Agricultural Systems 153 (2017) 101–108

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Yield comparison of simulated rainfed wheat and barley across Middle-East

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ARTICLE INFO

Article history:
Received 22 October 2016
Received in revised form 13 December 2016
Accepted 28 December 2016
Available online xxxx

Keywords:
Africa
Barley
Drought
Simulation
Wheat
Yield

ABSTRACT

Rain-fed wheat and barley are key crops in the Middle-East. A slight improvement in the effective use of water and in grain yield could greatly improve lives of subsistence farmers. This study aimed to evaluate the relative merits of wheat and barley in this region by simulating yields across 404 uniformly spread locations across 30 growing seasons. The results emphasized the primary importance of sowing date in each location. In comparison to wheat, barley generally was capable of rapid progress through its development stages allowing it to avoid deleterious late-season droughts and to have greater yields in low rainfall regions. A large part of Middle-East appeared unsuited for rain-fed production of these two grain species if seasonal yield variability is a concern.

1. Introduction

The domestication of wheat (*Triticum aestevium*) and barley (*Hordeum vulgare*) took place in the Middle-East and these species have remained key crops for this region. Barley is generally favored over wheat in drier regions because barley is often assumed to have superior yielding ability as compared to wheat under water-limited conditions (Teulat et al., 1997; Wahbi and Sinclair, 2005). Due to economic and socio-cultural factors, wheat is commonly grown in areas where these two crops produce approximately equal yields, but barley remains important especially because of its "high resistance" to salinity and tolerance of poor soils (Kaniewski et al., 2012).

In much of the Middle-East, wheat and barley are grown in rain-fed production systems. For example, in 2008 only 15% of the wheat and 18% of the barley growing areas in the Near East were irrigated (FAO, 2009). These numbers highlight the vital importance of appropriate germplasm to maximize productivity in arid and water-limited regions.

Unfortunately, there are very few references that compare yielding capability between wheat and barley in drought-prone locations. Carvalho et al. (2014) hypothesized that spring barley is better adapted to drought than durum wheat in Mediterranean conditions as a result of a higher root length density in the deep soil profile, but the experimental results did not confirm this hypothesis. This confirmed the results of other authors (Abeledo et al., 2004; Garcia del Moral et al., 1999; Arisnabarreta and Miralles, 2006) and supported the potential significance of these differences in modeling these species (Lafarge and Hammer, 2002; Kemanian et al., 2004). However, the experimental results in comparing wheat and barley are limited to the few locations and growing seasons.

To provide more expansive insight about selecting wheat or barley, simulation analyses using process-based crop models can be used to examine crop development, growth, and yield of each species over a wide range of locations and over a large number of growing seasons (Wahbi and Sinclair, 2005; Lobell and Burke, 2010). Since the late 1980s, separate models for wheat and barley have been constructed and their robustness were confirmed for assessing for each species their development, growth, and yield (Stapper and Harris, 1989; Amir and Sinclair, 1991a, 1991b; Sinclair et al., 1993; Goyne et al., 1993; Jones et al., 2003; Keating et al., 2003; Goyne et al., 1996; Milroy and Goyne, 1995; Hammer et al., 2010; Hoogenboom et al., 2012). However, to allow direct comparisons between simulation results for barley and wheat, it is desirable to use a model with the same structure for both species. In this case, only those variables that define distinguishing developmental traits between species are changed and all other aspects of the models remain identical (Wahbi and Sinclair, 2005).

The overall objective of this study was to use the Simple Simulation Model (SSM) for wheat and barley to compare yields across a grid of 404 locations located uniformly across Middle-East regions and over 30 cropping seasons. The SSM model was adapted from Soltani et al.

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http://dx.doi.org/10.1016/j.agsy.2016.12.017
0308-521X/

(2013) to take into account the phenological differences between wheat and barley that have been previously identified (e.g., Wahbi and Sinclair, 2005; Alzuelta et al., 2012). To better reflect the intra-specific variability, five genotypes of each species were used in the simulation to introduce genetic variability in phenological development. Four specific objectives were identified: i) Examine the effect of different sowing dates on wheat and barley yields across all the locations and years, ii) Determine if the use of an accumulated soil water content threshold to determine sowing date can be used to increase crop yield, iii) Compare wheat and barley projected yield performances, both in terms of maximum attainable yield and average yield and iv) Assess risks of occurrence of inadequate yields across growing seasons based on a minimum yield that may be acceptable to a grower.

2. Material and methods

The model used in this study is an updated version of the models developed by Sinclair and co-workers (Amir and Sinclair, 1991a, b; Sinclair and Amir, 1992; Sinclair et al., 1993; Wahbi and Sinclair, 2005; Soltani and Sinclair, 2012), which is now identified as the Simple Simulation Model (SSM) based on the terminology introduced by Soltani and Sinclair (2012). Importantly for the current study, the SSM approach was shown to be robust in simulation of bread wheat in Israel (Amir and Sinclair, 1991a, 1991b) and both wheat and barley in Syria and Lebanon (Wahbi and Sinclair, 2005). More recently the SSM-wheat model was assessed in six field experiments located in the vicinity of Gorgan, Iran during two cropping seasons (Soltani et al., 2013). This model was also compared with three other popular wheat models in respect to robustness and transparency, and the SSM model was found to be equal to or superior to the other three models based on these two criteria (Soltani and Sinclair, 2015).

2.1. Model description

SSM is a mechanistic model that incorporates the processes involved in crop development, growth, and yield formation. It describes key physiological processes to simulate crop response to incident radiation, water availability and nitrogen resources. Leaf area development is based on accumulated temperature, referred to as cumulative temperature units (°C). Daily temperature units are calculated based on a two-linear-segment model with a base temperature (equal to 0 °C for wheat and barley) of zero development, an optimal temperature (depending on genotype) and a critical temperature (equal to 40 °C for the two species) of zero development. The daily temperature used in these calculations is the mean of daily minimum and maximum temperatures. In the model, inadequate water or nitrogen supply decreases daily leaf area development rate and crop growth.

Daily crop growth is dependent on intercepted solar radiation as calculated from crop leaf area index (LAI), multiplied by radiation use efficiency (RUE). For optimum conditions RUE is set to 2.2 g MJ^{-1} photosynthetically active radiation (Wahbi and Sinclair, 2005) for all genotypes and species, but it is adjusted to lower values in SSM depending on temperature and soil water-deficit. Non-optimal soil moisture defined by the fraction of transpirable soil water (FTSW) also results in decreased N accumulation. Therefore, daily mass increase is calculated based on incident radiation, minimum and maximum temperature, LAI, and soil water content. Daily growth is used to update cumulative mass of the crop.

Before seed growth, daily N accumulation is calculated to meet daily demand as a result of increasing leaf area and stem dry matter. Constant values of N concentration in leaves and stems are used as targets when N uptake is not limited. Maximum daily rate of N accumulation in wheat was set at 0.25 g m^{-2} d^{-1} (Sinclair and Amir, 1992; Soltani and Sinclair, 2012) and the actual rate of accumulation is limited to this value even if the demand is higher. In these simulations, it was assumed that there was sufficient N in the soil to meet the daily N uptake.

At times when inadequate soil water resulted in N accumulation rate that did not fully meet the plant demand, the concentration of stem N is allowed to decrease to a minimum of 5 mg g^{-1} (Soltani et al., 2013). Under more severe N uptake limitation, leaf area development is inhibited and the stem can continue to grow at a minimum N concentration. Under extreme N limitation, leaf area development is set equal to zero and N can be remobilized by leaf senescence. As soon as the crop reaches the beginning of seed growth, seeds become the prime sinks for N and daily N demand is calculated as the product of seed growth rate and seed N concentration.

An important feature of the SSM model is that daily transpiration rate (TR) is calculated based on the fact that daily TR is very closely linked to daily CO_2 assimilation rate (Sinclair, 1984). This relationship allows TR to be defined by the daily crop growth multiplied by the atmospheric vapor pressure deficit, and divided by a constant, mechanistically defined transpiration coefficient, which is equal to 5.8 Pa for both wheat and barley. TR is calculated every day so that water for transpiration is removed from the soil, along with direct soil evaporation. Calculation of daily soil water status is completed by adding rainfall and snow melt, and removing water lost as run-off and percolation below the root zone. Based on Soltani et al. (2013), the soil profile was composed of five layers to a total depth of 1200 mm and is described in Table 1. Since extensive soil data were not available in the majority of the simulated locations, it was assumed that the soil was generally of the same type across the 404 locations and the volumetric transpirable soil water was set to 0.13 m^3 m^{-3} (Soltani et al., 2013). The daily increase in depth of water extraction is set to be 30 mm per biological day. The extension rate is set to zero before emergence, after beginning of seed growth, when dry matter production is zero, or the soil layer is dry ($FTSW = 0$). For each crop and genotype, the extraction depth began at 200 mm at plant emergence and the maximum rooting depth was set to 1000 mm.

2.2. Differences in phenology between wheat and barley

The development of the crop is calculated daily as a function of photoperiod and daily mean temperature. This calculation of crop development is based on the biological days (BD) concept, which defines daily progress to complete a phenological event (Soltani and Sinclair, 2012). The actual accumulation of BD on each day is calculated from functions dependent on temperature, vernalization and water-deficit. All these functions are described in Soltani and Sinclair (2012) and all the parameters used are shown in Table 2.

Wheat and barley are very similar crop species but commonly differ in the duration of their phenological stages. Barley is usually a shorter-season species, although some barley genotypes are longer season types and some wheat genotypes are shorter types. In their comparison of wheat and barley, Wahbi and Sinclair (2005) reported that barley in Syria and Lebanon had a 22% shorter time from end of leaf development to anthesis than wheat and a 14% shorter time from anthesis to the end of grain filling than wheat. These differences are reflected in SSM by the duration of individual developmental stages as defined by the BD needed for each development stage. The biological days of each development stage in the simulations for the two species are given in Table 3. All the others parameters were set equal between wheat and barley, except the potential slope of linear increase in harvest index. The increase in harvest index was set equal to 0.014 g g^{-1} $d^{-1}$for wheat and 0.018 g g^{-1} d^{-1} for barley; with the exception of the wheat cultivar Bezostaya set to 0.012 g g^{-1} d^{-1} and barley cultivar Arabic white set to 0.020 g g^{-1} d^{-1} (Soltani et al., 2013; Wahbi and Sinclair, 2005).

Genetic variation among genotypes within a species was also considered in simulating leaf development as defined by phyllochron, which is the biological time needed for each leaf to develop. Five Middle-East genotypes were considered for each species: Zargos, Tarjan, Koohdasht, Shirudi (Soltani et al., 2013) and Bezostaya (Soltani and Hoogenboom, 2007) for bread heat and Arabic white, Beecher,