

# Winter Wheat Phenology Simulations Improve when Adding Responses to Water Stress

Gregory S. McMaster, Debora A. Edmunds, Roger Marquez, Scott Haley, Gerald Buchleiter, Patrick Byrne, Timothy R. Green,\* Rob Erskine, Nathan Lighthart, Holm Kipka, Fred Fox, Larry Wagner, John Tatarko, Marc Moragues, and Jim Ascough II

## ABSTRACT

Phenology is critical in simulating crop production and hydrology and must be sufficiently robust to respond to varying environments, soils, and management practices. Phenological algorithms typically focus on the air temperature response function and rarely quantify the phenological responses to varying water deficits, particularly for versions of the Environmental Policy Integrated Climate model (EPIC)-based plant growth component used in many agroecosystem models. Three EPIC-based plant growth components (Soil Water Assessment Tool [SWAT], Wind Erosion Prediction System [WEPS], and the Unified Plant Growth Model [UPGM]) have been incorporated into the spatially distributed Agricultural Ecosystems Services model [AgES], and only the UPGM includes a phenological response to varying water deficits. These three plant components were used to evaluate the phenological responses of winter wheat (*Triticum aestivum* L.) to varying water deficits and whether having a water stress factor in UPGM improves the simulation of phenology. A 3-yr irrigation study and a 4-yr study across a rainfed landscape were used in the evaluation. Only the UPGM simulated all five of the developmental stages measured. The UPGM was the only component that simulated a phenological response to variable water deficits, resulting in better prediction of phenology. For example, the RMSE (days) and relative error (RE, days) decreased and index of agreement (d) increased in predicting maturity from SWAT (RMSE = 18.4; RE = 9.2; d = 0.34) to WEPS (RMSE = 6.2; RE = 1.0, d = 0.63) to the UPGM (RMSE = 6.1; RE = 0.1; d = 0.70). Incorporating phenological responses to varying water deficits improves the accuracy and robustness of predicting phenology, which is particularly important in spatially distributed agroecosystem models.

## Core Ideas

- Phenology is critical in accurately simulating crop production and hydrology.
- The AgES watershed model evaluated three EPIC-based plant growth components.
- Only UPGM was able to simulate phenological responses to varying water deficits.
- The results promote more robust simulation of phenology in varying environments.

Published in *Agron. J.* 111:1–11 (2019)

doi:10.2134/agronj2018.09.0615

Copyright © 2019 The author(s). Re-use requires permission from the publisher.

**S**PATIALLY DISTRIBUTED agroecosystem models simulate many biogeochemical processes across a landscape comprised of diverse land uses, environments, soils, and topography. Management practices also typically vary; for example, there are various irrigation strategies, ranging from full irrigation to dryland. The phenology component of these models is critical in accurately simulating crop production and hydrology for these various conditions.

Extensive phenological research has long-identified temperature (typically using air temperature) as the primary factor influencing plant development (e.g., McMaster, 1997; Reamur, 1735). Quantifying the temperature response has resulted in numerous thermal response functions used as the foundation of phenology algorithms. Models typically provide a default estimate of the thermal time (e.g., growing degree-days [GDD] and heat units) between developmental events. However, other environmental factors, such as water, light (photoperiod, quality, and intensity), nutrients, salinity, and CO<sub>2</sub>, have been shown to influence phenology (e.g., McMaster [1997] cites many references). These “secondary” factors are rarely considered in the phenology algorithms (notable exceptions are incorporating vernalization and photoperiod effects). Of particular concern is ignoring the clear impact of varying water deficits on phenology (e.g., Angus and Moncur, 1977; McMaster and Wilhelm, 2003; Singh et al., 1984). For instance, a nearly universal response among crops is delayed seedling emergence and shorter grain filling duration under water deficits (e.g., McMaster et al.,

G.S. McMaster, D.A. Edmunds, R. Marquez, G. Buchleiter, T.R. Green, R. Erskine, N. Lighthart, J. Ascough II, USDA–ARS, WMSRU, 2150 Centre Avenue Building D, Suite 320, Fort Collins, CO 80526; S. Haley, P. Byrne, M. Moragues, Dep. of Soil and Crop Sciences, Colorado State Univ., 1170 Campus Delivery, Fort Collins, CO 80523; H. Kipka, Dep. of Civil and Environmental Engineering, Colorado State Univ. 1170 Campus Delivery, Fort Collins, CO 80523; F. Fox, L. Wagner, J. Tatarko, USDA–ARS, RRSRU, 2150 Centre Ave. Building D, Fort Collins, CO 80526. Received 27 Sept. 2018. Accepted 21 Nov. 2018. \*Corresponding author (tim.green@usda.gov). Trade names, products, and varietal names are given for reference information only. USDA–ARS does not promote or otherwise recommend any particular commercial product.

**Abbreviations:** AgES, Agricultural Ecosystem Services; AI, anthesis irrigation; AS, anthesis start; DR, double ridge; DRY, dryland irrigation treatment; EPIC, Environmental Policy Integrated Climate model; FLC, flag leaf complete; FULL, full irrigation treatment; GDD, growing degree-day; GN, No-stress; GS, Stressed; JI, jointing irrigation treatment; JI+AI, jointing plus anthesis irrigation treatment; NOF, normalized objective function; RE, relative error; SWAT, Soil Water Assessment Tool; UPGM, Unified Plant Growth Model; WEPS, Wind Erosion Prediction System.

2008). One could hypothesize that incorporating phenological responses to varying water deficits would improve the accuracy and robustness of phenology algorithms.

To test this hypothesis, we evaluated the phenological responses of winter wheat to varying water deficits for three EPIC-based plant growth components incorporated into the spatially distributed Agricultural Ecosystems Services (AgES) model: the Soil Water Assessment Tool (SWAT), the Wind Erosion Prediction System (WEPS), and the Unified Plant Growth Model (UPGM). All three models used similar temperature response functions, with the UPGM adding a water stress response function.

## METHODS

### Model and Component Overviews

The AgES model (Cruz et al., 2017) was the platform used to run the SWAT, WEPS, and UPGM plant growth components. The AgES model is a modular, Java-based, spatially distributed hydrology/water quality agroecosystem model that implements hydrological processes as encapsulated in process-based modeling components (David et al., 2013). The hydrological routines of the AgES model (Ascough et al., 2012, 2015; Green et al., 2015) consist of modeling components for interception, snow accumulation and ablation, horizontal-differentiated soil water balance, groundwater balance, runoff generation, and explicitly computed lateral surface and subsurface flows, including flood routing in the watershed stream network. The nutrient transport modules evaluated in this study were adopted primarily from the SWAT watershed model, converted to Java for use in the European J2K-S model (Fink et al., 2007), and further modified for coupling to the AgES hydrologic components. The nutrient modules include components for simulating soil temperature, crop growth, and N turnover (Neitsch et al., 2009). Five different soil N pools are considered to allow modeling of different N inputs (e.g., inorganic fertilizer, organic manure) and N transformations between these pools. Nitrogen reduction, denitrification, volatilization, and plant uptake are modeled in conjunction with a dynamic crop growth module.

The EPIC plant growth component (Williams et al., 1989) from the Environmental Policy Integrated Climate model has been used as the foundation of many agroecosystem models including the SWAT (Arnold et al., 1995), WEPS (Wagner, 2013), and UPGM (McMaster et al., 2014) plant growth components incorporated into the AgES model and used in comparing their phenology algorithms in this paper. Whereas the SWAT model made few modifications to the EPIC plant growth component, considerable changes were made to the WEPS and UPGM to meet model purposes. All WEPS modifications were oriented toward better predictions of wind erosion, including (i) partitioning aboveground biomass to leaves, stems, and reproductive fractions (Retta et al., 1996, 2000); (ii) simulating plant shoot dynamics in much greater detail (shoot number, diameter, mass, and height) that respond to water stress; (iii) using partitioning to reproductive parts to determine yield (as opposed to the Harvest Index approach); and (iv) adding more phenological detail and incorporating a vernalization algorithm.

The WEPS plant growth component was restructured into FORTRAN 90/95 and was used as the platform for building the UPGM plant growth component (McMaster et al., 2014). Seedling emergence, canopy height, and phenology

algorithms that responded to varying amounts of water stress from PhenologyMMS (McMaster et al., 2011, 2013) and SHOOTGRO (McMaster et al., 1992; Wilhelm et al., 1993; Zalud et al., 2003) were incorporated into the UPGM. The FORTRAN 90/95 WEPS and UPGM plant growth components were incorporated into the Java-based AgES model, and the user selects the plant growth component to use in simulations. Recently, the WEPS and UPGM have been translated into Java to facilitate model maintenance and distribution.

Details for simulating phenology by the SWAT, WEPS, and UPGM are given in McMaster et al. (2014), but a general summary relevant to this paper follows. All phenology algorithms in the three models are based on using a thermal time approach. The SWAT and WEPS models use a similar temperature response function. Daily heat units (HU) are calculated as:

$$HU_i = T_{avg_i} - T_{base} \quad [1]$$

where  $T_{avg_i}$  is the average daily air temperature ( $^{\circ}\text{C}$ ) on day  $i$ , and  $T_{base}$  is the crop-specific base temperature ( $^{\circ}\text{C}$ ). All three models use  $0^{\circ}\text{C}$  for  $T_{base}$ . No growth occurs at or below  $T_{base}$ , and there is no upper temperature limit. Phenological development is viewed as a heat unit index (HUI) progressing from 0 (at planting) to 1 (physiological maturity for crops) and is determined by:

$$HUI_i = \frac{\sum_{j=\text{pdate}}^i HU}{THUM} \quad [2]$$

where HU is the sum of daily heat units from planting to current day ( $i$ ), and THUM is the crop-specific amount of heat units required from planting to maturity. For crops requiring vernalization, a delay is calculated and reduces the heat unit accumulation for the day.

Although the UPGM allows for selecting different temperature response functions, we used Method 1 (McMaster, 2009; McMaster and Wilhelm, 1997) to have the same temperature response function as shown in Eq. [1].

Crops have many developmental events, a number of which are not readily visible but are important (Fig. 1). The SWAT and WEPS models simulate only a few of these events. Both the SWAT and WEPS provide static default values that do not change with varying water deficits for (i) the number of heat units from planting to maturity, (ii) a 0 to 1 value for the proportion through the life cycle at which the canopy begins to senesce, and (iii) a 0 to 1 value for the proportion through the life cycle at which emergence occurs (WEPS only). The developmental event of jointing (J, when the first node is above the soil surface) (Large, 1954; Zadoks et al., 1974) was estimated in the WEPS as follows. The day that biomass partitioning to reproductive parts begins is assumed to be the double ridge (DR) stage (McMaster, 1997, 2005), and jointing occurs 180 GDD after DR (McMaster et al., 2005) (Fig. 1 and 2).

The UPGM explicitly simulates many of the developmental events shown in Fig. 1. Default thermal time estimates between developmental events for two extremes of water deficits, non-stressed (“No-Stress”, GN) and severely stressed (“Stressed”, GS), are provided for each crop. Nonstressed values would be for nonlimiting conditions such as full irrigation or high rainfall

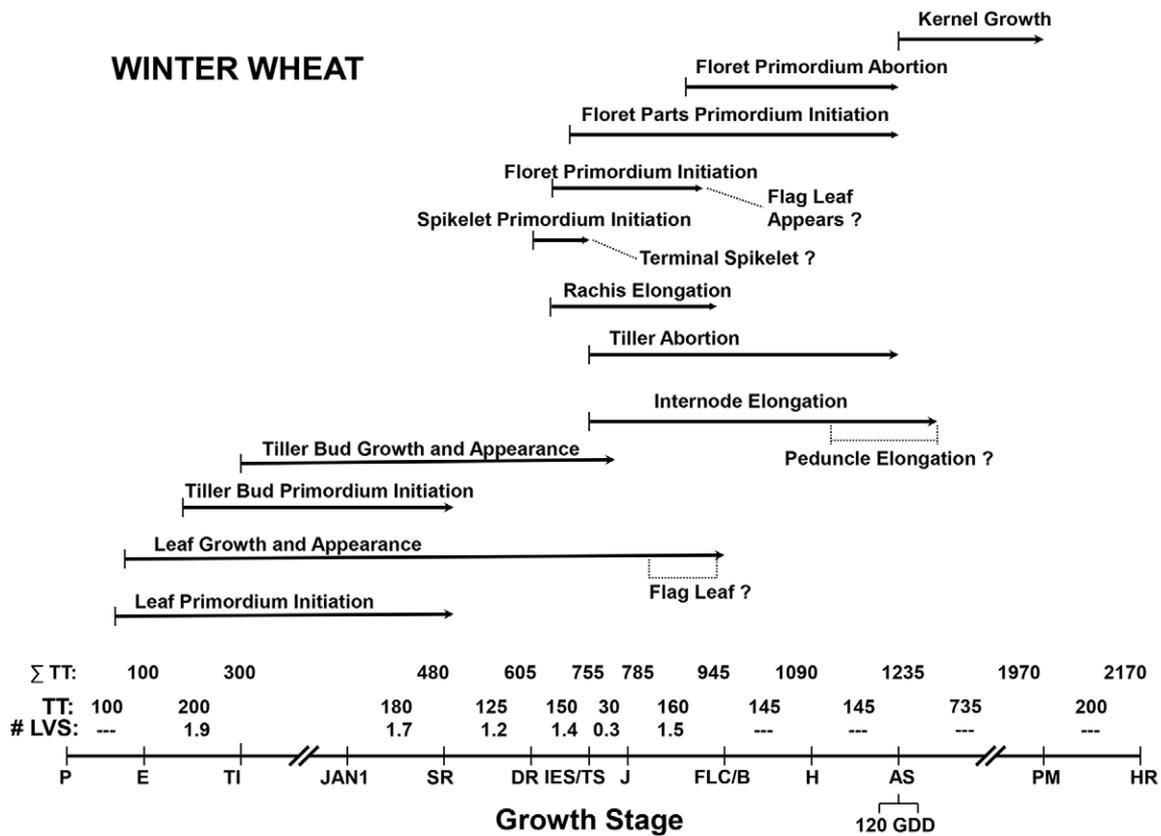


Fig. 1. Winter wheat shoot apex developmental sequence correlated with growth stages (Large, 1954) for conditions with no stresses. The time line is presented as thermal time (TT, in growing degree-days [GDD], using 0°C base temperature and Method I of McMaster and Wilhelm [1997]) and number of leaves (#LVS) for a generic medium-maturity variety used in the simulations. The “number of leaves” option after booting (B) is not meant to imply that more leaves are appearing; rather, it uses the phyllochron as the measure of thermal time. Question marks indicate areas of uncertainty or significant variation among cultivars or environments. See Fig. 3 for identification of growth stages on the time line. Adapted from McMaster et al. (2005)

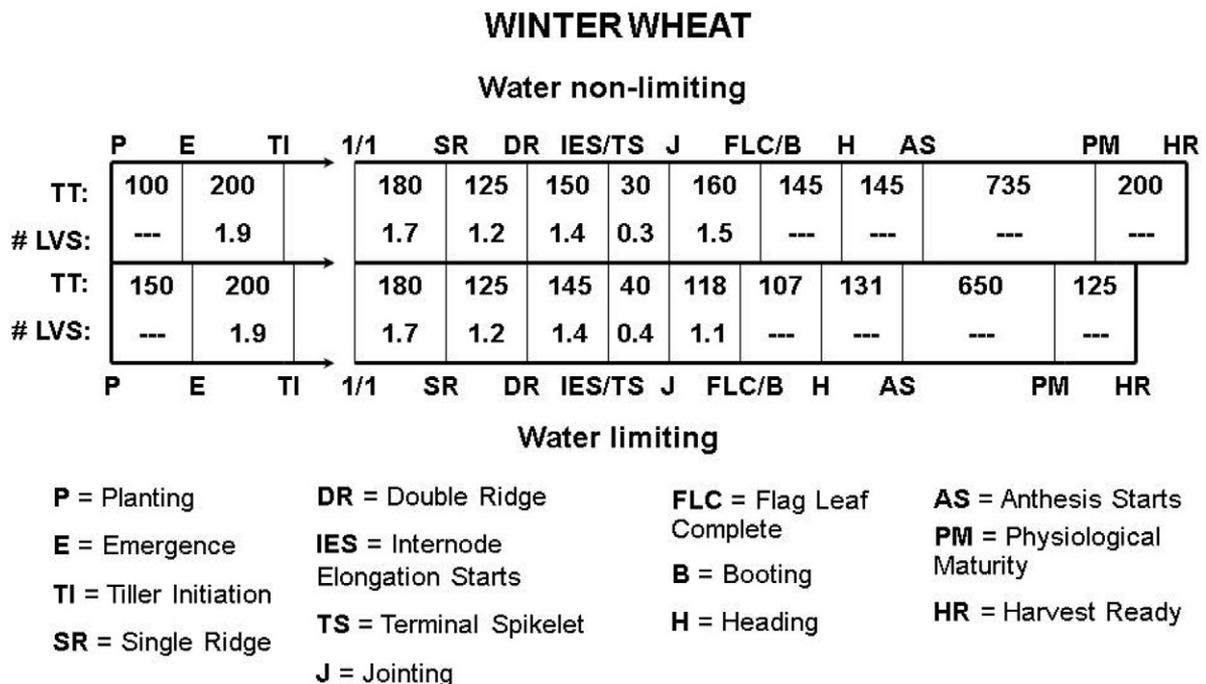


Fig. 2. Winter wheat phenology for both water nonlimiting (No-stress) and limiting (Stressed) conditions. Intervals between stages are shown as both thermal time (TT, in growing degree-days, using 0°C base temperature and Method I of McMaster and Wilhelm [1997]) and number of leaves (#LVS) for a generic medium-maturity variety used in the simulations. Adapted from McMaster et al. (2005).

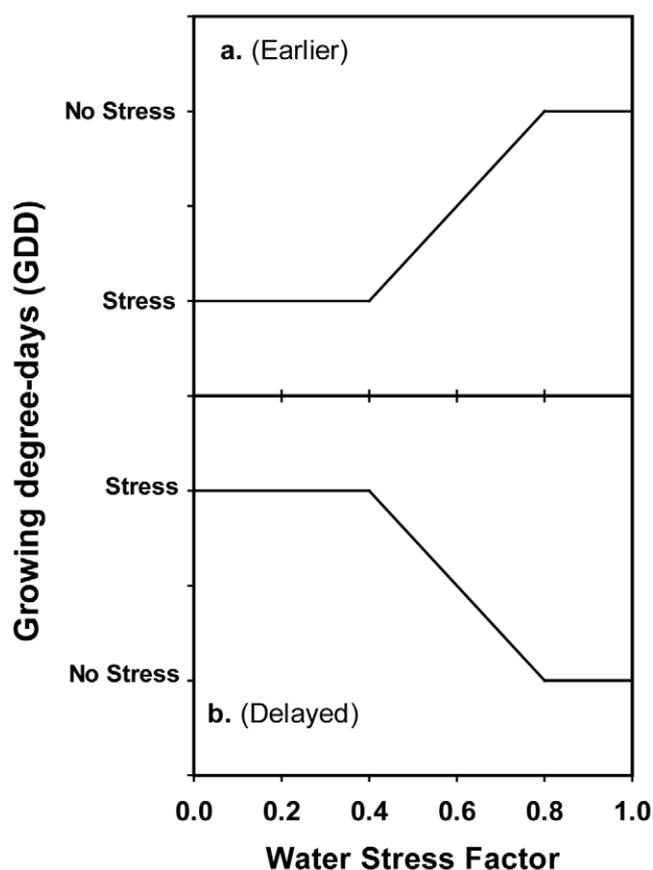


Fig. 3. Water stress response function used to adjust the growing degree-days (GDD) required to reach a developmental event as a function of water stress. Input values for nonlimiting water deficits (No-stress) or water-limiting deficits (i.e., just above permanent wilting point; Stress) are adjusted for intermediate 0–1 values of water stress. (a) Case where water stress results in the developmental event occurred earlier (i.e., fewer GDD required). (b) The opposite case where water stress delays the developmental event. Adapted from McMaster et al. (2013).

regions, and severely stressed values would be for extreme water deficits not leading to crop death (i.e., just above permanent wilting point) that can be found in drought years in semiarid environments (Fig. 2). For each crop, “No-Stress” and “Stressed” parameters are provided for early-, medium-, and late-maturity classes (or occasionally for crops such as corn by the number of days to maturity, e.g., 90-d, 100-d, etc.) as well as some specific varieties that the user can select.

We tested the UPGM for optimum/no-stress conditions for corn (McMaster et al., 2014) but not for conditions that were less than optimum. A water stress response curve from PhenologyMMS (McMaster et al., 2013) was used to adjust for varying water deficits (Fig. 3). A simple linear regression is used to interpolate between the default “No-Stress” and “Stressed” values. Threshold values for a water stress factor are set at 0.8, where plant water deficits above this are assumed to be not limiting, and at 0.4, below which no further adjustment to water deficits is expected.

### Experimental Data Sets

Two experimental data sets from semiarid northeastern Colorado were used in testing the SWAT, WEPS, and UPGM phenology models. Both data sets measured five developmental events: jointing (J; when the first node is above the soil surface),

flag leaf growth complete (FLC; flag leaf blade growth completed as measured by formation of the ligule on the flag leaf, which is the end of leaf appearance on a shoot), booting (B; defined to occur at FLC), heading (H; appearance of spike emerging from the flag leaf, not including awns), start of anthesis (AS; when the first anthers are visible in the spike), and physiological maturity (M; denoted by the absence of all green color in the spike and subtending peduncle) (Hanft and Wych, 1982). Further clarification on these developmental events can be found in Large (1954), McMaster (1997), and Zadoks et al. (1974).

The first data set was a 3-yr study (September 2008 to August 2011) conducted at the USDA–ARS Limited Irrigation Research Farm located near Greeley, CO (40° 26′ 57.13″ N; 104° 38′ 12.04″ W; 1427 masl). Soil texture at the site ranges from fine sandy loam to clay loam (mesic Usti Haplargids and mesic Aridic Arguistolls). Soils are comprised of aeolian material from Ogallala sediments and are deep and well drained.

Conventional pre-planting tillage consisted of disking (to ~10 cm depth) and roller-harrowing to prepare the seedbed. Based on soil tests, fertilizer was applied after disking and before roller harrowing to assure adequate plant nutrition for fully irrigated wheat production. Planting dates were 2 Oct. 2008, 6 Oct. 2009, and 8 Oct. 2010. Immediately after planting, sprinklers were used to apply 24, 25, and 43 mm of water in 2008, 2009, and 2010, respectively, to ensure emergence.

Each year, five irrigation treatments were randomly placed within three blocks per season. Twenty-four varieties were randomized within each irrigation treatment. Drip irrigation was used to precisely control the amount of water applied with minimal spatial variation. Irrigation generally did not begin until late March, shortly before the jointing stage. Irrigation treatments ranged from full irrigation (denoted “Full,” maintaining available soil water >75%) to dryland (denoted “Dry,” no irrigation). Three other irrigation treatments focused on alleviating water stress at the critical developmental stages of jointing and anthesis. The Jointing irrigation (JI) treatment brought the Dry conditions up to >80% available soil water, similarly for the Anthesis irrigation (AI) treatment. The fifth treatment was applying irrigation at both the jointing and anthesis developmental stages (JI+AI). The Dry, Full, JI, and AI treatments were done for all 3 yr; the JI+AI treatment was done for the first 2 yr. For the third year, a Full-low N treatment (half of the pre-plant fertilizer was applied, irrigated the same as for the Full treatment) replaced the JI+AI treatment. In this study, only the Full and Dry treatments were considered because we wanted to test the most extreme conditions in evaluating the phenological responses to varying water deficits.

Twenty-four varieties were observed that varied between hard red and white wheats, height classes, and maturity classes. We measured phenology data for 18 medium-maturity varieties (Above, Ankor, Avalanche, Baca, Bill Brown, BondCL, CO940610, Danby, Goodstreak, Hatcher, Jagalene, Keota, NuDakota, Platte, Prairie Red, RonL, Sandy, Yuma). Weather permitting, each plot was observed 3 d a week (typically Monday, Wednesday, and Friday), and the dates that the first shoots and when half of the shoots within a plot reached the developmental stage were recorded.

The second data set (denoted herein as Drake Farm) examined the spatial relationship across a landscape, taking advantage of the water routing capabilities of the AgES model. A

6-yr experiment was started in 2001 on a farm field (40.61N, 104.84W, 1559–1585 masl) located east of Fort Collins and west of Ault, CO. The field is approximately 100 ha with topographic undulations and soil variation (Green et al., 2009). Mapped soil units include Wagonwheel coarse silty-loam (mesic Aridic Ustorthents), Colby fine silty-loam (mesic Aridic Ustorthents), and Kim fine sandy-loam (mesic Ustic Torriorthents). Slopes at the phenology sites within the field vary from 0.65 to 8.4% ( $\text{m m}^{-1} \times 100\%$ ), and aspects range from 26 to 209 degrees clockwise from north. Data from the first 2 yr of the experiment are not included in this paper because the experiment was being established in 2001–2002 (planting year/harvest year) and in 2002–2003 the crop was lost due to drought.

A crop–fallow rotation was applied in approximately 120-m-wide strips across the field. Winter wheat was planted in autumn in the previous year’s fallow strips and harvested in summer of the following year. After harvest, the strips remained fallow until the second autumn (about 13–14 mo) before being replanted. Certified seed of the winter wheat cultivar Above (classified as medium-maturity) was planted at depths of 5 to 8 cm in alternating strips on 1 Oct. 2003, 23 to 27 Sept. 2004, 1 Oct. 2005, and 3 Nov. 2006.

Terrain attributes were computed from a 5-m grid digital elevation model. Raw elevation data were collected at 5-m spacing using a Trimble (Trimble Navigation Limited) survey-grade global positioning system. Erskine et al. (2006, 2007) described the data acquisition and interpolation onto a 5-m grid with a cross-validation error of 0.03 m for elevation. The terrain attributes were assessed for the mean of the 5-m attributes over the 30 × 30 m site area for each landscape position.

The AgES model requires the delineation of the landscape into “homogenous” hydrologic response units for spatial routing of water. Delineation based on land surface topography and crop management boundaries was performed using an AML tool, WDAML (Watershed Delineation in ARC Macro Language), as described in Green et al. (2014). This delineation resulted in 27 hydrologic response units within a 56-ha watershed containing the sample sites and draining to an outlet at the east edge of the field. Various AgES model soil and hydrologic input parameters were calibrated to observed soil moisture and runoff using a shuffled complex evolution calibration tool, Luca (Hay and Umemoto, 2006), which is included with the AgES model.

Ten 30 × 30 m sites were established each growing year from 2003–2004 through 2006–2007, with 2003–2004 and 2005–2006 having the same sites and 2004–2005 and 2006–2007 having the same sites. In each area, half of the 10 sites were located in one cropped strip and half were in a separate cropped strip. Phenology was observed over time at two locations within each 30 × 30 m site. Sites were chosen to sample a range of various terrain attributes such as slope, aspect, elevation, specific contributing area, and soil type. The field is representative of topographically undulating landscapes in eastern Colorado, but not all fields in the region have this much relief (~13% slope), so flatter fields are expected to display lesser topographic effects on phenology.

Wheat emergence and developmental stages for 4 yr beginning autumn 2003 were sampled at each of 10 landscape positions/sites per growing season. To measure the developmental stages, subsamples at two locations were made that were representative of the mean plant growth within each site just prior

to the jointing stage. For each subsample, 10 individual main shoots were tagged along 1 m of a cropped row. These tagged shoots were repeatedly observed (weather permitting, 3 d a week), and the day of year each main stem was first observed to have reached a developmental stage was recorded. The mean day of year of the 20 main stems was used to estimate when the developmental stage was reached.

Air temperatures were recorded every half hour at each of the 10 sites during the growing season. One thermocouple temperature probe (Water Temp Pro v. 1, Onset Computer Corporation) was installed at the center of each 30 × 30 m site for above-canopy air temperature. The sensor was placed at a 1-m height above the soil surface and maintained at this height regardless of the canopy height, which for our variety and environments was always less than the sensor height. Further details for this experiment can be found in McMaster et al. (2012).

### Model Runs and Evaluation Statistics

All model runs were made using default crop parameters for several reasons. Running spatially distributed agroecosystem models (e.g., AgES, SWAT, APEX) in watersheds must address simulating diverse environments, management practices (e.g., irrigation, fertilizers, tillage), soils, and land uses (e.g., different crops and varieties). Parameter calibration, or adjustment, is complex and time consuming even if the user has the knowledge, time, and interest to do so. Using default parameters would address the primary objective of determining whether adding a water stress response function to similar thermal-based phenology algorithms would increase model accuracy and robustness over a wide range of conditions. For the UPGM, (i) default phenology parameters for the medium-maturity class were used, and (ii) initial soil water at planting for the seedbed zone was set to “Optimum” for determining germination and emergence in both data set runs. Optimum for the Greeley data set runs seemed appropriate because sprinkler irrigation occurred immediately after planting. For the Drake Farm data set runs (dryland conditions), soil water at planting varied both spatially within the year and among years, making it unclear which category to choose. We did runs using “Medium,” and the results on phenology were essentially unaffected from optimum.

Four statistical evaluation criteria were used to assess model performance: RMSE, relative error (RE), index of agreement (d), and normalized objective function (NOF). The RMSE was calculated by:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \quad [3]$$

where  $P_i$  is the  $i$ th predicted value,  $O_i$  is the  $i$ th observed value, and  $n$  is the number of data pairs.

Relative error was expressed in percent as:

$$\text{RE} = \frac{(\bar{P} - \bar{O})}{\bar{O}} 100 \quad [4]$$

where  $\bar{P}$  is the predicted mean, and  $\bar{O}$  is the observed mean. Relative error is the measure of the mean tendency of the simulated values to be larger or smaller than the observed values.

Table 1. Weather and irrigation data for Greeley, CO, experiment. Long-term weather data are from 3 Mar. 1992 through 14 Aug. 2018. Weather data are given for different intervals related to seasons or periods for developmental stages. All irrigation was by drip irrigation, except all treatments were sprinkler irrigated immediately after planting to ensure emergence (24, 25, and 43 mm for 2008–2009, 2009–2010, and 2010–2011, respectively). Drip irrigation did not begin until “spring” (near jointing).

Period	2008–2009			2009–2010			2010–2011			Long-term mean	
	T <sub>avg</sub> †	Prec†	Irri†	T <sub>avg</sub>	Prec	Irri	T <sub>avg</sub>	Prec	Irri	T <sub>avg</sub>	Prec
	°C	mm		°C	mm		°C	mm		°C	mm
Year (1 Sept.–31 Aug.)	9.0	349	257	8.5	354	290	9.7	235	374	9.4	266
Growing season (1 Sept.–30 June)	6.7	234	257	5.7	270	264	6.9	169	374	6.9	195
Postvernalization (1 Jan.–30 June)	7.4	173	233	6.7	229	247	6.5	146	330	7.2	139
Autumn (1 Sept.–31 Dec.)	5.6	61	24	4.1	40.9	17	7.5	23	43.3	6.3	56
Winter (1 Jan.–31 Mar.)	1.3	5	27	−0.2	14.5	0	−0.3	7	69.4	0.2	17
Spring (1 Mar.–31 May)	8.9	85	233	8.4	141.5	97	8.6	124	190	9.2	99
Grain filling (1 May–30 June)	16.4	119	154	16.2	130.6	206	15.6	118	207	17	88

† Values are average temperature (T<sub>avg</sub>), cumulative precipitation (Prec), and irrigation for the Full treatment (Irri) for the period covered.

Values of 0 indicate no bias, positive values indicate a bias of the model overestimating the observed values, and negative values indicate a tendency to underestimate observed values.

The index of agreement (*d*) was calculated as:

$$d = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (|P_i| + |O_i|)^2}, 0 \leq d \leq 1 \quad [5]$$

where  $P_i$ ,  $O_i$ , and  $n$  are as previously defined;  $P'_i = P_i - \bar{O}$  and  $O'_i = O_i - \bar{O}$ , where  $\bar{O}$  is as previously defined; and the enclosing bars (| |) indicate absolute values. A *d* value of 1 indicates complete agreement between model predictions and observations; a *d* value of 0 indicates no relationship.

The NOF was calculated as:

$$\text{NOF} = \frac{\text{RMSE}}{\bar{O}} \quad [6]$$

where RMSE and  $\bar{O}$  are as previously defined. The NOF is a relative value to compare model performance for different data sets. When NOF = 0, there is a perfect fit between observed and simulated values, and values <1 may be viewed as having a simulation error of <1 SD around the experimental mean.

## RESULTS

The two experimental data sets provided a range of water deficits for evaluating the phenology algorithms of the three models. The Greeley data set allowed for a direct comparison between two

different water stress levels each year. The Full irrigation treatment attempted to keep available soil water above 75%, beginning just prior to the Jointing developmental stage through maturity. The Dryland treatment varied in total precipitation considerably among the 3 yr for the growing season (1 September–30 June), with the 2010–2011 period having the lowest precipitation (169 mm) when compared with 2008–2009 (234 mm) and 2009–2010 (270 mm; Table 1). Both 2008–2009 and 2009–2010 were above the long-term mean (195 mm). When combining precipitation with irrigation applied to the Full treatment, 2010–2011 had the greatest difference between the Full and Dry treatments (257, 264, and 374 mm for 2008–2009, 2009–2010, and 2010–2011, respectively). The 2010–2011 period also had the highest mean air temperature (6.9°C) when compared with 2008–2009 (6.7°C) and 2009–2010 (5.7°C), although it was equal to the long-term mean (6.9°C). Precipitation and air temperature also varied considerably during each year, particularly for the grain filling period (1 May–30 June).

The Drake Farm dryland data set provided a spatial dimension in a landscape that differed in soil water and precipitation among years (Table 2) (Green and Erskine, 2011). For the growing season (1 September–30 June), only the 2004–2005 period was above the long-term precipitation (321 and 265 mm, respectively), and much of this was due to 66 mm of rain occurring from 2 June through 4 June 2005. As with the Greeley data set, precipitation and air temperature also varied considerably during each year.

Observed data were available for five developmental stages: jointing (J), flag leaf growth complete/beginning of booting (FLC), heading (H), start of anthesis (AS), and physiological

Table 2. Weather data for the Drake Farm, CO, experiment. Long-term weather data are for all years collected at the study site (1 Jan. 2002–31 July 2018). Weather data are given for different intervals related to seasons or periods for developmental stages. Updated from McMaster et al. (2012).

Item	2003–2004 (Area 1)		2004–2005 (Area 2)		2005–2006 (Area 1)		2006–2007 (Area 2)		Study site	
	T <sub>avg</sub> †	Prec†	T <sub>avg</sub>	Prec	T <sub>avg</sub>	Prec	T <sub>avg</sub>	Prec	T <sub>avg</sub>	Prec
	°C	mm	°C	mm	°C	mm	°C	mm	°C	mm
Year (1 Sept.–31 Aug.)	9.6	232	9.9	340‡	10.3	194	9.2	277	9.7	342
Growing season (1 Sept.–30 June)	7.5	163	7.4	321‡	8.0	155	6.4	179	7.2	265
Postvernalization (1 Jan.–30 June)	7.7	136	7.5	234‡	8.1	65	6.9	106	7.3	183
Autumn (1 Sept.–31 Dec.)	7.2	27	7.3	87	7.8	90	5.7	73	7.0	77
Winter (1 Jan.–31 Mar.)	1.9	21	1.9	45	1.0	28	0.1	45	1.0	38
Spring (1 Mar.–31 May)	10.3	63	8.5	120	8.9	56	9.6	86	8.7	129
Grain filling (1 May–30 June)	15.9	88	15.6	144‡	17.9	28	16.7	41	16.2	105

† Values are average temperature (T<sub>avg</sub>) and cumulative precipitation (Prec).

‡ June precipitation = 105.8 mm

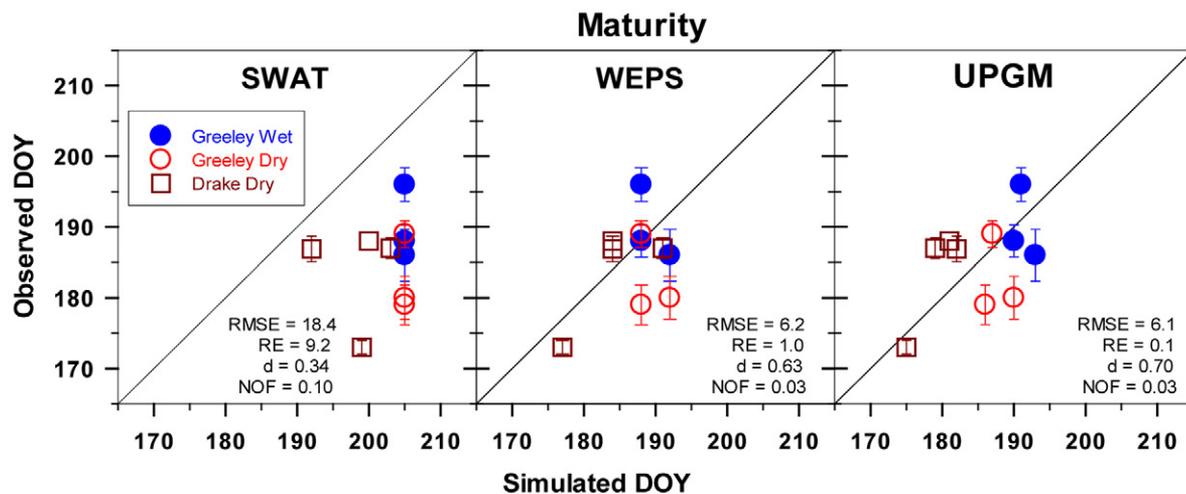


Fig. 4. Simulation of physiological maturity using default parameters. Greeley Wet is for Full irrigation treatment, Greeley Dry is for the dryland irrigation treatment, and Drake Dry is for the Drake Farm dryland experiment. Standard deviation bars for observed data are shown. *d*, index of agreement; DOY, day of year; RE, relative error; NOF, normalized objective function.

maturity (M) as described previously. All three plant growth components simulated the start of canopy senescence and M. Estimates of J were possible from the WEPS, and only the UPGM explicitly simulated all five developmental stages. The simulated phenological response to varying water deficits by the three models was evaluated using default crop parameters.

The SWAT, WEPS, and UPGM plant growth components simulated the end of crop growth associated with maturity (Fig. 4). Based on the model evaluation statistics, the WEPS and the UPGM were quite similar, and both models more accurately simulated M than SWAT. This difference was largely due to the default parameter for simulating M in SWAT being too high, resulting in a much later simulated date than the observed date. As expected, only the UPGM could simulate maturity differences observed among the Full and Dry treatments of the Greeley data set (resulting in UPGM having a lower RE).

All three plant growth components also simulated the start of leaf senescence, although the comparison was confounded

by how this stage is defined (Fig. 5). Both WEPS and SWAT have a parameter setting the time through the life cycle that “leaf” senescence begins (i.e., meaning when the canopy leaf area index starts to decline and ignoring the senescence of the earliest leaves). The UPGM simulates the stage when the flag leaf completes its growth (FLC), which is when the canopy leaf area index should start to decline because no more leaves appear and older leaves are senescing. Regardless, both the SWAT and WEPS started leaf senescence much later than the observed date of FLC, suggesting the default parameters were set too late. When comparing the overall models, the model evaluation statistics indicate that model accuracy improved from the SWAT to the WEPS to the UPGM. The UPGM showed a slight response to water deficits in the Greeley treatments (FLC was only measured for 2 of the 3 yr), which matched the very slight difference in the observed dates.

Only the UPGM was able to explicitly simulate the jointing developmental stage. The SWAT model provided no means to

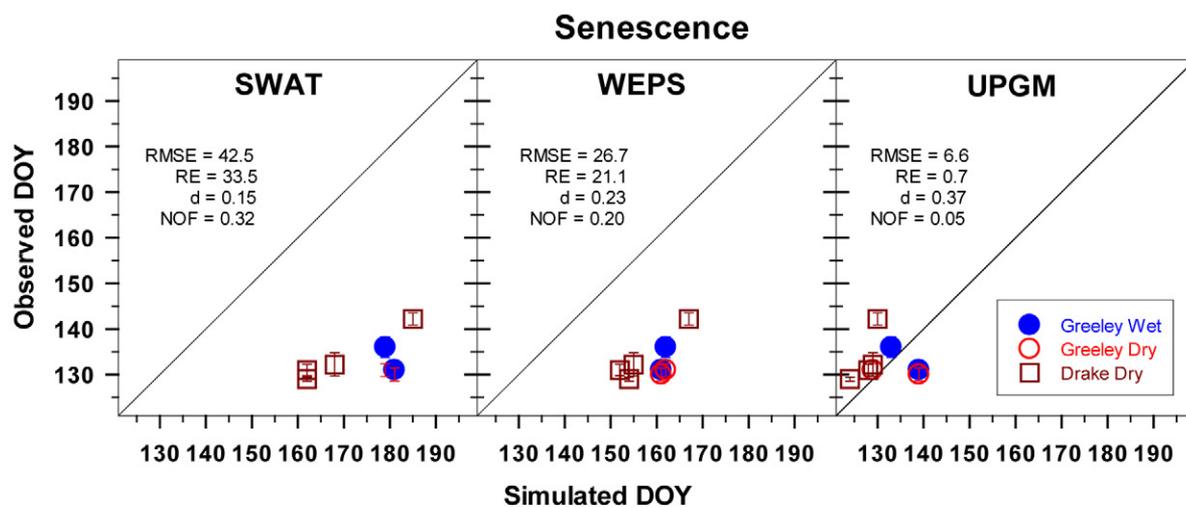


Fig. 5. Simulation of the start of canopy leaf senescence (i.e., decline in canopy leaf area index) using default parameters. Greeley Wet is for Full irrigation treatment (only observed data for 2008–2009 and 2010–2011), Greeley Dry is for the dryland irrigation treatment (only observed data for 2008–2009 and 2010–2011), and Drake Dry is for the Drake Farm dryland experiment. Start of canopy senescence was determined by the first day of decline in leaf biomass in the Soil Water Assessment Tool (SWAT) model and the Wind Erosion Prediction System (WEPS), and flag leaf growth complete (end of leaf appearance and growth) in the Unified Plant Growth Model (UPGM). Standard deviation bars for observed values are shown. *d*, index of agreement; DOY, day of year; RE, relative error; NOF, normalized objective function.

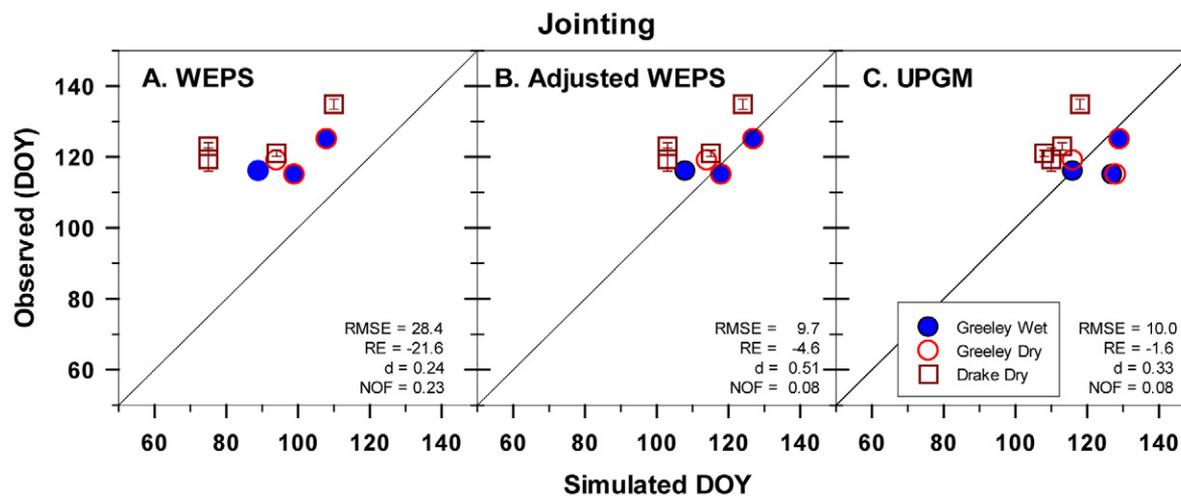


Fig. 6. Simulation of jointing. Greeley Wet is for the Full irrigation treatment, Greeley Dry is for the dryland irrigation treatment, and Drake Dry is for the Drake Farm dryland experiment. Only the Unified Plant Growth Model (UPGM) explicitly simulates the jointing growth stage. To estimate when jointing would be simulated by the Wind Erosion Prediction System (WEPS), the date of the beginning of reproductive biomass simulated by WEPS was assumed to be the double ridge stage for wheat. Because J occurs 180 GDD after the DR stage, it could then be estimated by the WEPS. No estimate of jointing was possible for the Soil Water Assessment Tool (SWAT) model. The Greeley observed data for jointing had a very small SD and error bars are therefore not shown. *d*, index of agreement; DOY, day of year; RE, relative error; NOF, normalized objective function.

estimate when J would be simulated; however, we were able to estimate jointing in the WEPS model as follows. The WEPS simulates the beginning of biomass partitioning to reproductive structures, which in the case of winter wheat would be approximately the DR developmental stage (McMaster, 1997, 2005). Jointing occurs approximately 180 GDD after DR (McMaster et al., 2005) (Fig. 1 and 2) and was added to the date of the beginning of biomass partitioning to reproductive structures (Fig. 6A) to estimate J (Fig. 6B). Both WEPS and UPGM simulated J equally well, although the UPGM model captured the slight difference between the Full and Dry treatments in the Greeley experiment better than WEPS.

The UPGM model explicitly simulates many additional developmental stages not considered in SWAT or WEPS, including the important developmental events of heading and start of anthesis shown in Fig. 7, for which we had observed data. Anthesis is particularly important because grain set occurs at this time when partitioning to stem biomass is ending and significant partitioning to seeds begins. The UPGM captures differences between the Full and Dry treatments in the Greeley experiment observed for both H and A.

In simulating the five developmental stages by UPGM (Fig. 7), model accuracy increased and RE is decreased as maturity is approached. This pattern can partly be explained by the observed difference between the Full and Dry treatments in the Greeley experiment increasing from the J stage (essentially no difference) to M (the Dry treatment occurring significantly earlier). Adding the water response function shifted the simulated Dry points for each year closer to the 1–1 line.

## DISCUSSION

All three EPIC-based plant growth components use a similar thermal time approach in simulating maturity. The SWAT and WEPS models provide static default input phenology parameters based on thermal time that do not respond to varying water deficits. It would seem likely that the accuracy and robustness

of simulating phenology across widely varying environments, such as fully irrigated to dryland treatments in a semiarid environment, would increase if a water stress response function was incorporated to alter the static default parameters for varying water deficits. Comparing the UPGM plant growth component that incorporates a water stress response function with the SWAT and WEPS plant growth components supported this expectation. The UPGM predicted the developmental stages of J, the start of canopy senescence, and M as well or better than the WEPS and was always better than SWAT. Most importantly, the UPGM was more robust because it could simulate appropriately the phenological responses to varying water deficits across a landscape or irrigation level.

Questions could arise whether the increased robustness by adding water stress responses comes at the cost of more parameters and whether it improves determining default parameters. To partially address these issues, consider the prediction of maturity. The WEPS and SWAT models require one parameter for the thermal time from planting to maturity, whereas the UPGM requires two parameters (the GN and GS values). Although the UPGM has an additional parameter, determining the second parameter involves little additional work. No additional parameters are required for the water stress response function. The disadvantage of using a single parameter in the SWAT and the WEPS is determining what the single default values should be. Should it be for optimal conditions (e.g., irrigated/high precipitation), extremely dry conditions (e.g., dryland/low precipitation), or somewhere in between? Regardless, there will be no response to varying water deficits.

The UPGM also explicitly simulates the response of many developmental stages to varying water deficits that are not simulated in the SWAT and WEPS models. We were able to evaluate two additional developmental stages with our observed data (H and AS). A general trend was found where accuracy increased and RE decreased as developmental stages approached maturity. The robustness in simulating the phenological responses to water

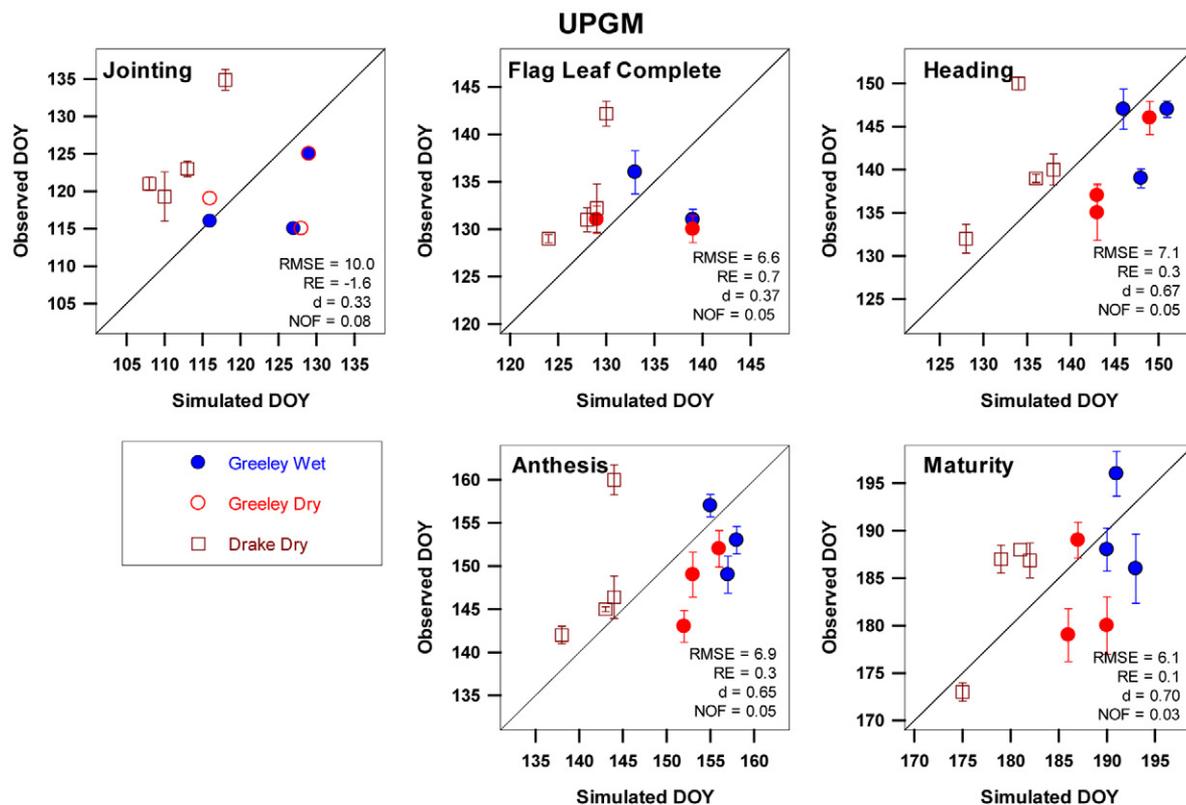


Fig. 7. Simulation of five developmental stages by the Unified Plant Growth Model (UPGM) using default parameters. Greeley Wet is for the Full irrigation treatment, Greeley Dry is for the dryland irrigation treatment, and Drake Dry is for the Drake Farm dryland experiment. Standard deviation error bars are shown for observed data. The Greeley observed data for jointing had a very small SD and are therefore not shown. The simulated date of the beginning of reproductive biomass by Wind Erosion Prediction System (WEPS), which was assumed to be the double ridge stage for wheat. McMaster et al. (2005) estimate that 180 growing degree-days occur from double ridge to jointing, and this value was used. *d*, index of agreement; DOY, day of year; RE, relative error; NOF, normalized objective function.

deficits of many developmental events is necessary for models, such as AgES, used in simulating crop production in a watershed addressing variable management practices for the same crop (e.g., dryland or irrigation) or varying spatial soil water based on soil characteristics and routing across the landscape.

Several possible enhancements were identified to improve the UPGM phenology component. Although the algorithm captured phenological responses to varying water deficits in this study with no adjustments to default parameters or to the algorithm, the water stress function incorporated from PhenologyMMS (Fig. 3) has not been rigorously tested for any crop. The water stress function has much uncertainty, with the threshold values somewhat arbitrarily set to 0.4 and 0.8 and a simple linear regression used to interpolate between the No-Stress and Stressed values. This function should be tested for a wide range of water deficits.

Implementing the water stress function into a model can be done in several ways. As currently implemented in AgES, we used the PhenologyMMS approach (McMaster et al., 2013), where the GDD required to reach the next stage is estimated daily using a linear regression to interpolate between the No-Stress and Stressed values. Sudden shifts in the environment (e.g., a significant rainstorm or an irrigation event) could reset the value to no-Stress even if drought was severe during the interval and near the Stressed value. We did not examine how often this occurred in our simulations of the Greeley Dry treatment and the Drake Farm dryland sites. If this is determined to

be a problem, one solution might be to use a running 5-d average of the water stress index as done in the SHOOTGRO model (McMaster et al., 1992; Wilhelm et al., 1993; Zalud et al., 2003). Another option is to use the water stress function to adjust the daily calculated GDD before accumulating to the required no-Stress value. Given the overall uncertainty in the water stress function and how to implement it into a model, working on these improvements may not lead to simulating phenology more accurately in complex spatially distributed models such as AgES.

All phenology components are challenged with determining the input parameters for the number of GDD between developmental events for various reasons. In UPGM, the No-Stress (for optimal water) and Stressed (above permanent wilting point values) default parameters for the GDD between successive developmental stages are difficult to measure under field conditions. It is difficult to maintain optimum or near-permanent wilting point water conditions for the full life cycle of the plant, and dryland treatments are affected by highly variable rainfall. As a result for our data set, the No-Stress values probably should be greater and the Stress values less than the default parameters.

Differences in parameters and their response to varying water deficits among genotypes are also well known. The SWAT and WEPS models provide default parameters for a “generic” crop, although it is not clear for what environmental conditions these apply (e.g., whether it is for irrigated/high rainfall or dryland in a semiarid environment). The user is able to change these default parameters to better match the environment and genotype they

are simulating, but little information on the range of values for a particular environment are provided. The UPGM provides parameters for the phenological responses to varying water deficits, thereby allowing the user to avoid the need to do this. In addition, the UPGM provides default parameters for each crop based on general classifications for maturity grouping common for most crops. For instance, corn is often classified into 100-d, 105-d, etc. maturity groups, and wheat is often ranked from early to late maturity classes. In the case of wheat, we provide default parameters for early-, medium-, and late-maturity classes as well as some specific varieties.

Although the approach used in the UPGM alleviates some problems with phenology parameterization, a major obstacle remains regarding how to parameterize the vast number of existing genotypes for a crop and the continued release of new genotypes. For several decades, considerable research (mostly on the flowering stage) has shed light on the genetic pathways controlling development (e.g., Brown et al., 2013; McMaster and Moragues, 2018) and genotype differences related to drought tolerance (e.g., Grogan et al., 2016a, 2016b). Numerous efforts have explored the hope that a priori setting of parameters using specific genes/alleles might avoid the prohibitively expensive phenotyping of numerous genotypes (e.g., Brown et al., 2013; Uptmoor et al., 2017; Welch et al., 2003; White and Hoogenboom, 2003).

Work is underway to take advantage of the ability of UPGM to explicitly simulate the response of many developmental events to varying water stress in models such as AgES and WEPS by better identifying the timing and activity of sources and sinks to improve aboveground partitioning (Fig. 1). For example, processes in SWAT and WEPS, such as the start of canopy senescence or partitioning to leaf, stem, and reproductive parts (WEPS only; Retta et al. [1996, 2000]) occur based on a static 0–1 input parameter representing the simulated proportion through the life cycle from planting/emergence to maturity. We are testing whether setting/adjusting the partitioning coefficients to leaves, stems, and reproductive plant fractions based on specific developmental stages that respond to varying water deficits will improve UPGM simulations of yield, biomass, and other plant traits.

## CONCLUSIONS

The UPGM simulations were more accurate and had less relative error than SWAT or WEPS plant growth components with similar thermal time algorithms for predicting phenology. A primary reason was adding a water stress response function to UPGM within the AgES distributed watershed model. The UPGM explicitly simulated many more developmental events than the SWAT or WEPS models, providing opportunities for more clearly identifying sources and sinks present throughout the life cycle and enhancing partitioning algorithms. These results infer more robust spatial simulation of plant growth with water and air temperature feedback in models such as AgES.

## ACKNOWLEDGMENTS

Many people have contributed in many ways to the modeling and experimental work leading to this paper. We particularly wish to acknowledge the contributions of Drs. James C. Ascough II and Marc Moragues, whose lives ended much too early. The USDA is an equal

opportunity provider and employer. Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation of endorsement by the USDA.

## REFERENCES

- Angus, J.F., and M. Moncur. 1977. Water stress and phenology in wheat. *Aust. J. Agric. Res.* 28:177–181. doi:10.1071/AR9770177
- Arnold, J.G., M.A. Wertz, E.E. Alberts, and D.C. Flanagan. 1995. Plant growth component. In: D.C. Flanagan, M.A. Nearing, and J.M. Lafflen, editors, *USDA-Water Erosion Prediction Project: Hillslope profile and watershed model documentation*, NSERL Report No. 10. USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, IN. p. 8.1–8.41.
- Ascough II, J.C., O. David, P. Krause, G.C. Heathman, S. Kralisch, M. Larose, L.R. Ahuja, and H. Kipka. 2012. Development and application of a modular watershed-scale hydrologic model using the Object Modeling System: Runoff response evaluation. *Trans. ASABE* 55(1):117–135. doi:10.13031/2013.41260
- Ascough, J.C., II, T.R. Green, O. David, H. Kipka, and G.S. McMaster. 2015. The spatially-distributed AgroEcoSystem-Watershed (AgES-W) hydrologic/water quality (H/WQ) model for assessment of conservation effects. In: *Proceedings AGU Hydrology Days*, Fort Collins, CO. 23–25 Mar. 2015.
- Brown, H.E., P.D. Jamieson, I.R. Brooking, D.J. Moot, and N.I. Huth. 2013. Integration of molecular and physiological models to explain time of anthesis in wheat. *Ann. Bot.* 112:1683–1703. doi:10.1093/aob/mct224
- Cruz, P.P.N., T.R. Green, R.O. Figueiredo, A.S. Pereira, H. Kipka, S.I. Saad, J.M. Silva, and M.A.F. Gomes. 2017. Hydrological modeling of the Ribeirão das Posses: An assessment based on the Agricultural Ecosystem Services (AgES) watershed model. *Ambiente Agua* 12:351–364. doi:10.4136/ambi-agua.2073
- David, O., J.C. Ascough, II, W. Lloyd, T.R. Green, K.W. Rojas, G.H. Leavesley, and L.R. Ahuja. 2013. A software engineering perspective on environmental modeling framework design: The Object Modeling System. *Environ. Model. Softw.* 39:201–213. doi:10.1016/j.envsoft.2012.03.006
- Erskine, R.H., T.R. Green, J.A. Ramirez, and L.H. MacDonald. 2006. Comparison of grid-based algorithms for computing upslope contributing area. *Water Resour. Res.* 42:W09416. doi:10.1029/2005WR004648
- Erskine, R.H., T.R. Green, J.A. Ramirez, and L.H. MacDonald. 2007. Digital elevation accuracy and grid cell size: Effects on estimated terrain attributes. *Soil Sci. Soc. Am. J.* 71:1371–1380. doi:10.2136/sssaj2005.0142
- Fink, M., P. Krause, S. Kralisch, U. Bende-Michl, and W.-A. Flügel. 2007. Development and application of the modelling system J2000-S for the EU-Water Framework directive. *Adv. Geosci.* 11:123–130. doi:10.5194/adgeo-11-123-2007
- Green, T.R., G.H. Dunn, R.H. Erskine, J.D. Salas, and L.R. Ahuja. 2009. Fractal analyses of steady infiltration and terrain on an undulating agricultural field. *Vadose Zone J.* 8:310–320. doi:10.2136/vzj2008.0021
- Green, T.R., R.H. Erskine, J.C. Ascough, II, B. Vandenberg, B. Pfennig, H. Kipka, O. David, and M.L. Coleman. 2014. AgroEcoSystem-Watershed (AgES-W) model delineation and scaling. In: D.P. Ames, N.W.T. Quinn, and A.E. Rizzoli, editors, *Proceedings of the 7th International Congress on Environmental Modelling and Software*, San Diego, CA, 15–19 June 2014.
- Green, T.R., and R.H. Erskine. 2011. Measurement and inference of profile soil-water dynamics at different hillslope positions in a semiarid agricultural watershed. *Water Resour. Res.* 47:W00H15. doi:10.1029/2010WR010074

- Green, T.R., R.H. Erskine, M.L. Coleman, O. David, J.C. Ascough, and H. Kipka. 2015. The AgroEcoSystem (AgES) response-function model simulates layered soil-water dynamics in semi-arid Colorado: Sensitivity and calibration. *Vadose Zone J.* 14. doi:10.2136/vzj2014.09
- Grogan, S.M., J. Anderson, P.S. Baenziger, K. Frels, M.J. Guttieri, S.D. Haley, et al. 2016a. Phenotypic plasticity of winter wheat heading date and grain yield across the U.S. Great Plains. *Crop Sci.* 56:2223–2236. doi:10.2135/cropsci2015.06.0357
- Grogan, S.M., G. Brown-Guedira, S.D. Haley, G.S. McMaster, S.D. Reid, J. Smith, and P.F. Byrne. 2016b. Allelic variation in developmental genes and effects on winter wheat heading date in the U.S. Great Plains. *PLoS One* 11(4):e0152852. doi:10.1371/journal.pone.0152852
- Hanft, J.M., and R.D. Wych. 1982. Visual indicators of physiological maturity of hard red spring wheat. *Crop Sci.* 22:584–587. doi:10.2135/cropsci1982.0011183X002200030036x
- Hay, L.E., and M. Umemoto. 2006. Multiple-objective stepwise calibration using Luca. Open-File Rep. 2006-1323. USGS, Reston, VA.
- Large, E.C. 1954. Growth stages in cereals. *Plant Pathol.* 3:128–129. doi:10.1111/j.1365-3059.1954.tb00716.x
- McMaster, G.S. 1997. Phenology, development, and growth of the wheat (*Triticum aestivum* L.) shoot apex: A review. *Adv. Agron.* 59:63–118. doi:10.1016/S0065-2113(08)60053-X
- McMaster, G.S. 2005. Centenary reviews: Phytomers, phyllochrons, phenology and temperate cereal development. *J. Agric. Sci.* 143:1–14.
- McMaster, G.S. 2009. Development of the wheat plant. In: B.F. Carver, editor, *Wheat: Science & trade*. Blackwell Publishing, Hoboken, NJ. p. 31–55. doi:10.1002/9780813818832.ch2
- McMaster, G.S., J.C. Ascough, II, D.A. Edmunds, D.C. Nielsen, and P.V.V. Prasad. 2013. Simulating crop phenological responses to water stress using the PhenologyMMS software component. *Appl. Eng. Agric.* 29(2):233–249. doi:10.13031/2013.42654
- McMaster, G.S., J.C. Ascough, II, D.A. Edmunds, L.E. Wagner, F.A. Fox, K.C. DeJonge, and N.C. Hansen. 2014. Simulating unstressed crop development and growth using the Unified Plant Growth Model (UPGM). *Environ. Model. Assess.* 19(5):407–424. doi:10.1007/s10666-014-9402-x
- McMaster, G.S., D.A. Edmunds, W.W. Wilhelm, D.C. Nielsen, P.V.V. Prasad, and J.C. Ascough, II. 2011. PhenologyMMS: A program to simulate crop phenological responses. *Comput. Electron. Agric.* 77:118–125. doi:10.1016/j.compag.2011.04.003
- McMaster, G.S., T.R. Green, R.H. Erskine, D.A. Edmunds, and J.C. Ascough, II. 2012. Interrelationships between wheat phenology, thermal time, and landscape position. *Agron. J.* 104:1110–1121. doi:10.2134/agronj2011.0323
- McMaster, G.S., and M. Moragues. 2018. Crop development related to temperature and photoperiod. In: R.A. Meyers, editor, *Encyclopedia of sustainability science and technology*. Springer-Verlag, Heidelberg, Germany. doi:10.1007/978-1-4939-2493-6\_384-3
- McMaster, G.S., J.W. White, A. Weiss, P.S. Baenziger, W.W. Wilhelm, J.R. Porter, and P.D. Jamieson. 2008. Simulating crop phenological responses to water deficits. In: L.R. Ahuja, V.R. Reddy, S.A. Anapalli, and Q. Yu, editors, *Modeling the response of crops to limited water: Recent advances in understanding and modeling water stress effects on plant growth processes*. ASA-SSSA-CSSA, Madison, WI. p. 277–300.
- McMaster, G.S., and W.W. Wilhelm. 1997. Growing degree-days: One equation, two interpretations. *Agric. For. Meteorol.* 87:291–300. doi:10.1016/S0168-1923(97)00027-0
- McMaster, G.S., and W.W. Wilhelm. 2003. Phenological responses of wheat and barley to water and temperature: Improving simulation models. *J. Agric. Sci.* 141:129–147. doi:10.1017/S0021859603003460
- McMaster, G.S., W.W. Wilhelm, and A.B. Frank. 2005. Developmental sequences for simulating crop phenology under water-limiting conditions. *Aust. J. Agric. Res.* 56(11):1277–1288. doi:10.1071/AR05068
- McMaster, G.S., W.W. Wilhelm, and J.A. Morgan. 1992. Simulating winter wheat shoot apex phenology. *J. Agric. Sci.* 119:1–12. doi:10.1017/S0021859600071483
- Neitsch, S.L., J.G. Arnold, J.R. Kiniry, J.R. Williams, and K.W. King. 2009. Soil and water assessment tool: Theoretical documentation. Version 2009, Technical Report TR-406. Water Resources Institute, College Station, TX.
- Reamur, R. 1735. Observations du thermomètre, faites à Paris l'année 1735, comparées à celles qui ont été faites sous la ligne à l'Isle de France, à Alger et en quelques-unes de nos îles de L'Amérique. *Mem. Acad. Roy. Sci. Paris.*
- Retta, A., D.V. Armbrust, and L.J. Hagen. 1996. Partitioning of biomass in the crop sub-model of WEPS (Wind Erosion Prediction System). *Trans. ASAE* 39:145–151. doi:10.13031/2013.27492
- Retta, A., D.V. Armbrust, L.J. Hagen, and E.L. Skidmore. 2000. Leaf and stem area relationships to masses and their height distribution in native grasses. *Agron. J.* 92:225–230. doi:10.2134/agronj2000.922225x
- Singh, N.T., G.C. Aggarwal, and G.S. Brar. 1984. Effect of soil-moisture stress on heat-unit requirement of wheat at maturity. *Indian J. Agric. Sci.* 54:442–444.
- Uptmoor, R., K. Pillen, and C. Matschegewski. 2017. Combining genome-wide prediction and a phenology model to simulate heading date in spring barley. *Field Crops Res.* 202:84–93. doi:10.1016/j.fcr.2016.08.006
- Wagner, L.E. 2013. A history of wind erosion prediction models in the United States Department of Agriculture: The Wind Erosion Prediction System (WEPS). *Aeolian Res.* 10:9–24. doi:10.1016/j.aeolia.2012.10.001
- Welch, S.M., J.L. Roe, and Z. Dong. 2003. A genetic neural network model of flowering time control in *Arabidopsis thaliana*. *Agron. J.* 95:71–81. doi:10.2134/agronj2003.0071
- White, J., and G. Hoogenboom. 2003. Gene-based approaches to crop simulation: Past experiences and future opportunities. *Agron. J.* 95:52–64. doi:10.2134/agronj2003.0052
- Wilhelm, W.W., G.S. McMaster, R.W. Rickman, and B. Klepper. 1993. Above-ground vegetative development and growth of winter wheat as influenced by nitrogen and water availability. *Ecol. Modell.* 68:183–203. doi:10.1016/0304-3800(93)90016-L
- Williams, J.R., C.A. Jones, J.R. Kiniry, and D.A. Spanel. 1989. The EPIC crop growth model. *Trans. ASAE* 32:497–511. doi:10.13031/2013.31032
- Zadoks, J.C., T.T. Chang, and C.F. Konzak. 1974. A decimal code for the growth stages of cereals. *Weed Res.* 14:415–421. doi:10.1111/j.1365-3180.1974.tb01084.x
- Zalud, Z., G.S. McMaster, and W.W. Wilhelm. 2003. Evaluating SHOOTGRO 4.0 as a potential winter wheat management tool in the Czech Republic. *Eur. J. Agron.* 19:495–507. doi:10.1016/S1161-0301(02)00186-7