaei et al., 2015). For example, when soils are wet, as after a rainfall or irrigation, T_c may be several degrees cooler than the air. In contrast, with a dry soil profile, canopies can be several degrees warmer than the air due to reduced transpiration rates associated with stomatal closure under water deficit (Clawson et al., 1989; Wall et al., 2006). However, low transpiration rates can also occur when soils are wet, for example when the air-canopy vapor pressure deficit (VPD) is low as is common in humid cool environments. Further, weather variables such as the amount of incident solar radiation and wind speed (which drives advection) have a large direct effect on T_c via the heat balance of the cropped surface (Monteith and Unsworth, 1990), and also indirectly through their influence on crop water use.

There are various way in which T_c for crop canopies can be simulated, ranging from very simple empirical relationships (e.g. Choudhury et al., 1986; Shuttleworth and Gurney, 1990) to solutions of the energy balance at a cropped surface. Within the energy balance approaches, there are two very different methods: complex energy balance approaches considering the stability conditions of the atmosphere (EBSC) (e.g. Thom, 1975) and greatly simplified methods which assume neutral atmospheric conditions (EBN). In any energy balance approach, net incident radiation, energy fluxes to the soil, latent energy to evaporate water from the cropped surface and sensible heat flux (energy to warm or cool the cropped surface) are summed to equal zero. Therefore, T_c can be solved from the sensible heat term. Both the latent and sensible energy terms depend on the resistance of the surface to transfer water vapour and heat to the air, respectively. The differences between the energy balance methods that assume neutral stability versus those that correct for atmospheric stability are related to how they calculate these aerodynamic resistance terms (Liu et al., 2007). To understand this difference, one must consider the concept of the dry adiabatic lapse rate (DALR). As imaginary small air pockets immediately next to the surface rise, they cool at the DALR, which is the equal to the temperature change needed to supply just enough energy to allow the expansion of the air such that its pressure decreases to that of the surrounding air (Monteith and Unsworth, 2008). The process is adiabatic as there is no net transfer of energy in or out of the air pocket. When air over hot and dry surfaces rises, it also cools at the DALR with the result that it is warmer than the surrounding air as it rises. As a result, the continued rise of the warmer (lighter) air is enhanced due to buoyant forces. The end result of this is that the resistance to heat and vapour transfer (via the rising air) is lower than it would be if the surface were not warm. The opposite occurs, i.e. resistance is greater, when a surface is relatively cool as occurs on clear nights with high radiative heat transfer from the surface, or under conditions with high evaporative cooling such as with wet soils in high and high evapotranspiration environments (Monteith and Unsworth, 2008). To account for this in energy balance methods requires iteration, as the solution and even the appropriate methods to determine the resistance terms are a function of the canopy (surface) temperature, which is unknown (Monteith and Unsworth, 2008). An alternative is to assume that the resistance is not affected by atmospheric stability, or that the actual lapse rate of the air is equal to the DALR, as assumed in the EBN methods. In this case, calculation of the resistance to heat and vapour transfer is just a function of the crop height and wind speed (Liu et al., 2007). However, the error made in this method may be significant depending on a number of factors.

To date, crop models typically employ more empirical (EMP) approaches (e.g. STICS) or the simplified EBN approach (e.g. Sirius2014). The more mechanistic EBSC approaches are found in other types of models for describing the plant environment (Mihailovic and Eitzinger, 2007) or ecosystem processes (Grant et al., 2012) or for controlling experimental heating for agronomic trials (Kimball