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Improvements to the Hybrid-Maize model for simulating maize yields in harsh rainfed environments

Haishun Yang[a,*], Patricio Grassini[a], Kenneth G. Cassman[a], Robert M. Aiken[b], Patrick I. Coyne[c]

[a] *Department of Agronomy and Horticulture, University of Nebraska – Lincoln, P.O. Box 830915, Lincoln, NE 68583-0915, USA*
[b] *Kansas State University Northwest Research-Extension Center, Colby, KS, USA*
[c] *Kansas State University Agricultural Research Center, Hays, KS, USA*

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ABSTRACT

This paper reports revisions in formulation and new features of the Hybrid-Maize model (released as HM2016), to better simulate yields in harsh rainfed environments. Revisions include updated subroutines for root growth and distribution within the soil profile, greater sensitivity of canopy expansion and senescence to water deficits, an expanded kernel setting period, and soil evaporation as influenced by surface cover with crop residues. The updated model also includes routines for simulating surface runoff and estimating soil water content at sowing based on simulation of soil water balance during the preceding fallow period. Revisions of model functions were based on recent advances in understanding and quantification of maize response to environmental factors and management practices, as well as characteristics of new maize hybrids. More robust simulation of maize yield was obtained with the updated model under rainfed conditions, especially in years and locations with severe drought or on soils with limited water holding capacity. Capability to quantify soil water content at sowing and to perform batch simulations makes HM2016 more useful for pre-season yield projections in years with below-normal soil water recharge and for in-season yield forecasting across a wide range of environments. Revisions to routines governing root distribution and kernel setting make HM2016 a more powerful tool for evaluating hybrid-specific traits and crop management practices for ability to mitigate yield loss from water deficits and for identifying management options for individual production fields.

1. Introduction

Crop simulation models have been widely used in research, education, extension, and to inform policy making (Bouman et al., 1996; Sinclair and Seligman, 1996; Boote et al., 2010). While performance of crop models is generally more robust under non-water stress conditions with good management of nutrients and biotic stresses, model performance for crops that experience water deficits (*e.g.*, in harsh rainfed systems with low and highly variable rainfall or soils with limited water holding capacity) has been less satisfactory (Ko et al., 2006; McMaster et al., 2011; Mastrorilli et al., 2003). Poor model performance has been attributed to relatively poor understanding and quantification of several key physiological processes that govern crop responses to limited water supply (Sinclair and Seligman, 1996; Roth et al., 2013) and phenotypic differences in new cultivars, compared to older ones, that are not yet used in model development and calibration (Boote et al., 1996). For maize (*Zea mays* L.) simulation models, several processes related to crop growth and yield formation under water deficit conditions have been suggested for improving some models, including crop root distribution and water uptake from soil (Hammer et al., 2009), leaf expansion and senescence (Ben Nouna et al., 2000; Cakir, 2004; Yang et al., 2009), and kernel setting (Andrade et al., 1999, 2002; Lizaso et al., 2007). In addition, the effects of crop residues covering the soil surface in conservation tillage systems on soil evaporation and surface runoff also need to be accommodated to improve model simulation of soil water balance throughout the growing season (Bu et al., 2013).

The Hybrid-Maize model (Yang et al., 2004, 2006; http://hybridmaize.unl.edu/) is a computer simulation model for maize under non-limiting (fully-irrigated) or water-limited

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Abbreviations: LAI, leaf area index; WSI, water stress index; DS, development stage; RGR, root growth rate (for depth); ET, evapotranspiration; ET0, grass-referenced evapotranspiration.

* Corresponding author.
E-mail address: hyang2@unl.edu (H. Yang).

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(rainfed or partially irrigated) conditions based on daily weather data. Specifically, it allows users to: (a) assess yield potential and its variability at a given location based on historical weather records, (b) evaluate changes in yield potential using different combinations of sowing date, hybrid maturity and plant density, (c) identify optimal timing and amount of irrigation applications for highest yield and irrigation water use efficiency, and (d) make in-season yield forecasts based on real-time weather up to the current date and a probability distribution of final yield based on historical weather records for the remainder of the growing season. The Hybrid-Maize model does not account for yield losses due to suboptimal nutrient management or from weeds, insects and pests, diseases, lodging, and other stresses.

The Hybrid-Maize model combines the strength of two maize simulation approaches represented by Wageningen models, including WOFOST (Van Diepen et al., 1989) and INTERCOM (Kropff and van Laar, 1993; Lindquist, 2001), and by the CERES-Maize model (Jones and Kiniry, 1986; Kiniry et al., 1997). The previous versions of the Hybrid-Maize were developed in 2004 (Yang et al., 2004) and 2006 (Yang et al., 2006). Since then, research has led to improved understanding and quantification of crop growth processes and responses to water deficit, and maize breeders have continued to improve drought tolerance and other traits of maize hybrids. These advances have not yet been incorporated into the Hybrid-Maize model to improve its robustness and applicability across diverse environmental and management conditions.

Earlier versions of Hybrid-Maize have been used to assess maize yield potential and yield gaps (Van Wart et al., 2013; Farmaha et al., 2016; van Ittersum et al., 2016), evaluate management options (Chen et al., 2011; Grassini et al., 2011a; Witt et al., 2006; Meng et al., 2013), the impact of climate change (Cassman et al., 2010; Chen et al., 2013; Lobell et al., 2009; Meng et al., 2014), water productivity (Grassini et al., 2009, 2011b), yield and production forecasting (Sibley et al., 2014; Morell et al., 2016), and nutrient management (Meng et al., 2012; Setiyono et al., 2011) across diverse maize systems and mostly favorable production environments worldwide. Feedback about performance under severe water deficit, however, indicated room for model improvement. Likewise, evolution of computer operating systems, software and hardware continue to provide opportunities to improve functionality of application software like Hybrid-Maize. As developers of the original Hybrid-Maize model, we also received feedback from users about opportunities for adding new model features and applications, all of which provided motivation for revision of the model.

Specific objectives of this paper are to: (1) document revisions to the Hybrid-Maize model as now included in HM2016, as compared to the 2006 version (HM2006), with regard to root distribution, canopy expansion and senescence in response to crop water deficit, kernel setting, surface runoff, soil evaporation and crop transpiration, estimation of soil water content at sowing based on simulation of water balance during the fallow period, and a new batch run function, and (2) evaluate the ability of the revised model to reproduce a wide range of measured maize yields from well-managed field studies under rainfed and irrigated conditions. Description of the model and a detailed user's guide describing all model functions and underpinning equations can be found at www.hybridmaize.unl.edu.

2. Revisions of model functions

2.1. Root growth and soil profile distribution

In HM2006, root length distribution by soil depth largely followed the CERES-Maize approach (Jones and Kiniry, 1986). In essence, rooting depth progresses following growing degree days (GDD) accumulation and reaches the user specified maximum depth at development stage (DS) 1.15. The rooting length distribution is V-shaped with the tip at the maximum rooting depth (Fig. 1). However, some studies have reported that roots of new maize hybrids can reach 150 cm or more in soils without constraints to root growth (Dardanelli et al., 1997; Djaman and Irmak, 2012; Tolk et al., 2016), and the effective lateral root length distribution is more cylindrical in the upper rooting zone (0–30 cm) followed by a conical shape at lower depths (Hammer et al., 2009) (Fig. 1). This suggests that, given the same soil depth, the soil volume from which the maize root system acquires water (and nutrients) is greater than simulated in HM 2006. In the revised routine of HM2016, maximum rooting depth still occurs at DS 1.15 (typically 5–7 days after silking), but the increase of rooting depth ($\text{Depth}_{\text{root}}$) from emergence to DS = 1.15 is simulated as a function of growing-degree days (GDD, $T_{\text{base}} = 10\,^{\circ}\text{C}$) as follows:

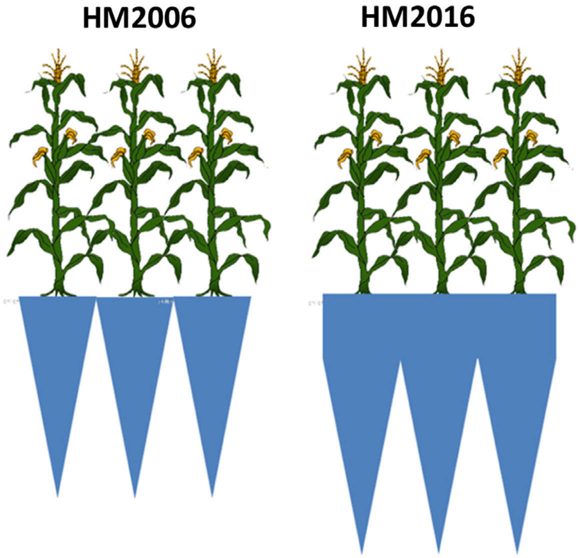

Fig 1. Schematic representation of root length distribution in HM2016 and HM2006.

$$\text{if} \text{Depth}_{\text{root}} < \text{Depth}_{\text{max}}, \text{then} \text{Depth}_{\text{root}} = \text{sumGDD10} * \text{RGR}$$

$$\text{else}, \text{Depth}_{\text{root}} = \text{Depth}_{\text{max}}$$

in which $\text{Depth}_{\text{max}}$ is the user-specified maximum soil rooting depth, sumGDD10 is the sum of growing degree days from germination to a particular date, and RGR is the root growth rate (cm per GDD). RGR is calculated as potential hybrid rooting depth (one of the hybrid-specific parameters that can be modified by the user and different from $\text{Depth}_{\text{max}}$) divided by sumGDD10 to DS 1.15. In general, root growth of most crops decreases substantially or ceases at onset of rapid dry matter accumulation in reproductive structures (Borg and Grimes, 1986). Although there are few data on genotypic differences in potential rooting depth of modern hybrids, we expect most commercial hybrids can extract water from 1.5 m depth which is the default setting for the hybrid-specific potential rooting depth in HM2016. We do not recommend that users modify this default value unless they have strong evidence that the hybrid they simulate has a deeper or shallower potential rooting depth. In contrast, $\text{Depth}_{\text{max}}$ represents the depth of soil without physical or chemical restrictions to root growth. Users should reduce the default value for simulations on soils with restrictions to root growth at a shallower depth due to hard pans, bedrock, caliche, sand lens, soil toxicity, salinity, or acidity. For example, if there is a hard pan at 75 cm depth that roots do not penetrate, then $\text{Depth}_{\text{max}}$ should be set at 75 cm.