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Application note

PhenologyMMS: A program to simulate crop phenological responses to water stress

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ABSTRACT

Crop phenology is fundamental for understanding crop growth and development, and increasingly influences many agricultural management practices. Water deficits are one environmental factor that can influence crop phenology through shortening or lengthening the developmental phase, yet the phenological responses to water deficits have rarely been quantified. The objective of this paper is to provide an overview of a decision support technology software tool, PhenologyMMS V1.2, developed to simulate the phenology of various crops for varying levels of soil water. The program is intended to be simple to use, requires minimal information for calibration, and can be incorporated into other crop simulation models. It consists of a Java interface connected to FORTRAN science modules to simulate phenological responses. The complete developmental sequence of the shoot apex correlated with phenological events, and the response to soil water availability for winter and spring wheat (*Triticum aestivum* L.), winter and spring barley (*Hordeum vulgare* L.), corn (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), proso millet (*Panicum milaceum* L.), hay/foxtail millet [*Setaria italica* (L.) P. Beauv.], and sunflower (*Helianthus annus* L.) were created based on experimental data and the literature. Model evaluation consisted of testing algorithms using "generic" default phenology parameters for wheat (i.e., no calibration for specific cultivars was used) for a variety of field experiments to predict developmental events. Results demonstrated that the program has general applicability for predicting crop phenology and can aid in crop management.

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1. Introduction

Phenology, or the relationship between climate and the sequence and timing of developmental events or stages, provides a foundation for understanding crop development and growth. Farmers increasingly are basing management on crop developmental stages to enhance economic crop yields while maintaining environmental quality. For instance, as non-agricultural demand for water increases in many arable lands, timing limited irrigation water with critical developmental stages to maximize yield is receiving much interest. Of similar importance, accurate prediction of developmental stages is needed in crop simulation models and decision support aids. Fortunately, a long history of research in plant development and phenology has created a significant understanding and ability to predict developmental events. This is founded on the fundamental concept that plant development is orderly and predictable (Rickman and Klepper, 1995; McMaster, 2005). The genetics of the plant determines the pattern of development, and environmental conditions (e.g., temperature, photoperiod, nutrients, and water availability) can alter the developmental rates.

Several deficiencies remain in accurately predicting phenology in variable environments and management systems. One deficiency is that considerably less research has examined the impacts of water deficits (degree, timing, and history) on crop phenology (McMaster et al., 2009), despite the obvious influence of water deficits on some developmental phases (e.g., germination, emergence, grain filling). Further, phenological responses to water deficits vary among crops, cultivars, and developmental events. With few exceptions (e.g., SHOOTGRO, Zalud et al., 2003), crop phenology simulation models do not explicitly consider the influence of water deficits on phenology. Simulation models with more detailed energy balance submodels (e.g., ecosys, Grant et al., 1995; STICS, Brisson et al., 2003) can somewhat address phenological responses to water deficits by estimating and using plant temperature rather than air temperature, yet plant temperature alone will not necessarily predict phenological responses to water deficits correctly (McMaster et al., 2009). Without fundamental knowledge of development and quantification of phenological responses to water deficits for specific crops, a suitable foundation does not exist to

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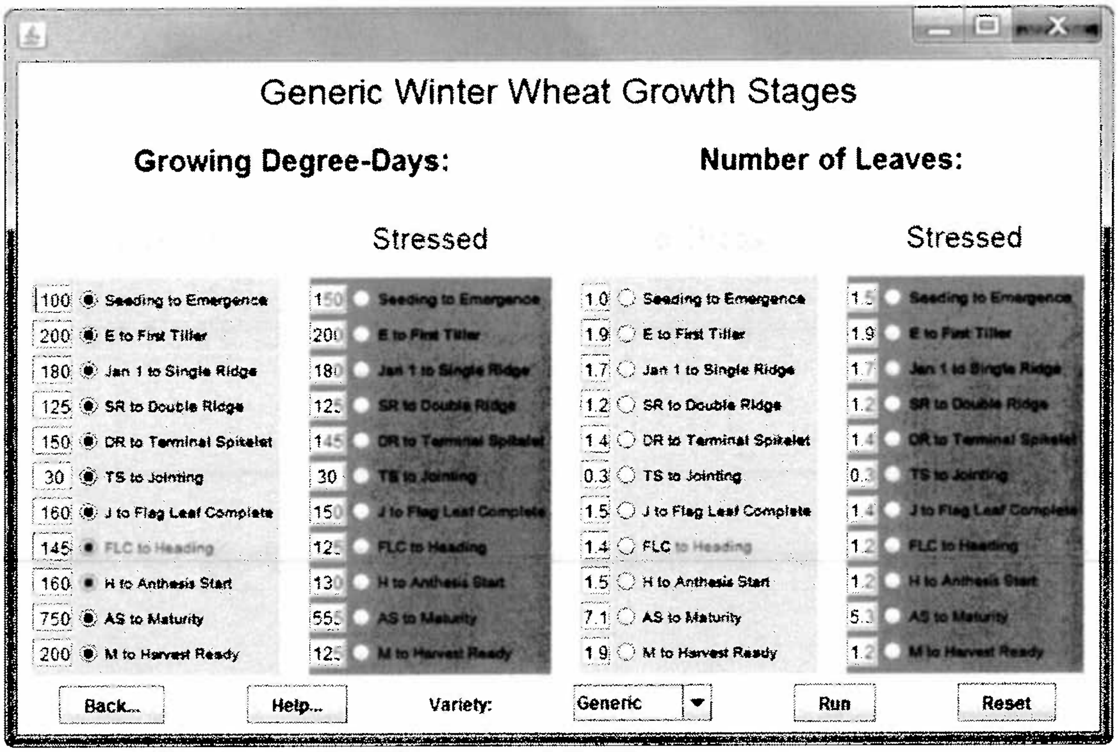

Fig. 3. Set Growth Stages screen. The default parameters for developmental stages for a generic winter wheat plant are shown.

- *No stress* refers to non-limiting conditions of an environmental factor, and we usually consider the environmental factor to be soil water availability. This option should be selected for irrigated or high rainfall conditions.
- *Stress* refers to the most limiting value of the environmental factor not leading to terminal stress (i.e., death of the plant). This option should be selected for most rainfed situations where soil water is often severely limiting, but not lethal. Because conditions are often between the *No stress* and *Stress* options, either the user can estimate which option is closest to the conditions to be simulated and select that option, or change the default values of one of the options to be intermediate between the two extremes.
- Within both the *No stress* and *Stress* options, two related estimates of thermal time (i.e., growing degree-days, GDD, or number of leaves produced between developmental events, NL) can be selected. Number of leaves for an interval is multiplied by the phyllochron (the thermal time between appearance of successive leaves, °C days) to convert to thermal time. This approach is based on predicting plant development by integrating it with the main stem leaf number (Rickman and Klepper, 1995; McMaster, 2005).

The default selection for the screen is to use the *No stress* option and GDD method. Any combination of the four options within a row may be selected regardless of selections in the other rows. As with the other screens, the user may run the model after accepting or modifying the parameters in the Set Growth Stages screen. When the Run button in any screen is selected, the Output screen (Fig. 4) is automatically generated, usually within a second or so. Fig. 4 shows the end of the Output file that can be saved by the user with all of the developmental events (= number of rows) shown in Fig. 3 for the crop. At the top of the Output file, all information on the initial inputs and parameter values selected in the Begin Setup (Fig. 1), Set Inputs (Fig. 2), and Set Growth Stages (Fig. 3) screens is echoed back into the Output screen. The user can save the Output screen, and also save the simulation scenario (i.e., values selected in Figs. 1–3) if desired, and then retrieve this scenario for simulation at a later time.

2.3. PhenologyMMS FORTRAN process-based science modules

The Java interface described above is used to input the parameters and drivers (e.g., weather) used by the separate process-based science modules coded in FORTRAN. A detailed description of the process-based science modules is provided in McMaster et al. (Submitted for publication), and only a brief description is provided here. The modules are primarily based on:

1. Simplifying an earlier and more detailed phenology model for wheat and barley (SHOOTGRO, McMaster et al., 1992b; Zalud et al., 2003), and
2. Summarizing and quantifying the entire developmental sequence of the shoot apex of other crops (e.g., corn, proso millet, hay millet, sorghum, and sunflower) and correlating the sequences with commonly used growth stage scales. Particular emphasis was focused on how water deficits impact the phenology of the crop. The template for this synthesis was based on that developed by McMaster et al. (1992a), and expanded by McMaster et al. (2005).

A series of steps were used to create the Set Growth Stages screen (Fig. 3) for each crop, which is important for simulating phenology. An overview describing the steps is provided here. The first step was to use the literature to summarize and quantify, to the extent possible, the entire developmental sequence

2.4. Data sets and model evaluation methods

Creating PhenologyMMS required collecting data sets for both model development and validation for each crop, yet comprehensive phenological data sets examining responses to variable water deficits are rare in general for major agronomic crops, and sometimes non-existent for many agronomic crops (McMaster et al., 2009). Detailed evaluation of PhenologyMMS for all crops is presented in McMaster et al. (Submitted for publication), and in this paper results are presented only for winter and spring wheat. These crops were chosen as the experimental data sets are representative of those commonly available to many users in that soil water deficit levels were not rigorously measured, a variety of cultivars were grown in a diversity of environments, and planting dates and management practices varied considerably. Because the data sets contained diverse cultivars and conditions, the default parameters for a generic winter or spring wheat cultivar were used in all simulations, with the exception that planting date was changed to the actual planting date. This evaluation would be typical for users that have little information or do not wish to get into a greater level of detail in running the program.

The following data sets were used for evaluating winter and spring wheat phenology: (1) a 2-year irrigation study for 12 cultivars at Fort Collins, CO and Akron, CO (McMaster et al., 2003a,b); (2) a 6-year tillage by residue cover study at Fort Collins, CO (McMaster et al., 2002b); (3) a 2-year planting date by heated soil study at Fort Collins, CO (McMaster et al., 2003b); (4) a 21 site-year study across the Great Plains, USA for a variety of cultivars, environments, and management (McMaster and Smika, 1988); and (5) a 6-year study examining spatial variation in phenology across a landscape about 15 miles east of Fort Collins, CO (unpublished data). Combining all experiments, over 25 cultivars were measured at regular intervals (often three days per week) for when the developmental stages of seedling emergence, jointing, flag leaf blade growth complete, heading, anthesis, and physiological maturity occurred in each experiment.

Relative error (RE) and root mean square error (RMSE) model evaluation statistics were calculated to compare modeled results to measured data. Relative error was expressed in percent as:

$$RE = \frac{(\bar{P} - \bar{O})}{\bar{O}} 100$$

where $\bar{P}$ is the predicted mean and $\bar{O}$ is the observed mean. The RMSE was calculated by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}}$$

where P_i is the ith predicted value, O_i is the ith observed value, and n is the number of data pairs. In some experiments, such as those that evaluated tillage and residue cover practices, treatment effects resulted in different observed dates for some developmental events (although the mechanisms explaining the differences were not clear). PhenologyMMS simulated the same day for the developmental stage regardless of treatment.

3. Results and discussion

An illustration of PhenologyMMS simulation model performance is presented for seedling emergence, floral initiation, flowering, and physiological maturity developmental events for winter and spring wheat. The RMSE for different developmental events ranged from 7.2 to 12.4 and 2.6 to 6.9 days for winter and spring wheat, respectively (Fig. 5). Model bias, or relative error (RE), for all developmental stages was slightly negative for winter wheat, indicating a bias towards simulating a developmental event earlier than observed; the slightly positive RE for spring wheat indicated a tendency to simulate later dates than observed.

Cultivar variation in the phase from seedling emergence to floral initiation can be considerable for winter wheat and has been noted in the literature (e.g., Jamieson et al., 2007; McMaster and Wilhelm, 1998). Our results showed the highest RMSE for this phase (as indicated by the developmental phase of jointing) of any developmental phase (12.4 days), and using default generic parameters as done in this evaluation cannot capture this variation. Furthermore, winter wheat genotypes have vernalization and often photoperiod, requirements that must be satisfied before floral initiation can occur. The PhenologyMMS model currently does not incorporate a photoperiod factor and assumes that vernalization has been satisfied by 1st January. This assumption is normally met in the environments and planting dates used in our evaluation data sets (based on running vernalization models and unpublished data from bringing in plants from the field to the greenhouse which subsequently flowered). The large variability noted in Fig. 5 for winter wheat reflects the likely need to include vernalization and photoperiod factors into the model to further improve the model. The duration of grain filling is significantly influenced by the interaction of temperature and water deficits, and genotypes can vary considerably in their response to these two environmental factors (McMaster and Wilhelm, 2003; McMaster et al., 2009). RMSE increased for winter and spring wheat for simulating physiological maturity when compared to flowering (Fig. 5).

A further illustration of PhenologyMMS simulation performance is provided by showing an application for assessing expected developmental timing across the Great Plains for a Regional Wheat Production Guide (McMaster and Wilhelm, 2010). In this application, all default values were used to simulate winter wheat jointing, anthesis, and maturity dates across locations throughout the Great Plains using historical weather data. Two scenarios were run representing the extremes of high (GN, irrigated/high precipitation) and low (GS, dryland, low precipitation) soil water levels. The general expected patterns of earlier anthesis and maturity under high water deficits and lower latitudes were observed, and mean simulated dates fit within the expected dates normally observed for the locations (Table 2).

One advantage of PhenologyMMS is that rather than using one set of parameters (as done in most model evaluation) to calculate phenology across a range of conditions at a location, the parameter set is adjusted to reflect the level of water deficits. Therefore, applications such as that shown in Table 2 are able to provide more realistic estimates of developmental stages across environments varying in water deficits than would a model using a single parameter set.

The evaluation and application results are encouraging and show that PhenologyMMS can adequately simulate wheat phenology. While not shown here, evaluation results for the other crops usually had lower RMSEs than for wheat (McMaster et al., Submitted for publication). This suggests that PhenologyMMS can be used as a decision tool for certain management decisions requiring knowledge of crop developmental stages. Certainly the accuracy of inputs and initial conditions are critical in quantifying model predictive ability, and decision makers will need to consider the degree of error (e.g., RMSE magnitude) acceptable in accepting or modifying default values.

4. Summary and future work

PhenologyMMS is intended to provide a simple and easy to use program to predict and understand crop phenology and how phenology responds to varying water deficits. The evaluation

Table 2
Mean simulated dates and range of days for a "generic" wheat variety to reach certain growth stages under optimal (i.e., irrigated) and stressed conditions (i.e., dryland) for various locations in the Great Plains, USA. Initial inputs assumed a 15th September planting date, optimal soil water at planting (Table 1 values), 5 cm seeding depth, and Method 1 for calculating thermal time with a 0 °C base temperature. The number of historical years of weather data used for each location are noted. (Adapted from McMaster and Wilhelm (2010)).

Location	# Years	Mean date/range (# days)						
		2 Leaves	Jointing		Anthesis		Maturity	
		Optimal	Optimal	Stress	Optimal	Stress	Optimal	Stress
Akron, CO	29	Oct. 10	Apr. 28	Apr. 27	Jun. 2	May 29	Jul. 9	Jun. 28
Range		−6 to 11	−19 to 21	−19 to 22	−13 to 14	−15 to 15	−9 to 12	−10 to 12
Colby, KS	21	Oct. 8	Apr. 18	Apr 17	May 22	May 18	Jun. 27	Jun. 16
Range		−5 to 9	−17 to 19	−16 to 19	−14 to 14	−13 to 14	−8 to 12	−9 to 13
Durant, OK	74	Sep. 30	Mar. 9	Mar 9	Apr. 12	Apr. 8	May 21	May 9
Range		−3 to 4	−24 to 30	−24 to 30	−22 to 24	−21 to 24	−16 to 22	−18 to 20
Fort Collins, CO	30	Oct. 14	May 1	May 1	Jun. 5	Jun. 1	Jul. 13	Jul. 1
Range		−10 to 10	−24 to 12	−24 to 12	−25 to 8	−25 to 8	−18 to 9	−19 to 9
Rocky Ford, CO	28	Oct. 8	Apr. 14	Apr. 14	May 18	May 14	Jun. 25	Jun. 13
Range		−5 to 23	−20 to 14	−21 to 13	−20 to 17	−20 to 13	−15 to 16	−17 to 14
Shelton, NE	14	Oct. 9	Apr. 27	Apr. 26	May 29	May 25	Jul. 3	Jun. 22
Range		−4 to 4	−12 to 14	−12 to 15	−11 to 11	−11 to 11	−4 to 10	−7 to 10
Sidney, NE	23	Oct. 14	May 3	May 3	Jun. 6	Jun. 2	Jul. 13	Jul. 2
Range		−7 to 9	−13 to 17	−14 to 16	−14 to 12	−14 to 13	−7 to 9	−8 to 9
Sterling, CO	13	Oct. 10	Apr. 27	Apr. 26	May 31	May 27	Jul. 7	Jun. 26
Range		−5 to 3	−11 to 9	−10 to 10	−11 to 7	−11 to 7	−8 to 7	−9 to 8
Stratton, CO	19	Oct. 8	Apr. 21	Apr. 21	May 27	May 23	Jul. 3	Jun. 22
Range		−3 to 4	−10 to 16	−11 to 16	−10 to 11	−10 to 11	−7 to 10	−7 to 10
Walsh, CO	12	Oct. 6	Apr. 7	Apr. 7	May 14	May 10	Jun. 21	Jun. 9
Range		−5 to 4	−8 to 15	−8 to 14	−11 to 10	−11 to 10	−7 to 8	−9 to 9

region. Planned PhenologyMMS enhancements based on feedback from users and evaluation results include: (1) adding and validating more crops, (2) including more approaches for estimating thermal time (i.e., more temperature response functions), (3) adding vernalization and photoperiod factor submodels, (4) providing more variety choices, (5) enhancing the information system, and (6) having more historical weather data included with the software and provide options to change weather data for different possible environmental scenarios (e.g., hot and dry, cool and wet, etc.). To better quantify phenological responses to varying water deficits, PhenologyMMS is also being integrated into an existing crop growth model that has a mechanistic water balance submodel. The ultimate goal is to incorporate a simple water balance submodel into PhenologyMMS so that the default parameters are adjusted for water deficits between the two extremes.

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