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Multi-Crop Plant Growth Modeling from Field to Watershed for Water Quality and Management

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Abstract: Agricultural models and decision support systems (DSS) for assessing water quality and management are increasingly being applied to diverse geographic regions at different scales. This requires models that can simulate many different common and alternative crops. However, very few plant growth models are available that "easily" can simulate the growth of many crops, and these models lack the scientific detail incorporated into crop-specific models. One option available is a suite of plant growth models based on the original plant growth model used in the Environmental Policy Integrated Climate (EPIC) model. Various versions of the original EPIC plant growth model have been used in other models such as the Great Plains Framework for Agricultural Resource Management (GPFARM) DSS, Water Erosion Prediction Project (WEPP) model, Wind Erosion Prediction System (WEPS) model, Soil and Water Assessment Tool (SWAT), and the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model. While these versions are quite similar, slight improvements have been made for specific model objectives. Unfortunately, improvements to individual models have generally not been incorporated into the other models. This paper discusses efforts to develop the Unified Plant Growth Model (UPGM) from existing EPIC-based plant growth models, recode and modularize the UPGM, and then enhance specific sub-modules (e.g., phenology, seedling emergence) for improved overall model predictive accuracy. Several issues involved with developing this generic plant growth model are also covered including developing default plant parameters, needed improvements for simulating many diverse agricultural management practices across different soils and environments (while keeping the model simple to use), and evaluation of both specific sub-modules and overall plant growth model.

Keywords: Crop growth and development; Phenology; Seedling emergence; Modeling, Scaling

1. INTRODUCTION

The USDA-ARS Agricultural Systems Research Unit (ASRU) has developed a number of agricultural simulation models and decision support systems [(e.g., Great Plains Framework for Agricultural Management, (GPFARM, Andales et al., 2003; McMaster et al., 2002; Shaffer et al., 2000); Root Zone Water Quality Model, (RZWQM, Ahuja et al., 2000); SHOOTGRO (McMaster et al., 2002, Wilhelm et al., 2003); Nitrogen Leaching and Economic Package (NLEAP, Shaffer et al., 2001)] that can apply to assessing water quality and management. These and other agricultural models and decision support systems for assessing water quality and management are increasingly being applied to diverse geographic regions at different spatial scales. These efforts, combined with policy pressures for national assessment of the effects of conservation practices and systems, have resulted in the inter-agency Conservation Effects Assessment Project (CEAP). The role of ASRU in the CEAP effort is to extend previous field-scale modeling efforts to a watershed-scale level simulation model using the latest in scientific understanding within the Object Modeling System (OMS) Framework (David, 2002)

Most modeling efforts at smaller spatial scales from small plots to landscape position on a catena have generally used detailed plant growth models that are often crop-specific and have many parameters to adjust for cultivar differences. Many of these parameters are not easily determined, and considerable effort can be needed for calibrating the models for new environments, regions, and cultivars. Modeling larger scales approaching watersheds has typically required use of much simpler generic plant growth models for different species with no distinction among cultivars. Modeling at this scale normally requires that parameters must be easily determined and usually default parameters are provided and rarely altered by users.

The original objectives of the agricultural models now being applied to assess water quality and management have differed. A generalization could be made that those with detailed plant growth models sought accurate yield predictions, and those with simpler plant growth models emphasized biomass, canopy height, and groundcover estimates for use in assessing other objectives (e.g., as erosion prediction and off-site environmental impacts). Therefore, when assessing water quality and management, selection of models should consider the strengths of the model (likely reflected in the original intentions for building the model).

Selection of the appropriate model also should consider the spatial scale of interest. Increasing the spatial scale results in greater diversity of species/cultivars, soils, and environments present within the land unit of consideration. One frequent approach has been to use detailed crop-specific models as point-models on a grid within the unit of consideration and aggregate the results over the region of interest. For instance, in many U.S. erosion and watershed scale model development projects [e.g., Water Erosion Prediction Project model (WEPP, Flanagan and Nearing, 1995), Wind Erosion Prediction System (WEPS, Wagner, 1996), Soil and Water Assessment Tool (SWAT, Arnold et al., 1995)] the point model has been based on the EPIC plant growth model (Williams et al., 1989). Obvious problems with this approach are: 1) that only a small subset of species diversity can be simulated by these models; 2) the models may be difficult and time consuming to parameterize; and 3) simulation of interactions among points for the distribution and movement of abiotic factors (e.g., water, nutrients, temperature) is normally poor, if even present. Unfortunately few models exist that avoid these problems.

Three important areas for effort stand out for ASRU to meet the CEAP Project goals for developing a watershed scale model that can address the effects of conservation practices and systems: 1) better methods for scaling from small plots to watersheds, 2) better routing and distribution of abiotic factors within the watershed, and 3) improvement in simulating the plant growth component of watersheds. The objective of this paper is to discuss our approach for improving the simulation of plant growth in the CEAP watershed model development effort.

2. SOME RELEVANT REVISIONIST HISTORY

In 2003, the USDA-ARS Agricultural Systems Research Unit released Version 2.6 of the GPFARM DSS. The primary objective was to provide producers and agricultural consultants with a strategic planning tool for managing each field on their farm. The crop growth model in GPFARM was derived from the WEPP model, which itself was a modification of the EPIC plant growth model (Williams et al., 1989). The GPFARM plant growth model has been described elsewhere (e.g., Arnold et al., 1995; McMaster et al., 2002; Shaffer et al., 2004; Williams et al., 1989), and will only briefly be discussed here.

The generic plant growth simulation model is intended to simulate many different crops. A radiation use efficiency approach is used to simulate daily growth of shoots and roots, with a harvest index determining seed yield. Leibig’s Law of the Minimum is used to apply the effects of stress factors on crop growth and development. That is, stresses are estimated (e.g., temperature, water, N) and the most limiting factor is used to adjust the processes.

Evaluation of the crop growth model used in GPFARM has produced mixed results (Andales et al., 2003; McMaster et al., 2003; Shaffer et al., 2004). Generally, the model was able to reasonably simulate long-term crop yield (with relative error usually within ±15%) and biomass production in response to different management systems and environments necessary for strategic planning. However, year-to-year prediction of specific crop yield and biomass production for specific management systems and environments was much less satisfactory. An overall conclusion derived from the evaluations was that significant improvements were needed in simulating the responses to various stresses, particularly water stress.

Other researchers have used the EPIC-based plant growth model in their agricultural system models. In addition to GPFARM, the WEPP, WEPS, ALMANAC (Kiniry et al., 1992), and SWAT models have made modifications and enhancements to the original EPIC plant growth model. As expected, model performance is similar to that found for GPFARM because these models use most of the underlying processes of the EPIC plant growth model. To meet the objectives of these various diverse modeling efforts and the ASRU CEAP objective, the need for improvements in predicting plant growth and yield has become clear. Therefore, we are working towards consolidating modifications from these different efforts into a Unified Plant Growth Model (UPGM) to serve as the foundation for further improvements.

3. APPROACH FOR CREATING UPGM

The process for creating the foundation of the UPGM was to extract the plant growth model from

WEPS and create a stand-alone version that reads weather data and other inputs from driver files. Plant parameters for 130+ crops/cultivars previously developed for the WEPS model are available for use. This work has been essentially completed.

Areas identified for possible improvements came from several approaches and were identified by McMaster et al. (2005a). Briefly they can be summarized as follows:

- A thorough testing and sensitivity analysis of the GPFARM plant growth model.
- A thorough physiological evaluation of each process in the stand-alone plant growth model was conducted to determine opportunities for improving the scientific conceptualization and quantification of these processes.
- Notes were developed while conducting the physiological analysis for improving the conceptual representation of the processes. These notes are the basis for developing stand-alone process components.
- The stand-alone plant growth model needs to be modularized so changes identified above and different modifications and enhancements by various projects using the EPIC-based plant growth model can more easily be incorporated into the model.

3. PREVIOUS WORK IN WEPS AND GPFARM ON EPIC-BASED PLANT GROWTH MODEL

There are a few significant differences between the WEPS-based and GPFARM-based plant growth models. The WEPS model computes more detailed above ground plant components needed for wind erosion prediction (e.g., number of stems, stem silhouette factor, spring regrowth of perennials, etc.). The GPFARM model has some modifications of LAI and plant density processes derived from the ALMANAC model (Kiniry et al., 1992). The ALMANAC model also has the ability to simulate up to 11 species, which allows weed/crop interaction and intercropping.

4. POSSIBLE ENHANCEMENTS IDENTIFIED FROM GPFARM EVALUATION AND PHYSIOLOGICAL EVALUATION

Six high priority areas for modifying the EPIC-based plant growth model were discussed in McMaster et al. (2005a) including seedling emergence, phenology, generating plant biomass, partitioning biomass, root growth, and better characterization and interaction of abiotic stress factors. Only seedling emergence and phenology will be discussed in this paper.

4.1 Seedling Emergence

In many systems, particularly semi-arid production systems such as the western Great Plains, seedling emergence is critical in determining biomass accumulation and final yield. Beside the obvious important reason that if the stand does not come up in a timely manner yield and biomass accumulation will be adversely affected, seedling emergence is critical in determining development rates and thus the pattern of biomass accumulation and yield formation. Delaying emergence often results in the plant growing under conditions it was not adapted to and bred for, and stressful environments that might have been avoided if timely emergence had occurred. Staggering emergence over long time intervals also results in lower yields, harvesting problems, and reduced quality.

In the EPIC-based plant growth model, seedling emergence is based solely on temperature, whereby the thermal time (in the form of growing degree-days, GDD) from sowing to emergence is an input parameter for each species. Thermal time is calculated using only a base temperature and no upper threshold temperature which may be problematic for many spring-sown crops. Other factors, particularly soil moisture, have no impact on this static parameter. This poses particular problems for simulating observed differences among tillage practices that alter seedbed soil moisture and for management practices such as planting into dry soil in anticipation of subsequent rainfall to germinate the crop. Also, large temporal variability due to weather variations in soil moisture in the seedbed zone is common in most systems. While as a general rule using thermal time when seedbed conditions are reasonably good for germination can work adequately for large scale modelling applications, deviating from these conditions can result in significant prediction errors.

Numerous seed germination and emergence models have been developed, with the most simple based on assuming germination rate is a function of some measure of soil water content, and that shoot elongation, or emergence rate, is then a function of thermal time. Detailed variations on this general form are available including adding soil strength and crusting impacts on elongation rate, correcting for seeding depth, and creating an emergence curve over time or by breaking it up into cohorts based on emergence time. The SHOOTGRO small-grains simulator model (Wilhelm et al., 1993) encapsulates these enhancements of the general seedling emergence model and is used as the basis for creating a new seedling emergence sub-model in UPGM.

Seedling emergence in SHOOTGRO is a function of temperature (i.e., accumulated thermal time), soil water content of the seedbed zone, and seeding depth. Germination and seedling elongation rates are based on four general categories of soil water based on water-filled pore space: optimum, barely adequate, dry, and planted in dust. Seedling emergence follows a normal distribution with a default variance for the distribution that may be changed if desired. Seedlings may be divided into 6 cohorts if desired.

We are incorporating this sub-model into UPGM using the following approach. First, insert the sub-model without the cohort component for a few selected species (wheat, corn, and barley) to evaluate degree of improvement. If successful improvement occurs (based on standard model evaluation procedures such as RMSE, regression, simulated and observed coefficient of variation, and relative error), then formal integration into the model will be done, which mainly involves adding a few parameters to the plant parameter default input file. These parameters would be germination and elongation rates based on the seedbed zone soil water content. For many crops these are readily available parameters.

4.2 Phenology

Phenology likely is the next most important process in accurately simulating biomass accumulation and final yield. Development stage of the plant influences many plant processes including biomass generation, partitioning, root growth, and final yield. If sufficient detail is involved, an accurate assessment of source and sink presence and activity at any point in time is possible, thereby increasing the accuracy of simulating the above processes. Essentially all crop growth models have some form of a phenology sub-model, with great variations existing in how processes are simulated and degree of detail incorporated.

For most crops, temperature is the primary driving factor controlling phenology, although many other factors can be important including photoperiod, water, nutrients, CO_2, and salinity (McMaster, 1997). The EPIC-based phenology sub-model uses thermal time (i.e., GDD as an input parameter for each species) to simulate the time from sowing to maturity, with no adjustment for other factors known to impact development. Each annual crop life cycle progresses from 0 (at sowing) to 1 (maturity), and a few growth stages are designated as occurring as some fraction. For instance, start of canopy senescence and anthesis (start of grain filling) are input parameters for each species. This approach has greatest validity for spring-sown crops, but can be very problematic for winter-sown crops such as winter wheat, winter barley, and canola. The difficulty lies in winter crops that require vernalization before initiating reproductive development. Different fall planting dates can result in significant differences in the accumulation of thermal time before the vernalization requirement is satisfied. The result is that spring/summer growth stages (i.e., start of senescence and reproductive development) can be simulated too early, and occasionally in the fall/winter which should not occur.

This low level of phenological detail also creates problems in the EPIC plant growth model for reasonable partitioning and re-translocation algorithms among leaves, stems, roots, and seeds because it lacks sufficiently precise definition of when specific sources and sinks are present and active. In addition, current coding does not compute the number of organs (leaves, stems, seed) in the plant or canopy. Both number and time of appearance of organs dramatically impact partitioning and translocation.

Finally, because the input parameters are species-based, rather than cultivar-based, there is no representation of genotypic differences in phenology (or other plant parameters), and consequently genotype by environment interaction cannot be simulated (McMaster et al., 2003).

Enhancements of the phenology sub-model are based on a stand-alone model for predicting multi-crop phenology (Phenology MMS) that has been developed and incorporates stress responses, particularly to water availability (McMaster, 2004; McMaster et al., 2005a, 2005b). Keys to this model are the developmental sequences of the shoot apex and correlating the sequences with developmental stages on a thermal timeline. Composite diagrams (as depicted in Fig. 1) are then adjusted appropriately by the impact of abiotic stresses on the thermal time (as depicted in Fig. 2). Developmental sequences have been developed to date for winter and spring wheat, winter and spring barley, corn, sorghum, proso millet (*Panicum miliaceum* L.), foxtail/hay millet [*Setaria italica (L.)* P. Beauv.], and pearl millet (*Pennisetum americanum* L.). Current work is underway for soybean, sunflower, dry beans, and canola.

We are using the same approach for incorporating the Phenology MMS sub-model into UPGM as being done with the seedling emergence sub-model. First, the sub-model will be inserted for a few selected species (wheat, corn, and barley) to evaluate the degree of improvement. If successful improvement occurs (based on standard model evaluation techniques mentioned for seedling emergence), then formal integration into the model will be done. Because more parameters are involved with the developmental sequence diagram, it is less clear how best to approach this with a generic model for simulating many crops where not all these parameters are readily available. For crops where the developmental sequence has already been developed this issue has been resolved. If parameters for detailed developmental stages cannot be readily derived from the literature for the other crops, then simplified sequences will be constructed, mainly for the beginning and end of root, leaf, and stem growth and time of flower initiation, flowering/anthesis, and maturity. Some of these stages have been directly or indirectly specified in the existing plant growth model. Some parameters for this diagram are already parameter inputs in the current plant growth model and others can reasonably be derived from general patterns of plant development.

5. SUMMARY

We have presented an approach for creating a generic unified plant growth model (UPGM) that incorporates modifications to the different versions of the EPIC-based plant growth model and other enhancements developed independently. Initial efforts in improving the seedling emergence and phenology processes are discussed. The UPGM will be integrated into the interagency watershed-scale model currently under development for the Conservation Effects Assessment Project (CEAP).

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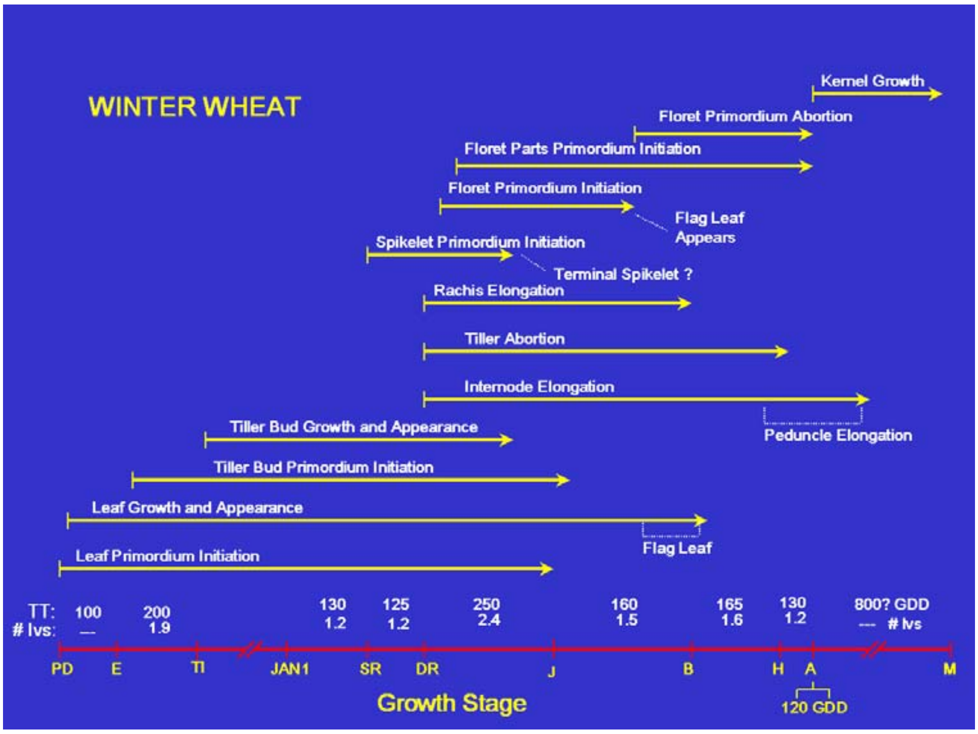
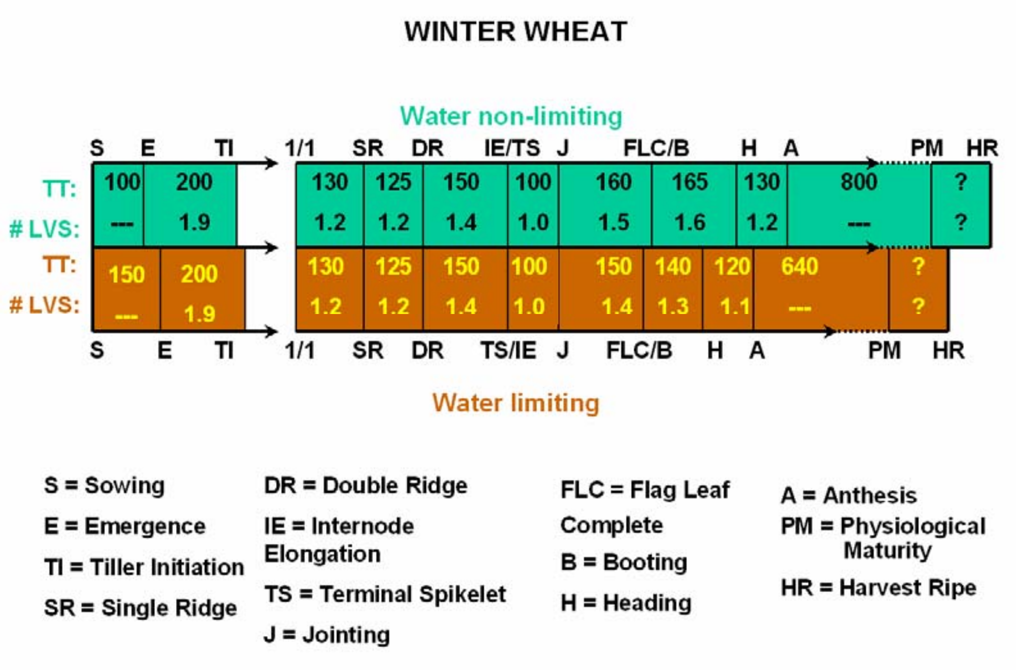


Figure 1. Developmental sequence for winter wheat - see Fig. 2 for growth stage abbreviations (Adapted from McMaster, 1997).



S = Sowing
E = Emergence
TI = Tiller Initiation
SR = Single Ridge

DR = Double Ridge
IE = Internode Elongation
TS = Terminal Spikelet
J = Jointing

FLC = Flag Leaf Complete
B = Booting
H = Heading

A = Anthesis
PM = Physiological Maturity
HR = Harvest Ripe

Figure 2. Timing of growth stages for selected a generic winter wheat plant for water non-limiting and limiting conditions (After McMaster et al., 2005b).