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Simulating Unstressed Crop Development and Growth Using the Unified Plant Growth Model (UPGM)

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Abstract Since initial development of the EPIC model in 1989, the EPIC plant growth component has been incorporated into other erosion and crop management models (e.g., WEPS, WEPP, SWAT, ALMANAC, and GPFARM) and subsequently modified to meet research objectives of the model developers. This has resulted in different versions of the same base plant growth component. The objectives of this study are the following: (1) describe the standalone Unified Plant Growth Model (UPGM), initially derived from the WEPS plant growth model, to be used for merging enhancements from other EPIC-based plant growth models; and (2) describe and evaluate new phenology, seedling emergence, and canopy height sub-models derived from the Phenology Modular Modeling System (PhenologyMMS V1.2) and incorporated into UPGM. A 6-year (2005–2010) irrigated maize (*Zea mays* L.) study from northeast Colorado was used to calibrate and evaluate UPGM running both the original (i.e., based on WEPS) and new phenology, seedling emergence, and canopy height sub-models. Model statistics indicated the new sub-models usually resulted in better simulation results than the original sub-models. For example when comparing original and new sub-models, respectively, for predicting canopy height, the root mean square error (RMSE) was 53.7 and 40.7 cm, index of agreement (*d*) was 0.84 and 0.92, relative error (RE) was 26.0 and −1.26 %, and normalized objective function (NOF) was 0.47 and 0.33. The new sub-models predict leaf number (old sub-models do not), with mean values for 4 years of 2.43 leaves (RMSE), 0.78 (*d*), 18.38 % (RE), and 0.27 (NOF). Simulating grain yield, final above ground biomass, and harvest index showed little difference when running the original or new sub-models. Both the new phenology and seedling emergence sub-models respond to varying water deficits, increasing the robustness of UPGM for more diverse environmental conditions. Future research will continue working to incorporate existing enhancements from other EPIC-based plant growth models to unify them into one model such as multispecies competition and N cycling.

Keywords Seedling emergence · Phenology · Canopy height · Growth stages · Leaf production · Simulation model

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1 Introduction

A rich history of cropping system models has developed since the mid-1970s. Some of the initial work began in The Netherlands, at Wageningen with the generic Simple and Universal CROp growth Simulator crop model for potential production simulation (SUCROS) [48]. SUCROS formed the basis for recent Wageningen crop models such as WOFOST, MACROS, and ORYZA [47]. Concurrently, other important agricultural models with detailed crop growth components were developed in the USA in the 1980s including the Environmental Policy Integrated Climate model (EPIC) [56]. Since the initial development of the EPIC model, the EPIC plant growth component has been modified and incorporated in a wide variety of agricultural system models such as the Wind

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Erosion Prediction System model (WEPS) [17, 51, 52], the Water Erosion Prediction Project model (WEPP) [15], the Soil and Water Assessment Tool model (SWAT) [2], the Agricultural Land Management Alternatives with Numerical Assessment Criteria model (ALMANAC) [25], and the Great Plains Framework for Agricultural Resource Management model (GPFARM) [3, 29, 31]. Most modifications of the EPIC crop growth component have addressed perceived shortcomings in model science or specific research needs of the models and have been extensively evaluated throughout the world. For example, the EPIC crop growth component was used to simulate various management options in different agroecosystems to predict effects on crop production [4, 26, 53]. Another common EPIC application is simulating interactions between crop yield and levels of agricultural inputs such as water or nitrogen fertilizer [9, 20, 46, 57]. The EPIC crop growth component has also been used to assess the sustainability of existing cropping systems and potential for yield improvement through introduction of alternative crop rotations in a limited water context [5, 21]. Other research efforts have focused on improving specific component processes, such as phenology [6, 7], or competition by simultaneously simulating multiple species [24, 25]. The WEPS adaptation of the EPIC crop growth component is noteworthy in that it simulates plant shoot dynamics in much greater detail (shoot number, shoot diameter, leaf mass, stem mass, reproductive mass, stem area index, and plant height), among other enhancements, for simulating plant effects on wind erosion [43–45].

Unfortunately, implementation of the EPIC crop growth component in the various agricultural system models listed above has resulted in a suite of similar crop growth components differing in inputs, required parameters, and approaches used to simulate specific processes. This has lead to a number of problems including the following: (1) hindering the ability of users to understand differences among the plant growth components of the models, and therefore limiting their appropriate use; (2) improvements in one plant growth component have not been implemented into the other plant growth components; and (3) end users such as the Conservation Delivery Streamlining Initiative of the USDA-Natural Resource Conservation Service (NRCS) (CDSI; http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/about/cdsi) must simulate different resource concerns using different models and databases to provide required inputs.

Having multiple versions of similar and widely used EPIC-based crop growth components resulted in a long-term goal of integrating component enhancements into a singular or "universal" crop growth model that could be further improved, while continuing to meet the objectives of the parent agricultural system model (e.g., wind and water erosion, water quality assessment, farm and ranch decision support, etc.). The beginning task was to extract the plant growth component from the WEPS model into a standalone Unified Plant Growth Model (UPGM), which is intended to be the cropping system model platform for reaching the long-term goal. The WEPS model crop growth component was selected because: (1) it simulates plant growth dynamics in much greater detail than other EPIC-based crop growth component implementations, and (2) adding these changes into the other EPIC-based plant growth models would be more difficult than the reverse. Before beginning the process of merging different model enhancements into UPGM, we derived new sub-models for phenology, seedling emergence, and canopy height that we hypothesized would improve the WEPS plant growth model. The objective of this paper is to describe the process of developing, enhancing, and initial evaluation of the UPGM platform. The architecture and general science behind UPGM are described, including the new sub-models for phenology, seedling emergence, and canopy height derived from the Phenology Modular Modeling System (PhenologyMMS V1.2) software tool [30, 32]. Finally, general responses and resultant evaluation of UPGM for growing maize under non-limiting water conditions in northeastern Colorado are presented, emphasizing the new enhancements on phenology, seedling emergence, and canopy height.

2 Methods and Materials

2.1 UPGM Original Model Development

The initial step in developing UPGM was to extract the plant growth component from the WEPS model [17, 18, 51] into a standalone FORTRAN 90/95 program. We chose the WEPS version of the EPIC-based plant growth component because it had extensive modifications needed for simulating wind erosion but also could be used for other erosion and crop management simulation objectives. Enhancements included in the WEPS plant growth component compared to other existing EPIC-based crop growth components were as follows: (1) more detailed representation of plant shoot dynamics (shoot number, shoot diameter, leaf mass, stem mass, reproductive mass, stem area index, and plant height), (2) changing from a harvest index approach for estimating grain yield to partitioning daily into reproductive parts using a heat index approach, (3) the addition of a vernalization algorithm affecting phenology, and (4) reducing simulated canopy height by water stress.

In WEPS, as in other agricultural system models containing the EPIC-based crop growth component, a single modeling approach is used for simulating multiple crops by changing input parameter values. The general architecture of UPGM

follows that of WEPS in having the same crop FORTRAN subroutines and calling structure. The primary ASCII input files are daily weather (UPGM_CLI.DAT for historical and CLIGEN.CLI for generated climate), crop parameters (CROPXML.DAT, Table 1), water stress factor (UPGM_STRESS.DAT), management practices (UPGM_MGMT.DAT), and crop parameters from the PhenologyMMS model (UPGM_CROP.DAT, Tables 2 and 3). Daily weather inputs consist of maximum and minimum temperature, precipitation, and solar radiation. The crop parameters for over 200 crops/variety groups were adapted from the extensive WEPS database which was mostly compiled from EPIC and other literature. Two main ASCII output files (SEASON.OUT and CROP.OUT) provide general simulated values such as final grain yield, maturity, canopy height, root depth, and biomass for stems, leaves, and reproductive components, and SHOOT.OUT provides results on below ground processes up to seedling emergence. UPGM is currently developed within the Microsoft Visual Studio 2010.NET integrated development environment (IDE) using the Intel FORTRAN Composer XE compiler Version 2013.0.089 with no graphical user interface.

Only the highlights of the WEPS crop growth component emphasizing those processes most relevant to UPGM model development are discussed here. Both the EPIC and WEPS models use thermal time, as represented by heat units (HU, or also commonly called growing degree-days, GDD), for

Table 1 Important maize parameters from the CROPXML.DAT file. The initial values were derived from the 100-day maturity group provided from the WEPS crop database. The values given are following calibration using the 2007 data, and those with an asterisk were modified

Variable	Definition	Units	Value
plantpop	Plant population	# m^{-2}	8.0*
dmaxshoot	Maximum number of shoots per plant	# $plant^{-1}$	1.0
grf	Harvested fraction of plant component (grain fraction etc.)	Fraction	0.8
ck	Light extinction coefficient		0.65
hui0	Heat unit index at start of senescence	Fraction	0.8
hmx	Maximum crop height	m	2.6*
growthdepth	Starting depth of growing point	m	0.05
rdmx	Maximum root depth	m	2.0
tbas	Minimum temperature for plant growth	°C	10.0
topt	Optimum temperature for plant growth	°C	30.0
thudf	Crop maturity measurement method 0=days; 1=heat units	Unitless	1*
thum	Heat units to maturity	°C· day	1320*
verndel	Thermal delay coefficient pre-vernalization		0.0
bceff	Biomass conversion efficiency	(tons ha^{-1})/(MJ m^{-2})	40.0*
a_lf	Leaf fraction coefficient a	Unitless	0.0031
b_lf	Leaf fraction coefficient b	Unitless	0.923
c_lf	Leaf fraction coefficient c	Unitless	0.327
d_lf	Leaf fraction coefficient d	Unitless	−0.044
a_rp	Reproductive mass coefficient a	Unitless	0.0
b_rp	Reproductive mass coefficient b	Unitless	0.976
c_rp	Reproductive mass coefficient c	Unitless	0.511
d_rp	Reproductive mass coefficient d	Unitless	0.0287
a_ht	Crop height coefficient a	Unitless	0.327
b_ht	Crop height coefficient b	Unitless	−0.044
sla	Specific leaf area	m^2 kg^{-1}	17.4
huie	Heat unit index at emergence	Unitless	0.075*
diammax	Maximum growth diameter of a single plant	m	0.9
storeinit	Planted mass, dry weight	mg $plant^{-1}$	333.33
mshoot	Root storage mass required for each regrowth shoot	mg $shoot^{-1}$	333.33
leafstem	Ratio of leaf mass/stem mass in shoot	Unitless	2.65
fshoot	Ratio of stem diameter to stem length	Unitless	0.03
leaf2stor	Fraction of leaf mass partitioning diverted to root storage	Fraction	0.0
stem2stor	Fraction of stem mass partitioning diverted to root storage	Fraction	0.0
stor2stor	Fraction of repo mass partitioning diverted to root storage	Fraction	0.0

Table 2 Germination and seedling elongation rate parameters for specific crops and seedbed conditions used in UPGM. Parameters are provided in the UPGM_CROP.DAT file (after McMaster et al. [30, 32])

	Crop								
Soil moisture	Winter wheat	Spring wheat	Maize	Winter barley	Spring barley	Sunflower	Sorghum	Proso millet	Hay millet
Germination (∑GDD[a])									
Optimum[b]	80.0	80.0	30.0	80.0	80.0	40.0	40.0	80.0	80.0
Medium	90.0	90.0	60.0	90.0	90.0	50.0	50.0	90.0	90.0
Dry	110.0	110.0	90.0	110.0	110.0	70.0	70.0	110.0	110.0
Dust[c]	700.0	700.0	500.0	700.0	700.0	500.0	500.0	700.0	700.0
Elongation rate (mm GDD^{-1})									
Optimum	0.50	0.50	1.3	0.50	0.50	1.5	1.5	0.50	0.50
Medium	0.40	0.40	1.1	0.40	0.40	1.0	1.0	0.40	0.40
Dry	0.33	0.33	1.0	0.33	0.33	0.6	0.6	0.33	0.33
Dust	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Planting depth (cm)	5	4	5	4	4	5	5	2	2

[a] Accumulated growing degree-days (GDD) required to initiate germination. All crops use Eq. 5 (method 1) for calculating GDD except for maize, sunflower, and sorghum that use Eq. 6 (method 2)

[b] Seedbed conditions are based on percent water-filled pore space: optimum (>45 %), medium (35–45 %), dry (25–35 %), and dust (<25 %)

[c] Soil moisture in this category is below the minimum threshold to initiate imbibition processes

phenological development. EPIC uses a common approach to calculate daily heat units (HU) as shown in Eq. 1:

$$\mathrm{HU}_i = \frac{\left(T_{\max,i} + T_{\min,i}\right)}{2} - T_{\mathrm{base}} \tag{1}$$

where $T_{\max,i}$ and $T_{\min,i}$ are maximum temperature and minimum temperature (°C), respectively, on day i, and T_{base} is the crop-specific base temperature (°C). No growth occurs at or below T_{base}, and there is no upper temperature limit. WEPS modifies this approach by using a sinusoidal approximation for the daily air temperature and finds the heat units as the integration of the sinusoidal air temperature curve over 24 h between the base and optimal growth temperatures. 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:

$$\mathrm{HUI}_i = \frac{\sum_{j=\mathrm{pdate}}^{i} \mathrm{HU}}{\mathrm{THUM}} \tag{2}$$

where HU is the sum of daily heat units from planting (pdate) 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.

In addition to THUM, crop-specific input parameters for HUI values required for emergence and beginning of senescence are provided. The assumption is that while THUM changes among crops (and genotypes within a crop), developmental processes still occur at the same relative time during the life cycle. Therefore, both models use a static HUI value for determining when 50 % seedling emergence or the beginning of leaf senescence occurs. Default values for seedling emergence tend to be for non-limiting conditions, but can be adjusted by the user. Beginning of leaf senescence is defined as when LAI begins to decline, which for determinate crops such as wheat, barley, sunflower, sorghum, and maize should occur shortly after the flag leaf (i.e., last leaf produced on the shoot) has completed growth (ending leaf appearance).

Daily potential biomass production ($\Delta \mathrm{PB}_i$, kg m^{-2}) is determined by the radiation use efficiency approach. This approach uses the interception of solar radiation by the canopy (as represented by the LAI and light extinction coefficients) and a crop-specific energy-to-biomass conversion factor (BCEFF, kg MJ^{-1}). Interception of photosynthetic active radiation (PAR, MJ m^{-2}) is estimated with Beer's law [40], and $\Delta \mathrm{PB}_i$ is calculated according to Monteith [41]. The $\Delta \mathrm{PB}_i$ is adjusted by the most limiting of the plant water and temperature stress factors (WEPS does not consider nitrogen or phosphorus stress factors as EPIC does) to calculate the actual daily total biomass production (ΔB_i, kg m^{-2}). Because the WEPS water balance routines were not incorporated into the current version of UPGM, UPGM does not include water stress as a growth limiting factor. Therefore, daily water stress values were set to 1 (meaning no stress) in the water stress

Table 3 Important maize parameters used in the new phenology and canopy height sub-models from the UPGM_CROP.DAT file. The initial values were derived from the 100-day maturity group provided from the PhenologyMMS V1.2 crop database. The values given are following calibration using 2007 data, and those with an asterisk were modified

Variable	Definition	Units	Value
pchron	Phyllochron	°C day	35
Tbase	Base temperature	°C	10
Tupper	Upper threshold above which GDD are not accumulated in method 2 (Eq. 6)	°C	30
gmethod	Method used in calculating GDD (Eq. 6)	N/A	2
ecanht	Maximum final potential canopy height at end of phase 1	cm	15
maxht	Maximum final potential canopy height (at end of phase 2)	cm	260*
Dummy2(1)	GDD[a] between emergence and V4 for GN[b] conditions	°C day	140
Dummy2(2)	GDD between V4 and tassel initiation for GN conditions	°C day	70
Dummy2(3)	GDD between V4 and ear initiation for GN conditions	°C day	75
Dummy2(4)	GDD between V4 and internode elongation for GN conditions	°C day	80
Dummy2(5)	GDD between V4 and V12 for GN conditions	°C day	270*
Dummy2(6)	GDD between V12 and tasseling for GN conditions	°C day	270*
Dummy2(7)	GDD between V12 and silking (R1) for GN conditions	°C day	280
Dummy2(8)	GDD between R1 and blister (R2) for GN conditions	°C day	149
Dummy2(9)	GDD between R2 and milk (R3) for GN conditions	°C day	99
Dummy2(10)	GDD between R3 and dough (R4) for GN conditions	°C day	72
Dummy2(11)	GDD between R4 and dent (R5) for GN conditions	°C day	149
Dummy2(12)	GDD between R5 and physiological maturity (R6) for GN conditions	°C day	181

[a] GDD is the growing degree-days between successive events and calculated by the method selected by the user. Method 2 (Eq. 6) was used to calculate GDD for these parameters

[b] GN denotes non-limiting water conditions

input parameter file (UPGM_STRESS.DAT). The temperature stress factor is calculated as:

$$T_{\mathrm{ave},i} = \frac{\left(T_{\max,i} + T_{\min,i}\right)}{2} \tag{3}$$

$$\mathrm{TS}_i = \left\{ \sin\left(\frac{\pi}{2} \frac{T_{\mathrm{ave,i}} - T_{\mathrm{base}}}{T_{\mathrm{opt}} - T_{\mathrm{base}}} \right) \right\}^{0.25} \tag{4}$$

where TS_i is the daily temperature stress factor (0–1) on day i, $T_{\mathrm{ave},i}$ is the average daily temperature (°C), T_{base} is the crop-specific base temperature (°C), and T_{opt} is the crop-specific optimum temperature (°C). WEPS considers the plant fully stressed (i.e., TS_i=0) when the air temperature is above T_{base} more than two times the range between T_{opt} and T_{base}. In addition, Eq. 4 is raised to the 0.25 power in WEPS to reduce the temperature stress factor around T_{opt}.

Once ΔB_i is determined, biomass is partitioned to various plant components (e.g., roots, leaves, stem, and reproductive structures). First, partitioning to roots is determined where the fraction of ΔB_i is linearly partitioned to roots assuming a fraction of 0.4 at emergence and 0.2 at maturity, with the remainder going to the canopy [56]. Partitioning within the canopy uses separate partitioning curves for leaf and reproductive structures defined by four input parameters controlling the shape of each curve with any remaining biomass sent to the stem fraction [44]. In calculating LAI, EPIC has a maximum LAI while WEPS does not. Biomass partitioned to leaf mass becomes LAI based on the specific leaf area (SLA; crop-specific input parameter). The beginning of the decline in LAI is a crop-specific input parameter, and once started it declines by a set fraction per day. In WEPS, potential daily increment in canopy height is calculated with a sigmoidal curve as a function of HUI and the maximum plant height of the plant (a square root function is used in EPIC). WEPS reduces the potential height increase on the current day by the minimum of the temperature and water stress factors to calculate the actual plant height increase that is added to current day plant height.

WEPS differs from EPIC in the approach used to estimate annual crop yield. EPIC estimates yield (kg m^{-2}) using the harvest index (HI) concept, which is adjusted throughout the growing season according to water stress constraints. HI increases nonlinearly from zero at planting, and for crops such as corn where the maximum economic yield development occurs in the second half of the growing season, significant increase in the HI is delayed until HUI reaches 0.5. Grain yield in WEPS is determined by daily partitioning of a portion of the total biomass available for growth to reproductive biomass, rather than calculating grain yield as a result of using the HI approach. At physiological maturity, grain yield is determined by apportioning the reproductive biomass into "chaff" and "grain" masses and then converting the grain mass into yield at a given moisture content. Greater detail on the WEPS and EPIC plant growth components is provided in [2, 12, 25, 31, 43, 44, 51, 54, 56].

2.2 UPGM Enhanced Model Development

The original UPGM standalone model, adopted from the WEPS plant growth component, has several processes that could be improved, including phenology, seedling emergence, and canopy height. Specific limitations of the phenology

processes of WEPS and other EPIC-based plant growth models include the following:

1. Only a few developmental stages are explicitly predicted (e.g., seedling emergence, start of leaf senescence, and physiological maturity).
2. The length of the plant life cycle uses a static input parameter of the required thermal time (i.e., heat units) for the plant to progress through its life cycle from planting to maturity. However, if seedling emergence is delayed due to non-optimal conditions, the heat units required from planting to start of leaf senescence (HUI0) or maturity (THUM) are not changed. Therefore the timing of these developmental events will be increasingly inaccurate as seedling emergence is delayed.
3. Most EPIC-based plant growth models do not adjust THUM for winter crops such as wheat and barley that have vernalization requirements or respond to photoperiod (or both). Planting dates can vary considerably for many reasons, but until vernalization/photoperiod requirements are satisfied, progression towards maturity is delayed. Without accounting for these factors, earlier planting dates start accumulating heat units sooner and result in reaching post-vernalization developmental events (e.g., leaf senescence and maturity) too soon. The WEPS phenology sub-model has a vernalization, but not photoperiod, factor, partly alleviating this problem.
4. In all EPIC-based phenology processes, phenology is not influenced by water stress, yet certainly water stress can influence the timing of developmental stages [34, 36].
5. Important developmental stages such as the onset of floral initiation, beginning of stem growth, and flowering/anthesis are not explicitly simulated. Without such information, the user has little help in adjusting the partitioning parameters for root, leaf, stem, and reproductive fractions, and could limit future modifications of the model.

Several ramifications of the influence of seedling emergence on predicting subsequent developmental events of leaf senescence and maturity were mentioned above. One potentially limiting simplification in both WEPS and EPIC is that seedling emergence is driven solely by thermal time. A single default input parameter represents the proportion through the life cycle for 50 % seedling emergence, and the default value typically assumes non-limiting soil water conditions. For instance, in 100-day maize, the default value is 0.05. Soil water does not affect germination, and as soil water availability decreases the default value should be increased to delay emergence. However, with a static input value, no adjustment in seedling emergence timing is possible as soil water content changes.

In addition, WEPS uses a sigmoidal curve to simulate canopy height as a function of the heat unit index and reduces the potential height by the minimum of temperature and water stress factors. While this works well, some crops have distinct phases of growth. For instance, many annual grasses such as winter wheat and barley have an initial rosette phase of growth during the fall through early spring. Plants stay in the rosette form until the second phase where the signal to begin internode elongation occurs, leading to rapid increase in canopy height. Therefore, while the sigmoidal curve reflects overall the canopy height, the distinct phases in canopy height are poorly delineated and changes in planting and emergence dates in the fall can cause deviations from the default sigmoidal curve.

To address the identified problems in the phenology, seedling emergence, and canopy height processes in the WEPS crop growth component, the original standalone UPGM model was modified by incorporating the phenology, seedling emergence, and canopy height sub-models from PhenologyMMS V1.2 [30, 32]. A detailed description of PhenologyMMS V1.2 can be found in McMaster et al. [30, 32]; however, a general overview of the phenology, seedling emergence, and canopy height sub-models are presented below.

The new phenology sub-model, as in the original EPIC and WEPS crop growth modules, assumes the dominating role of temperature in controlling plant phenology. However, the user can select different approaches for calculating thermal time, with the two most frequently used approaches basically the same as used in EPIC. The first method (method 1) [35] calculates growing degree-days (GDD) as with Eq. 1:

$$\mathrm{GDD} = \sum_{i=1}^{n} \left(\frac{T_{\max,i} + T_{\min,i}}{2} \right) - T_{\mathrm{base}}, \quad \mathrm{GDD} \geq 0 \qquad (5)$$

where $T_{\max,i}$ and $T_{\min,i}$ are the daily maximum and minimum temperature for day i (°C), respectively, and T_{base} is the base temperature (°C), and the daily values greater than zero are summed daily over a period of n days. Winter crops or cool-season grasses such as wheat and barley typically have used method 1. Method 2 [35] uses the same basic equation, but adds an upper temperature threshold (T_{upper}) and manipulates $T_{\max,i}$ and $T_{\min,i}$ based on the base and upper thresholds:

$$\mathrm{GDD} = \sum_{i=1}^{n} \left(\frac{T_{\max,i} + T_{\min,i}}{2} \right) - T_{\mathrm{base}}, \quad 0 \leq \mathrm{GDD} \leq T_{\mathrm{upper}} \qquad (6)$$

where T_{upper} (°C) is the crop-specific upper temperature threshold above which additional GDD are not accumulated. T_{base} and T_{upper} are also used in the manipulation of the equation, where if $T_{\max,i}$ and/or $T_{\min,i} < T_{\mathrm{base}}$, $T_{\max,i}$ and/or $T_{\min,i} = T_{\mathrm{base}}$ and if $T_{\max,i}$ and/or $T_{\min,i} > T_{\mathrm{upper}}$, then $T_{\max,i}$

and/or $T_{min,i}=T_{upper}$. Crops such as maize, sorghum, and sunflower typically use method 2 and generally have higher base temperatures than those crops using method 1.

Simulation of developmental growth stages is based on accumulation of thermal time over some time interval. This could be from emergence, or from when the crop was fully vernalized, or from an earlier developmental phase. To determine the thermal time requirements for a crop, first the entire developmental sequence of all canopy structures under non-limiting conditions was summarized and correlated with developmental events (i.e., this is the genetic blueprint, or pattern, for how the crop develops). Following this, the influence of water deficits on the timing of the developmental events was estimated. Each crop, and possibly developmental stage, can differ in response to water deficits. The literature, expert opinion, and experimental data were used to create these developmental sequences and the phenological responses to water deficits. The developmental sequences were first presented for winter wheat in McMaster et al. [38]; spring wheat, winter and spring barley, and maize in McMaster et al. [37]; sorghum in McMaster et al. [34]; and sunflower, proso millet, and hay millet in McMaster et al. [30].

The developmental sequences were the foundation used to simulate the developmental stages of the crop. Thermal time estimates between developmental stages for two extremes of water deficits, non-stressed ("No-stress") and severely stressed ("Stressed") are provided for each crop (and either variety or maturity group). Non-stressed values would be for non-limiting conditions and severely stressed values would be for extreme water deficits not leading to crop death.

Incorporating the new phenology sub-model into UPGM required additional plant input parameters. An ASCII file (UPGM_CROP.DAT; Table 3) was created for the new parameters including the cardinal temperatures required for all temperature response functions (e.g., T_{base}; the lower optimum temperature, $Topt_{lower}$, °C; the upper optimum temperature, $Topt_{upper}$, °C; and T_{upper}), the method to use in calculating thermal time, the phyllochron (PCHRON, rate of leaf appearance in °C day), and all "Stressed" and "No Stressed" values for each developmental event of the crop/variety selected. Regardless of whether the user chooses to use the original or the new phenology sub-model, a new ASCII output file (PHENOL.OUT) is always created to show the output for the new phenology sub-model. Some phenological information from the new phenology sub-model is written to the main output files of UPGM, such as anthesis/flowering and maturity dates (SEASON.OUT). Options were incorporated into UPGM to run either the original or new phenology sub-model and determine sub-model calling placement within the plant growth model code structure. Both phenology sub-models predict the date of physiological maturity, and reaching this date ends the call to the plant growth model processes.

The new seedling emergence sub-model in UPGM was incorporated from PhenologyMMS V1.2, which is a simplified version of the SHOOTGRO model [33, 55]. Three factors control the time of seedling emergence: soil moisture near the seed, temperature, and planting depth. It is assumed that soil moisture and temperature control the beginning of imbibition and germination (Germ):

$$\mathrm{Germ} = \sum_{i=\mathrm{Pdate}}^{\mathrm{Gday}} (\mathrm{GDDG}_i) \tag{7}$$

where the daily growing degree-days ($GDDG_i$) is summed from planting day (Pdate) until the required number of growing degree-days ($GDDG_{req}$) for germination is reached. Gday is the day that germination occurs. $GDDG_{req}$ is based on the soil moisture conditions of the seedbed zone. Table 2 presents the default crop-specific values for $GDDG_{req}$ (note: if the starting level is "planted in dust," then accumulation of thermal time does not begin until the soil moisture category is at least "dry"). GDD are currently calculated using either method 1 (Eq. 5) or 2 (Eq. 6) selected for the crop. Once germination has occurred, temperature and soil moisture drive the rate of shoot growth ($ElongRate_i$) from the seed leading to emergence. The thermal time required for the shoot to emerge after germination ($GDDE_{req}$) is calculated by:

$$\mathrm{GDDE}_{\mathrm{req}} = \frac{\mathrm{Pdepth}}{(\mathrm{ElongRate}_i/10)} \tag{8}$$

where $ElongRate_i$ is the shoot elongation rate (mm °C$^{\cdot}$ day^{-1}) for day i based on the soil water content (see Table 2 for default crop-specific values) and Pdepth is the planting depth (cm). Seedling emergence (Emerge) is then determined by multiplying the daily elongation rate by the daily GDD (GDD_i) until the required GDD ($GDDE_{req}$) have been accumulated:

$$\mathrm{Emerge} = \sum_{i=\mathrm{Gday}}^{\mathrm{Eday}} ((\mathrm{ElongRate}_i/10) \times \mathrm{GDD}_i) \tag{9}$$

Seedling emergence occurs the day (Eday) that Emerge equals $GDDE_{rep}$.

Crop-specific parameters for germination and elongation rate in Table 2 are based on four general categories of soil moisture in the seedbed layer: optimum (>45 % water-filled pore space), medium (35–45 %), dry (25–35 %), and planted in dust (< 25 %). These values do not need to be precisely estimated; rather the user can choose the category based on general conditions. The standalone version of UPGM lacks a soil water balance module, so a surrogate approach to vary soil

moisture conditions for simulating seedling emergence was to use precipitation during this time period. In PhenologyMMS V1.2, daily rainfall amounts from 5 to 7 mm increment the soil moisture category to the next higher level of soil moisture. Rainfall events from 7 to 12 mm increment the soil moisture category two levels. Preliminary evaluation of the seedling emergence sub-model in UPGM uncovered instances of emergence occurring too early when selecting medium or dry soil water conditions. One solution tested was to create intermediate categories between dry and medium, and medium and optimum levels. Germination and elongation rate values for the intermediate categories are the mid-points between the initial soil water values for optimum, medium, or dry as appropriate, and this is done internally so the user is not required to provide additional input values. The first rainfall event ≥7 mm increases the initial soil water level to the intermediate level, and the second rainfall event ≥7 mm increments it to the medium level. If the original condition was planted in dust, then the model was modified so that if rainfall is from ≥7 to 12 mm the soil moisture level is advanced to dry, rainfall from ≥12 to 20 mm results in medium level, and if rainfall ≥20 mm soil water condition is optimum. Testing of these changes was limited to running winter wheat and maize for a variety of planting dates and weather files with selection of the four levels of initial soil water and examining the distribution of seedling emergence times as to whether they matched expert opinion and unpublished data.

The call to the new seedling emergence sub-model was included in the SHOOT_GROW subroutine where seedling emergence is simulated. As with the phenology sub-model, the user chooses between running the original seedling emergence sub-model or the new sub-model. The estimated date of seedling emergence is then passed to the new phenology sub-model which predicts the remaining developmental stages. With the integration of both the new seedling emergence and phenology sub-models, the user now has the choice between the original and new approaches for estimating the beginning and end of crop growth.

The new canopy height sub-model in UPGM allows for two linear phases of canopy growth. Depending on the crop, these two phases may not be distinct. However, for crops such as winter wheat and winter barley, the first phase applies to the rosette growth habit from emergence in the fall until the beginning of internode elongation in the spring. The second phase is the period of greatest increase in plant height resulting from internode elongation. For simplicity, a linear daily growth rate in canopy height ($\mathrm{CanopyHt}_i$) is assumed during each phase:

$$\mathrm{CanopyHt_i} = \mathrm{CanopyHt}_{i-1} + (\mathrm{HtRate}_i \times \mathrm{GDDday}_i) \qquad (10)$$

where $\mathrm{CanopyHt}_i$ for day i is determined by summing the previous day's canopy height ($\mathrm{CanopyHt}_{i-1}$) with the increase for day i in canopy height (HtRate_i, cm °C· day^{-1}) multiplied by the growing degree-days for day i (GDDday_i). HtRate_i is calculated during each phase as:

$$\mathrm{HtRate}_i = \frac{\mathrm{FinalMaxHt}_j}{\mathrm{GDDsum}_j} \qquad (11)$$

where the final maximum potential height ($\mathrm{FinalMaxHt}_j$, cm) of each phase (j=1 or 2) is an input parameter and GDDsum_j is the sum of the growing degree-days for the duration of the phase. Phase 2 for most crops (e.g., wheat, barley, maize, sorghum, and proso and hay millets) should normally begin at the start of internode elongation (just before the stage of jointing when the first node appears above the soil surface) and end near the time of flowering/anthesis. However, for ease of obtaining data and simplicity, the default values are usually set to begin phase 2 at the stage of jointing and end at the beginning of flowering/anthesis.

The canopy height sub-model in PhenologyMMS V1.2 only simulates canopy height under non-limiting conditions (i.e., potential height). The sub-model was modified to use the WEPS stress factor for estimating the actual daily increase in height (Ahtinc_i):

$$\mathrm{Ahtinc}_i = \mathrm{Phtinc}_i \times \mathrm{Strs}_i \qquad (12)$$

$$\mathrm{Phtinc}_i = \mathrm{HtRate}_i \times \mathrm{GDDday}_i \qquad (13)$$

where Phtinc_i is the potential increase in height (cm) for day i and Strs_i is the most limiting of the temperature and water stress factors.

The new canopy height sub-model is called from the phenology module to estimate the potential daily height increase (Phtinc_i). This value is then passed to the GROWTH subroutine in UPGM to determine the actual increase in height. As with the phenology and seedling emergence sub-models, the user chooses between running either the original or new canopy height sub-model. The two input parameters (in UPGM_CROP.DAT) required for the new canopy height sub-model are the maximum potential height at the end of phase 1 (ECANHT) and phase 2 (MAXHT, the final canopy height).

2.3 Data Set for Calibration and Validation

A variable irrigation cropping systems field experiment was conducted from 2005 to 2010 near Fort Collins, Colorado (40° 39′ 09″ N, 105° 00′ 00″ W, 1,558 m elevation). Only the fully irrigated treatment for continuous maize (i.e., the full

ET requirement was supplied throughout the growing season) to simulate non-limiting water conditions is discussed here. The experiment was arranged as four randomized complete blocks. Plots consisted of 12 rows spaced 76 cm apart and 26 m long. All data were collected from the middle four rows to minimize boundary effects. A linear-move sprinkler system applied the irrigation water.

Soil at the experimental site was a Fort Collins Loam (fine-loamy, mixed, superactive, mesic Aridic Haplustalf). An on-site weather station collected daily precipitation, solar radiation, minimum and maximum temperature, vapor pressure, and wind run and is part of the Colorado Agricultural Meteorological Network (http://ccc.atmos.colostate.edu/~coagment/; station FTC03). A tornado near the field site on 22 May 2008 damaged the weather station, so missing data from 20 May through 16 June 2008, as well as any other missing data, were replaced by data from the nearby Wellington, Colorado station (2 km north; 40° 40′ 34″ N, 104° 59′ 49″ W, 1,568 m elevation; station WLT01).

Several hybrids were planted with seeding rates between 7.9 and 8 seeds m^{-2} depending on the year (Table 4). Planting dates ranged from 30 April to 13 May. Based on soil sampling, fertilizer applications at either planting or mid-season, or both times, were assumed to result in negligible N stress. Plant measurements taken included canopy height, leaf number, developmental stages, final grain yield, biomass, and harvest index (HI; Table 3). Measurements often varied yearly in detail, frequency of measurements through the growing season, and usually were stopped at about anthesis. Canopy height through the growing season was measured as average peak height of five representative plants from each plot. Leaf number counted collared leaves on 10 representative plants in a plot during the growing season, except in 2008 total number of leaf tips present were counted. Leaf area was non-destructively sampled on two representative plants within a plot by measuring the length and width of each leaf on the plant and multiplying by 0.74 [23]. Emergence was noted in only 2007 (85 % of final seedling emergence was recorded on 25 May) and 2009 (plots varied from 25 to 75 % emergence on 29 May), V stages (or leaf number) were described as above, and anthesis and maturity were occasionally noted by scoring the plots for these days. Final grain yield was obtained by plot combine for all years. A hail storm on 14 August 2008 reduced final grain yield. The observed leaf area reduction and developmental stage were used to adjust for hail damage [50]. Final above ground biomass samples were taken during late grain-filling to predict silage yield, with dates varying each year. This resulted in underestimating final above ground biomass and overestimating HI (ratio of final grain yield to final above ground biomass). Additional details on the experiment can be found in DeJonge et al. [13].

2.4 Model Calibration and Validation Runs

Whenever possible, the default parameters provided from the WEPS and PhenologyMMS models were used in running UPGM. The 100-day maize data set was selected from the WEPS crop parameter database for the CROPXML.DAT input parameter file, and the 100-day maize maturity group was selected from PhenologyMMS database for the UPGM_CROP.DAT input parameter file. The 2007 year was used to calibrate parameters in both files (weather data are presented in Table 5), beginning with calibrating seedling emergence, anthesis, and maturity values using the Garst 8827 hybrid. Initial soil water was not known for any years; however, when looking at the date of 85 % emergence in 2007 (25 May), it was 17 days after planting suggesting that soil water was sub-optimal (Table 6). Therefore, the portion through the life cycle from planting to emergence in the original WEPS sub-model in CROPXML.DAT (HUIE) was increased from 0.05 to 0.075 to delay emergence, and the medium soil moisture conditions were selected for PhenologyMMS parameters. Data were only available to calibrate the anthesis developmental event (not maturity) but WEPS does not predict anthesis, so general knowledge of maize maturity dates were used to assess maturity in both databases. The PhenologyMMS default values for 100-day maize seemed reasonable as the simulated anthesis date was within 2 days of the observed and maturity date was 5 October (Table 6). Thus, no changes were made in the PhenologyMMS parameters. However, maturity was predicted too late (11 October) in the original WEPS sub-model based on general maturity dates for the region and compared to the new phenology sub-model. Therefore the thermal time required from planting to maturity (THUM) was reduced from 1,450 to 1,320 GDD. The reduced value was close to 1,336 (T_{base}=10 °C, upper threshold=32 °C) for Pioneer 3732 one hundred-day hybrid [42]. These changes reduced simulated yield and above ground biomass, which were over-predicted based on the observed values. Small changes in the biomass to energy conversion factor (BCEFF) did not improve the fit of the two variables with the observed so the default value of 40 (tons ha^{-1})/MJ m^{-2}) was kept. Both parameter files had a default value for maximum potential canopy height, with 2.5 m in CROPXML.DAT and 1.9 in UPGM_CROP.DAT. Although 2007 had an unusually low final plant height, and it appeared measurements ended before final height was reached, we examined final plant height in the other years and noted that it was between 2.5 and 2.6 m. Therefore, 2.6 m was used as the maximum potential default value in both canopy height sub-models. The new phenology sub-model assumes a default phyllochron of 35 GDD $leaf^{-1}$, and after making slight adjustments to the parameters and comparing with observed leaf number data, we chose not to change this parameter. All parameters related to agronomic practices were

Table 4 Management and plant measurement information for limited-irrigation maize study in northeastern Colorado

Variable	2005	2006	2007[a]	2008	2009	2010
Hybrid	N/A	Garst 8827	Garst 8827	Pioneer 38P43	Pioneer P9512XR	Producer Hybrid
Planting date	N/A[b]	10 May	8 May	30 April	13 May	4 May
Seeding rate (# m^{-2})	N/A	7.9	8.0	7.9	7.9	7.9
Emergence	No	No	Yes[c]	No	Yes[d]	No
Silking	No	No	Yes	No	No	Yes[e]
Maturity	No	No	Yes[f]	No	No	No
Number of collared leaves	No	No	Yes	Yes[g]	Yes	Yes
Phyllochron (°C day)	No	No	Yes	Yes	Yes	Yes
Canopy height (cm)	Unitless	No	Yes	Yes	Yes	Yes
Yield (Bu ac^{-1} and kg ha^{-1})	Yes	Yes	Yes	Yes, corrected for hail	Yes	Yes
Harvest Index (HI)	Yes	Yes	Yes	Yes	Yes	Yes
Final above ground biomass[h]	Yes	Yes	Yes	Yes	Yes	Yes

[a] Year 2007 data were used for model calibration
[b] Year 2007 planting date was assumed
[c] Data were for 85 % emerged
[d] Data ranged among plots from 25 to 75 %
[e] Plots ranged from R1 to R1
[f] Data were for the dent stage (R5)
[g] Data were for total number of leaf tips present
[h] Data were taken prior to maturity

set to match the actual practices (e.g., seeding rate in CROPXML.DAT was changed from 6 to 8 seeds m^{-2}), and planting date was set to actual dates in Table 4. Planting depth was assumed to be 5 cm. Final calibration results are shown in Figs. 1, 2, and 3 and Table 6. Years 2005–2010, excluding 2007 used for calibration, were used to evaluate model performance for canopy height, leaf number, phenology, final grain yield, final biomass, and HI. For each year, UPGM was run using both the original and new sub-models for calculating phenology, seedling emergence, and canopy height. In evaluating simulated output, leaf number is not predicted in the original WEPS model, so simulated leaf number is only from the new sub-models.

2.5 Model Statistical Evaluation

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

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \tag{14}$$

where P_i is the ith predicted value, O_i is the ith observed value, and n is the number of data pairs. RE was expressed in percent as:

$$\mathrm{RE} = \frac{\left(\overline{P} - \overline{O}\right)}{\overline{O}} 100 \tag{15}$$

where $\overline{P}$ is the predicted mean and $\overline{O}$ is the observed mean. RE is the measure of the mean tendency of the simulated values to be larger or smaller than the observed values. 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:

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} \left(\left| P_i' \right| + \left| O_i' \right| \right)^2} \right], 0 \le \mathrm{d} \le 1 \tag{16}$$

where P_i, O_i, and n are as previously defined, $P_i' = P_i - \overline{O}$ and $O_i' = O_i - \overline{O}$ where $\overline{O}$ is as previously defined, and the enclosing bars (| |) indicate absolute values. A d value of one

Table 5 Weather data for the Agricultural Research, Development and Education Center (ARDEC). Years 2005–2010 were for the 6-year study with 2007 being the calibration year. GDD (growing degree-days) and Prec (precipitation) are sums for the month or time period

Period	Tavg[b] °C	Long-term[a] GDD[c] °C day	Prec[d] mm	Tavg °C	2005 GDD °C day	Prec mm	Tavg °C	2006 GDD °C day	Prec mm	Tavg °C	2007 GDD °C day	Prec mm	Tavg °C	2008 GDD °C day	Prec mm	Tavg °C	2009 GDD °C day	Prec mm	Tavg °C	2010 GDD °C day	Prec mm
Jan	−2.3	15.7	2.7	−1.1	26.6	4.6	7.1	32.3	0.0	−6.8	0.5	2.1	−3.5	3.3	0.0	−0.3	36.2	1.1	−2.1	2.8	1.0
February	−1.0	17.9	2.8	1.2	24.6	2.5	−2.0	29.8	2.0	−1.3	5.3	2.1	−0.6	16.3	0.0	1.3	29.3	0.6	−3.0	0.0	3.7
March	3.6	62.0	9.8	3.9	52.4	19.0	2.2	45.0	13.0	6.7	97.2	30.3	2.9	42.6	11.5	3.9	71.5	4.1	4.1	54.4	10.0
April	7.6	97.6	39.1	7.6	98.6	42.3	9.9	146.0	4.0	7.7	94.3	26.3	6.8	96.6	40.2	7.0	88.0	64.9	7.7	80.3	85.6
May	13.2	174.5	50.2	12.9	169.9	55.1	14.8	213.0	15.0	13.5	183.0	22.6	12.2	172.0	40.5	14.0	175.7	35.8	11.8	141.0	41.7
June	18.1	251.7	43.3	17.7	247.7	81.3	21.5	319.4	6.0	19.3	276.4	13.2	18.3	258.6	42.0	16.8	219.4	95.3	19.0	269.1	33.4
July	21.6	333.6	35.2	22.8	347.4	7.1	23.0	365.0	14.8	23.5	377.7	41.0	22.8	356.3	12.1	20.2	305.1	40.3	21.5	330.7	21.8
August	20.1	306.9	32.0	19.9	300.7	22.1	21.1	330.9	7.4	22.2	356.1	62.6	19.8	290.4	112	19.7	297.1	2.7	21.3	334.4	10.2
September	15.5	215.6	24.5	16.9	248.3	3.0	13.6	179.6	21.1	16.6	235.1	29.3	14.8	193.3	25.0	15.8	220.4	6.6	16.9	249.7	1.3
October	8.7	117.6	23.9	9.9	125.0	56.0	7.9	103.3	18.9	10.2	142.1	33.0	9.2	123.4	10.0	4.7	60.9	21.8	11.0	146.3	18.5
November	2.3	45.8	7.3	4.3	63.3	2.0	2.6	50.2	3.8	3.3	68.7	3.0	4.8	64.9	0.3	3.7	57.0	8.1	N/A*	N/A*	N/A*
December	−2.4	13.8	2.4	−2.3	21.2	0.0	−2.5	10.4	6.1	−5.5	8.5	7.9	−4.2	12.5	2.8	−6.1	2.3	4.7	N/A*	N/A*	N/A*
May–October[e]	16.2	1,400	209	16.7	1,439	225	17.0	1,511	83	17.5	1,570	202	16.2	1394	242	15.2	1,279	203	16.9	1,471	127
Year	9.0	1,653	273	9.5	1,725	295	9.6	1,824	112	9.2	1,844	273	8.6	1630	296	8.4	1,563	286	N/A*	N/A*	N/A*

[a] Long-term is for the years 1992–2010

[b] Mean average daily temperature for the time period (Tavg is the daily maximum plus minimum temperature divided by 2)

[c] Cumulative growing degree-days during the time period, calculated according to Eq. 11 using daily values

[d] Cumulative precipitation during the time period

[e] For the period 1 May through 31 October (approximately the growing season)

Table 6 Simulated and observed (Obs) phenological events. Simulated values are for running either the original (Orig) or new (New) sub-models. All simulated developmental events between emergence and maturity, other than "reproductive store start," are only simulated by the new sub-models. "Reproductive store start" is intended in the original sub-model to be near the time of flowering/anthesis, and therefore analogous to the silking (R1) event

Developmental event	2005		2006			2007[a]			2008			2009			2010		
	Orig	New	Obs	Orig	New	Obs	Orig	New	Obs	Orig	New	Obs	Orig	New	Obs	Orig	New
Planting date	8 May[b]	8 May	10 May	10 May	10 May	8 May	8 May	8 May	30 April	30 April	30 April	13 May	13 May	13 May	4 May	4 May	4 May
Emergence	24 May	23 May		24 May	22 May	25May[c]	25 May	20 May		22 May	19 May	29May[d]	30 May	29 May		29 May	27 May
V4		17 June			7 June	6 June		11 June			10 June	30 June		21 June			14 June
Ear formation		23 June			13 June			19 June			18 June			29 June			22 June
Internode elongation		24 June			14 June			19 June			19 June			29 June			23 June
V12		12 July			2 July	12 July		6 July			7 July			17 July	14 July		12 July
Tasseling (VT)		5 August			25 July	19 July		28 July			31 July	4 August		14 August			5 August
Silking (R1)		6 August			26 July	27 July		29 July			31 July	4 August[e]		15 August	23 July[f]		6 August
Reproductive store start	2 July			21 June			29 June			29 June			7 Jul			30 June	
Dent (R5)		27 September			12 September	7 September		10 September			28 September			12 November			24 September
Maturity (R6)	16 October	10 November		20 September	16 October		18 September	5 October		31 October	17 November		20 May	10 May		5 October	24 October

[a] Year 2007 data were used for calibration

[b] Planting date unknown, set to 2007 (calibration) planting date

[c] Emergence was for 85 % of plants

[d] Emergence ranged among plots from 25 to 75 %

[e] Twenty percent of plants were at silking

[f] Plots ranged from R1 to R2

indicates complete agreement between model predictions and observations and zero indicates no relationship. NOF was calculated as:

$$\mathrm{NOF} = \frac{\mathrm{RMSE}}{\overline{O}} \tag{17}$$

where RMSE and $\overline{O}$ are as previously defined. 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 less than 1 may be viewed as having a simulation error of less than 1 standard deviation around the experimental mean.

3 Results

Monthly temperature, accumulated thermal time, and precipitation varied among the 6 years of the data set (Table 5). Focusing on thermal time during the growing season from 1 May to 31 October, the long-term accumulated thermal time was 1,400 GDD. The 6 years varied around this long-term mean, with 2009 (1,279 GDD) and 2008 (1,394 GDD) below the long-term mean, and the other years above (2005=1,439 GDD; 2010=1,471 GDD; 2006=1,511 GDD, and 2007=1,570 GDD). These values are important in determining whether the crop will reach maturity in the fall.

Model calibration using 2007 data was hindered by canopy height measurements ceasing prior to final canopy height, but when reviewing the original and new sub-models simulated results (Fig. 1), we felt that the simulated heights were acceptable and chose not to change the default parameters. Because we did not change any canopy height parameters (other than increasing the maximum potential canopy height to 2.6 m for both models), we included the 2007 year with the other 3 years (2008, 2009, and 2010) that had canopy height data in our validation data. For all model evaluation statistics, the new canopy height sub-model was better than the original sub-model for all years except 2010 (Fig. 1). The mean of the 4 years for each model statistic calculated for the original and new sub-model, respectively, was 53.7 and 40.7 cm (RMSE), 26.0 and −1.3 % (RE), 0.84 and 0.92 (*d*), and 0.47 and 0.33 (NOF).

As expected from the sub-model structure, the general pattern of canopy height over time for each sub-model followed the same pattern (sigmoidal for the original and linear for the new sub-model). The original sub-model simulated a greater rate of canopy height increase during the season in all years and tended to reach final canopy height slightly earlier than the new sub-model and observed data, and except for 2008, predicted a slightly higher final height. For maize plant development, the beginning of internode elongation should begin stem growth (about the V6 stage) and end at tasseling, and these are the default developmental stages ending phases 1 and 2, respectively, in the new canopy height sub-model. Assuming the V6 and tasseling stages are simulated accurately, when examining Fig. 1, it appears that the maximum potential canopy height at the end of phase 1 needs to be increased for the new sub-model and that the original canopy height model ceases growth a little early (i.e., before tasseling).

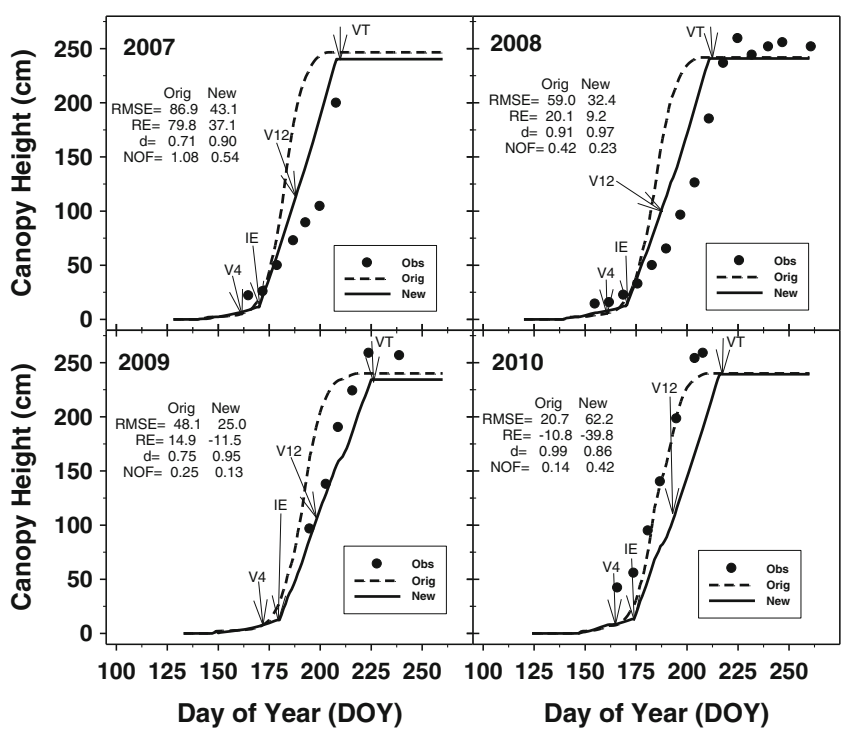

Fig. 1 Observed (*Obs*) and simulated canopy height. Simulated canopy height from the original sub-models (*Orig*) is shown as a *dashed line*; simulated canopy height from the new sub-models (*New*) is shown as a *solid line*. Model evaluation statistics are shown for each year. Relevant developmental stages predicted by the new phenology sub-model are the following: *V4*, fourth collared leaf is present; *IE*, the beginning of internode elongation (marking end of phase 1 of canopy height growth and beginning of second phase); *V12*, 12th collared leaf is present; and *VT*, tasseling (the end of canopy height increase for phase 2)

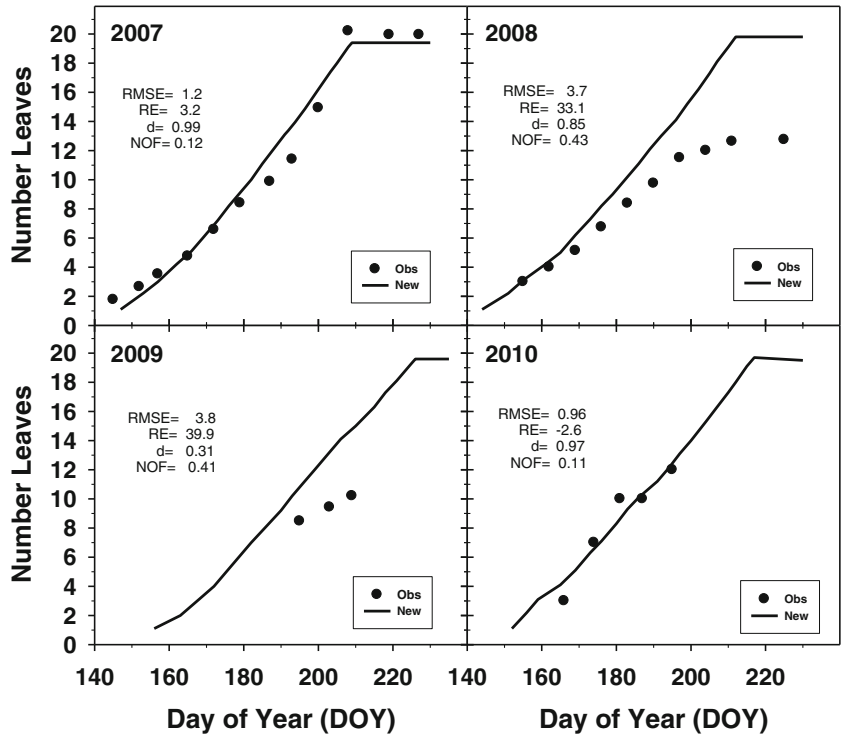

Fig. 2 Observed (*Obs*) and simulated (*New*) number of collared leaves. The original plant growth sub-model does not simulate leaf number, so only the simulated leaf number from the new sub-model is shown (as a *solid line*). Model evaluation statistics are shown for each year. Observed data for 2008 used number of leaf tips appearing rather than number of collared leaves. Model statistical measures are root mean square error (*RMSE*), relative error (*RE*), index of agreement (*d*), and normalized objective function (*NOF*)

Calibrating to the 2007 data with the default phyllochron of 35 °C· day leaf^{-1} resulted in good model prediction of leaf number (Fig. 2). Therefore, we chose not to change the default phyllochron and included the 2007 year with years 2008–2010 for validating simulated leaf number. Unfortunately, years other than 2007 had fewer observed data and measurements tended to cease prior to the flag leaf. In 2008, two problems with the observed data were noted: (1) total number of leaf tips were measured rather than collared leaves used in the other years and predicted by the phyllochron; and (2) leaf number leveled off suggesting reaching final number of leaves, but this number was clearly too low. It is possible that the hail in 2008 influenced these results. Despite these problems, the different model evaluation statistics all showed values equal to 2007 (2010) or were slightly poorer (2008 and 2009). The mean of the 4 years for each model statistic calculated for the new sub-model was 2.4 leaves (RMSE), 18.4 % (RE), 0.78 (*d*), and 0.27 (NOF). When calculating the phyllochron value for each year (using the second earliest leaf number in 2007 and 2008, the last leaf number not including the flag leaf, and summing the thermal time between these leaves), the phyllochron varied considerably among years: 41 (2007), 55 (2008), 90 (2009), and 33 (2010)°C days leaf^{-1}. For 2009 and 2010, all the observed leaf numbers were used because there were a small number of observations. The 2009 value is unrealistically high and likely due to the small number of observations (3).

Minimal observed phenological data were available to evaluate either phenology sub-model (Table 4). With no maturity and limited seedling emergence observations (the two main developmental events of the original WEPS sub-model), we focus here on the simulation results from the new phenology sub-model within UPGM (Table 6). Simulated dates of seedling emergence for the original seedling emergence sub-model ranged from 1 day (2005 and 2009) to 5 days (2007) later than the new seedling emergence sub-model (Table 6). Observed date of seedling emergence in 2007 was 25 May (85 % emerged), the same as the original sub-model simulated date and later than the new sub-model date (20 May). In 2009, the original sub-model simulated date was 1 day later than both the observed date and the new sub-model simulated date (29 May). Examining the observed data for 2007, simulated date of V4 was 5 days later than observed, but simulated date of V12 was 6 days earlier than observed (these results are reflected in Fig. 2), and simulated dates were later than observed dates for tasseling (9 days), silking (9 days), and dent (3 days) stages. However, simulated results for V4 (2009) was 1 day earlier than observed and was 2 days later for V12 (2010). Simulated dates were later than observed dates for tasseling (2009, 10 days) and silking (2009, 11 days; 2010, 14 days), similar to 2007. The WEPS User Manual [54] suggests that the reproductive store biomass (i.e., grain + chaff) should be zero before the time of flowering/anthesis (which would be silking/R1). The original sub-model predicted the beginning of grain biomass at least a month prior to when the new sub-model predicted silking. Maturity was predicted considerably earlier by the original phenology sub-model than the new sub-model in all years, except 2009 (which did not accumulate the required thermal time to reach maturity in the fall).

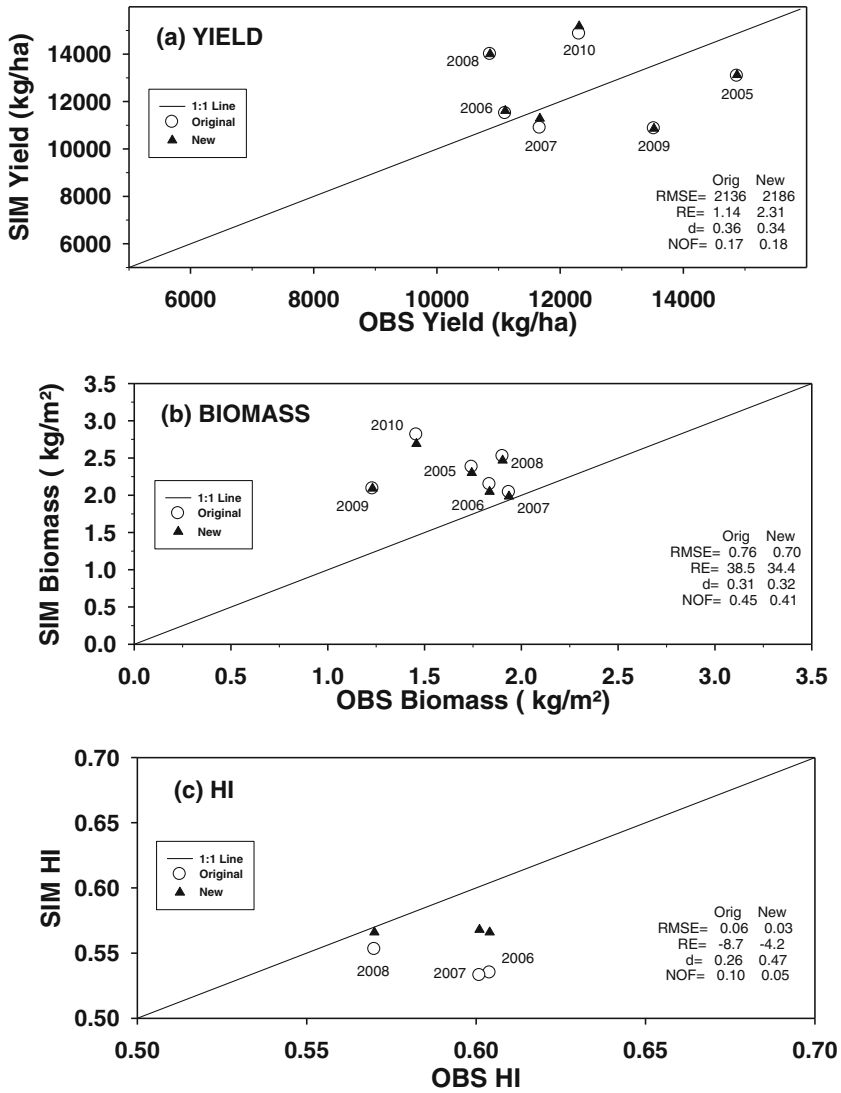

Fig. 3 Observed (*OBS*) and simulated (*SIM*) grain yield (**a**), final above ground biomass (**b**), and harvest index (HI, **c**). Simulated values from the original sub-models (*Orig*) are shown as *open circles*, simulated values from the new sub-models (*New*) are shown as *solid triangles*. Data from 2007 were used for calibration

End of season model simulation results for grain yield, final above ground biomass, and harvest index (HI) are presented in Fig. 3. Data from 2007 were used for calibration, and no modification of default parameters (other than those related to the phenology, seedling emergence, and canopy height models) was performed. In 2007, yield, biomass, and HI were predicted slightly better when running with the new sub-models than the original sub-models. Accuracy of yield prediction was variable based on the year, and overall little difference was noted between simulating with the original or new sub-models, but the original sub-models had slightly better simulation results (Fig. 3a). Other than 2006, simulated yields were different from observed yields with a RMSE of about 2,100 kg ha^{-1} and no apparent bias (RE between 1 and 2 %). Higher simulated than observed yields in 2008 likely were the result of the hail storm, but differences between simulated and observed yields in 2005, and 2009, and 2010 cannot be explained.

Final above ground biomass measurements were taken prior to maturity and this partly explains the higher simulated values by both models than observed (RE between 34 and 38 %; Fig. 3b). In all years, the model evaluation statistics (except *d*) indicated that using the new sub-models resulted in very slightly more accurate simulation of final biomass than the original sub-models. The results for final above ground biomass will greatly influence the HI results. The new sub-models predicted HI slightly better than the original sub-models when combining all years (Fig. 3c), but both models predicted HI values within expected levels [22, 28]. Both models tended to underpredict observed HI (RE=−4.2 % for new sub-models and −8.7 % for original sub-models). The years 2005, 2009, and 2010 were omitted from the analysis as the total aboveground biomass was measured shortly after flowering while final grain yield was measured at maturity, resulting in unreasonable HI values greater than 0.7. The UPGM model predicted a relatively stable HI varying from

0.519 to 0.553 (original sub-models) and 0.518 to 0.569 (new sub-models) when simulating all 6 years (2005–2010).

4 Discussion

Few observed data were available for calibrating or validating the seedling emergence sub-models. We adjusted the default parameter (HUIE) in the original sub-model to delay emergence from optimal conditions, and in the new sub-model chose the medium soil water category over the default optimum to more realistically simulate time of emergence for the growing conditions of the study. While this seemed to work adequately for the 6-year data set, the new sub-model should be more responsive to changes in soil moisture (from precipitation or irrigation) after planting than the original sub-model that uses a static thermal time value. As a result, the new sub-model should be more robust in simulating highly variable soil water conditions, particularly for rain-fed systems where soil water at planting varies from planted in dust to near optimal conditions with unpredictable precipitation events after planting.

Data were also limited to calibrate and evaluate the phenology sub-models. Although the new phenology sub-model predicted silking (R1) 2 days after the observed date in the 2007 calibration, it predicted silking much later in 2009 (11 days) and 2010 (14 days) than observed. The new sub-model always predicted maturity later than the original sub-model, except for 2009. The default thermal time required from planting to maturity (THUM) in the original model was reduced in our calibration using the 2007 data and it is likely that this value needs more adjustment. The default thermal time requirements leading to maturity for 100-day maize in the new phenology sub-model were not adjusted. It might have been better to have selected a 95-day hybrid, which is also closer to reported values for a couple of the hybrids used in the data set, and to adjust the parameters for silking and tasseling. Adjusting these parameters would potentially avoid problems in years such as 2009 where simulated maturity did not occur until the following year due to insufficient accumulated thermal time from May through October (Table 5). Further, simulated maturity dates in mid-November (2005 and 2008) seem late [10, 42].

The original phenology sub-model predicts a limited number of developmental events (e.g., seedling emergence and maturity). The new phenology sub-model added to UPGM predicts the timing of many additional developmental stages, and this information might be useful in determining or changing input default parameters. For example, daily biomass is distributed among canopy components of leaf, stem, and reproductive structures [43–45]. Default parameters control the partitioning curves for leaf and reproductive curves, with any remaining biomass going to the stem component. Parameters influence the beginning or ending of partitioning to the component, and knowledge of the developmental events should aid in determining these coefficients. To illustrate this, maize leaf appearance and growth occurs from emergence until the flag leaf completes growth (at about the tasseling stage). After the flag leaf, canopy senescence occurs until no live leaves are present (near physiological maturity). Partitioning to reproductive material begins at the time the tassel and ears are being formed (near the V6 stage) and ends at physiological maturity (R6). However, significant biomass partitioning does not occur until the time of tasseling (VT)/silking (R1) when grain set occurs. This is why the WEPS User Manual [54] says the reproductive biomass should be zero before the time of flowering, although some partitioning should occur prior to flowering. While partitioning to stem biomass occurs only if biomass is available after leaf and reproductive partitioning occurs, nevertheless the pattern should follow what normally occurs, and for an annual grass, stem material is not formed until the beginning of internode elongation (near V6 stage) and continues until the tasseling stage.

Examples of changing parameter values during the life cycle would include the energy to biomass, or radiation use efficiency, coefficient (BCEFF) and specific leaf area (SLA) parameters. Both parameters may change based on either environment or leaf age or both. For instance, it is well known that BCEFF is affected by environment [27, 58] and should decrease as a leaf ages and loses photosynthetic efficiency [11, 14, 39]. Considering the development of the canopy and LAI, the increase is characterized by the dynamic interaction of new leaves appearing (and usually increasing in area ontologically) and older leaves senescing up to the flag leaf (ending leaf appearance). Following the flag leaf, all leaves are aging and senescing. Therefore, the parameter likely should be reduced over time following flag leaf appearance. Similarly, specific leaf area is greatly influenced by environmental conditions during the appearance and growth of the leaf, but it also can change ontologically with leaf number [8, 49].

5 Summary and Conclusions

A standalone plant growth model, UPGM, was derived from the WEPS model as the platform for unifying enhancements from other EPIC-based plant growth models. We also added new phenology, seedling emergence, and canopy height sub-models from the PhenologyMMS V1.2 software program. We expect the new sub-models should improve the model robustness across different environments as they incorporate responses to varying water deficits.

Both the WEPS plant growth component [1, 16, 18, 19, 43–45] and PhenologyMMS [30, 32] have been previously applied and evaluated. The focus in this paper was not to

thoroughly calibrate and evaluate UPGM, rather to initially assess whether the new sub-models more accurately simulated plant processes than the original sub-models under assumed non-limiting water conditions. Model evaluation statistics (RMSE, RE, *d*, and NOF) for the calibration year (2007) canopy height, leaf number, grain yield, final above ground biomass, and HI index were quite good, with the new sub-models predicting slightly more accurately than the original models. Validation results for canopy height and leaf number were similar to the calibration results, but grain yield, final above ground biomass, and HI results were not simulated as well, and in most instances the new sub-models improved the simulation results.

A series of steps have been identified to further develop UPGM to better incorporate existing modifications to the EPIC-based plant growth model and new enhancements. The next key step is to create a more useable and complete standalone plant growth model by linking UPGM with a simplified WEPS interface focusing only on processes related to UPGM, incorporate the WEPS water balance algorithms and management practices database, and add output visualization routines. Following this, work will continue on improving the linkage of the new phenology, seedling emergence, and canopy height sub-models with the original code, and expanding the number of crops simulated by the new sub-models. A nitrogen balance sub-model will need to be re-introduced into UPGM as this is not part of the WEPS model. Other existing enhancements such as the ability to simultaneously simulate multiple species as done in ALMANAC will also be incorporated.

Acknowledgments The PhenologyMMS software may be downloaded at http://www.ars.usda.gov/services (select "Software") or http://arsagsoftware.ars.usda.gov.

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