Multi-Crop Plant Growth Modeling for Agricultural Models and Decision Support Systems

G.S. McMaster, J.C. Ascough, II, D.A. Edmunds, A.A. Andales, L. Wagner and F. Fox

U. S. Department of Agriculture, Agricultural Research Service, E-Mail: Greg.McMaster@ars.usda.gov

Keywords: Simulation models; Plant growth; GPFARM; iFARM.

EXTENDED ABSTRACT

Agricultural models and decision support systems are becoming increasingly available for a wide audience of users. The Great Plains Framework for Agricultural Resource Management (GPFARM) DSS is a strategic planning tool for farmers, ranchers, and agricultural consultants that incorporates a science simulation model with an economic analysis package and multi-criteria decision aid for evaluating individual fields or aggregating to the entire enterprise.

The GPFARM DSS is currently being expanded to include 1) better strategic planning by simulating a greater range of crops over a wider geographic range and management systems, 2) incorporating a tactical planning component, and 3) adding a production, environmental, and economic risk component.

The plant growth component within the science simulation model is subdivided into separate submodels for crops and rangeland forage. User requirements have determined that the DSS must be easy to use in terms of setup, and therefore little parameterization or calibration for a specific site can be required.

Based on evaluation of both the crop and rangeland forage growth module of GPFARM, improvements are needed to more accurately simulate plant responses to varying levels of water availability. This paper presents our approach and some preliminary results for improving the plant growth models.

Our approach is based on using the stand-alone plant growth model derived from the Wind Erosion Prediction System (WEPS), which is based on the EPIC plant growth model. Steps that should improve the plant growth models include 1) incorporate modifications from work done to other models that are based on the EPIC plant growth model (e.g., GPFARM; Water Erosion Prediction Project, WEPP; ALMANAC; and Soil and Water Assessment Tool, SWAT), and 2) thoroughly evaluate how the plant processes are represented in these models.

Deficiencies in adequately simulating plant growth responses to water availability can fall under two general categories: inadequate quantification of the process or omission of a needed process in the model. High priority needs identified to date include: 1) seedling emergence, 2) phenology, 3) biomass generation, 4) biomass partitioning, 5) root growth, and 6) plant stress factors.

Initial work has created stand-alone submodels for predicting seedling emergence (as a function of soil water and thermal time) and phenology (by predicting specific growth stages and responses to different levels of soil water availability). Evaluation of alternative approaches for generating biomass (e.g., radiation use efficiency, transpiration use efficiency, plant growth analysis), biomass partitioning (e.g., modifications to generating LAI and partitioning coefficients partly based on better phenology prediction), and stress factors (e.g., single-most limiting, additive, multiplicative) is underway. We envision that these modifications and enhancements should improve model responses to varying levels of soil water availability.

1. INTRODUCTION

Increasingly, agricultural decision support systems are being delivered for use under various cropping and management systems over large geographic areas with diverse environments and soils. When primary users are producers, agricultural consultants, or agribusiness, reasons for limited adoption of products include difficulty in installation and use, long run-time, and confusing presentation of results (Ascough et al., 2002).

The USDA-ARS Great Plains Systems Research Unit has released a decision support system called GPFARM (Great Plains Framework for Agricultural Resource Management). The primary objective was to provide producers and agricultural consultants with a strategic planning tool for managing each field on their farm. GPFARM utilizes stand-alone components including a user interface, process-oriented simulation model, and databases (McMaster et al., 2002; Shaffer et al., 2000). When combined with other components (e.g., economic budgeting and multi-criteria decision analysis), producers have an integrated tool for farm and ranch management.

Two key submodels of the process-oriented simulation model are the crop growth and forage production modules. The forage module was created specifically for GPFARM (Andales et al., 2005). Daily growth and senescence of functional groups (e.g., C_3 grasses, C_4 grasses, forbs, shrubs, cacti) can be simulated in response to water and nutrient availability and temperature.

The crop growth model in GPFARM is derived from the Water Erosion Prediction Project model (WEPP, Flanagan and Nearing, 1995), which was a modification of the EPIC plant growth model (Williams et al., 1989). The plant growth model has been described elsewhere (e.g., McMaster et al., 2002; Shaffer et al., 2004; Williams et al., 1989), and only a brief overview is provided here. This 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 (e.g., Andales et al., 2003; McMaster et al., 2003; Shaffer et al., 2004) and rangeland forage (e.g., Andales et al., 2005) growth models used in GPFARM has produced mixed results. Generally, the models are able to reasonably simulate long-term crop yield 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, making tactical applications of the DSS problematic. An overall conclusion derived from the evaluations was that improvements were needed in the crop and range growth models to better simulate responses to various stresses, particularly water stress. However, improving these responses was going to be difficult given the species-approach used for plant parameters that does not adequately deal with cultivar differences and the nearly ubiquitous reality of genotype by environment interaction.

The iFARM (Integrated Farm and Ranch Management) DSS project began after the release of GPFARM 2.6 in 2003. The main objectives of iFARM were to a) expand the crop and forage growth modules to simulate more systems and environments (especially geographic) to expand the strategic planning capabilities, b) add tactical decision making capabilities (e.g., opportunity cropping, grazing on live crops, and improve phenological predictions for aiding tactical decision making based on crop growth stage), and c) expand the economic and environmental risk component.

To meet these main iFARM objectives it was clear the rangeland forage and EPIC-based crop growth modules would need substantial improvements, or an alternative plant module was needed. Some difficulties with finding an alternative plant module were that few existing models simulate the required wide variety of crops, have been adequately evaluated across a wide range of management systems and environments, and are freely available for distribution. Therefore, we are working on developing and improving the range and crop growth models of GPFARM.

The objectives of this paper are to outline the plan for improving the crop growth module (with some references to the forage module), particularly in responding to different levels of water availability, and present progress towards this goal. We refer to the new model as the Unified Plant Growth Model (UPGM) for reasons explained below.

2. APPROACH FOR CREATING THE 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 completed.

Areas identified for possible improvements come from several approaches.

1) A thorough testing and sensitivity analysis of the GPFARM plant growth models.

2) A thorough physiological evaluation of each process in the stand-alone plant growth model is being conducted to determine opportunities for improving the scientific conceptualization and quantification of these processes.

3) Notes are developed while conducting the physiological analysis for improving the conceptual representation of the processes. These notes are the basis for development of stand-alone components for the processes.

4) The stand-alone plant growth model needs to be modularized so changes identified above can more easily be incorporated into the model. Work by others on EPIC-based plant growth models can then be incorporated. For instance, in addition to GPFARM, other work such as the Water Erosion Prediction Project (WEPP, Flanagan and Nearing, 1995), Wind Erosion Prediction System (WEPS, Wagner, 1996), ALMANAC (Kiniry et al., 1992), and Soil and Water Assessment Tool (SWAT, Arnold et al., 1995) have made modifications and enhancements to the original EPIC plant growth model. The major goal of the UPGM is to consolidate these modifications and serve as the foundation for further improvements.

3. PREVIOUS WORK 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 that are 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

This section presents planned enhancements to the plant growth model based on evaluation of the GPFARM plant growth model and physiological processes; six areas have been identified where enhancements are possible.

4.1. Seedling Emergence

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. 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 the seedbed soil moisture and for practices of planting into dry soil in anticipation of subsequent rainfall to germinate the crop.

4.2. Phenology

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 phenology submodel 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 and barley. 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., reproductive development) are simulated too early.

The low level of phenological detail also creates problems 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, the 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), consequently genotype by environment interaction cannot be simulated (McMaster et al., 2003).

4.3. Generating Plant Biomass

The EPIC-based plant growth models are similar to the vast majority of plant growth models in that they are energy-driven. Therefore, generating and partitioning biomass is critical to model performance. For generic plant growth models, three general ways are used to generate biomass: a radiation use efficiency approach (RUE), a transpiration use efficiency approach (TUE), and plant growth analysis approach. All approaches have fundamental similarities in that a fraction of incoming energy (i.e., radiation, temperature) is intercepted by the canopy (usually via LAI and a light extinction or absorption coefficient) and is converted to biomass via a use-efficiency factor. Once generated, biomass is partitioned to various plant parts.

The RUE approach is currently used in EPIC-based models (Russell et al., 1989). Several equations determine daily potential biomass production. Interception of photosynthetic active radiation (PAR) is estimated with Beer's law (Monsi and Saeki, 1953):

$$PAR_i = 0.02092(RA_i)(1.0 - e^{-0.65LAI})_i \qquad [1]$$

where *PAR* is intercepted photosynthetic active radiation (MJ m^{-2}), *RA* is solar radiation (Langleys), *LAI* is leaf area index, and subscript *i* is the day of the year.

Potential biomass production per day is estimated with the equation (Montieth, 1977):

$$\Delta BP_i = 0.0001(BE_j)(PAR_i) \qquad [2]$$

where ΔBP_i is the potential increase in total biomass on day i (kg m^{-2}), and BE_j is the energy to biomass conversion parameter for crop j (kg MJ^{-1}). *BE* is an input as a plant parameter that does not change during the life cycle.

Actual daily biomass accumulation is determined by applying Leibig's Law of the Minimum. The daily potential biomass accumulation (Eq. 2) is adjusted daily if one of the plant stress factors (water, N, or temperature) is less than 1.0 using the equation:

$$\Delta B_i = (\Delta BP_i)(REG) \qquad [3]$$

where *REG* is the crop growth regulating factor (the minimum of the water, N, and temperature stress factors) calculated for day *i*. The adjusted daily total biomass production ΔB_i is accumulated through the growing season.

4.4. Biomass Partitioning

Partitioning of daily biomass generated is slightly different among versions of the EPIC-based plant growth models. In general, the approach divides biomass between roots and shoots using a constant value for the root/shoot ratio input as a plant parameter for the crop. In EPIC and ALMANAC, LAI is calculated as a function of heat units, and a maximum LAI (input parameter) for each species. In WEPS, LAI is based on shoot biomass using a constant conversion factor for the life cycle of the plant. Seed biomass is derived from an adjusted harvest index algorithm that modifies a harvest index parameter input for specific crops.

4.5. Root Growth

Root growth is based on partitioning a fraction of daily biomass generated to root growth using the root/shoot ratio. Maximum rooting depth (with minimal flexibility for different root morphologies) is an input parameter for each crop. Rooting depth increases over time according to a function based on thermal time accumulated until maximum rooting depth is reached.

4.6. Stress Factors

Different 0-1 stress factors are calculated (e.g. water, N, temperature) to reduce the rate of some processes. The most limiting factor is used to adjust a potential rate based on optimal conditions (i.e., Leibig's Law of the Minimum). Calculation of stress factors is described in detail in McMaster et al. (2003).

5. PHYSIOLOGICAL CONCEPTUALIZATION OF PROCESSES

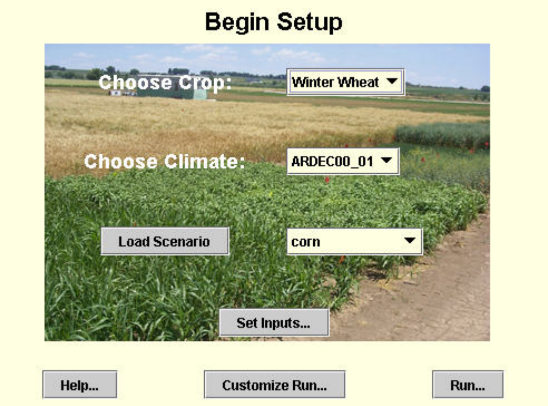
This section briefly mentions some conceptualization and preliminary work for the areas of improvement needed for the UPGM. Stand-alone components are being developed for these processes (e.g., seedling emergence, phenology) that will be incorporated into the UPGM.

5.1. Seedling Emergence

This submodel is based on the conceptualization used in the SHOOTGRO small-grains simulator model (Wilhelm et al., 1993). Seedling emergence 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.

5.2. Phenology

A stand-alone model for predicting multi-crop phenology (Phenology MMS) has been developed that incorporates stress responses, particularly to water availability (McMaster, 2004). This model has a Java interface that calls a Fortran simulation model for simulating phenology. The Java interface allows the user to either accept the default values or to simply change them. For instance, the user begins by selecting the crop and site/weather file or loading a previously created scenario as shown in Figure 1. If the user so chooses, they can then run the program at this time, or continue to modify other inputs.


Begin Setup

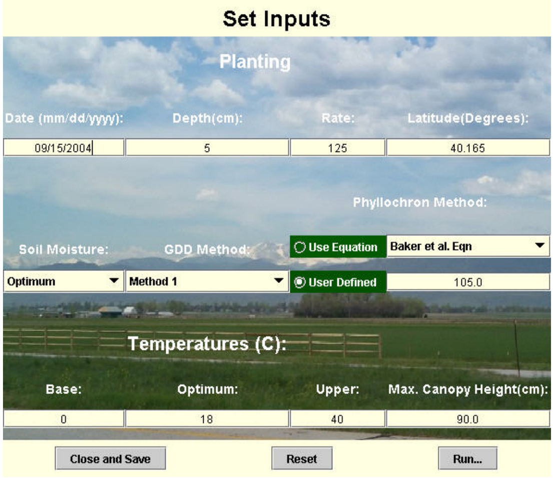
Choose Crop: Winter Wheat

Choose Climate: ARDEC00_01

corn

Figure 1. This screen is the first screen the user sees when entering the program.

When the crop has been chosen (Fig. 1), then initial inputs may be changed by the user if they do not want to accept the defaults (Fig. 2). Again, the user can then run the model.


Set Inputs

Planting

Date (mm/dd/yyyy): 09/15/2004

Depth(cm): 5

Rate: 125

Latitude(Degrees): 40.165

Soil Moisture: Optimum

GDD Method: Method 1

Phyllochron Method:
○ Use Equation Baker et al. Eqn
● User Defined 105.0

Temperatures (C):

Base: 0

Optimum: 18

Upper: 40

Max. Canopy Height(cm): 90.0

Figure 2. Example of initial inputs needed for the simulation model, with default values for winter wheat (*Triticum aestivum* L.) grown in eastern Colorado, USA.

After selecting a crop (Fig. 1), for each species a "generic" cultivar is assumed. If the user wishes to change the default parameters for a generic cultivar, or if they want to change the method of calculating thermal time (e.g., growing degree-days or leaf number), or if they want to change the stress level for a certain growth phase they can modify the parameters shown in Figure 3. Also, the user may select from a list of varieties (bottom of screen) and accept the parameters specified for the selected cultivar or change selected parameters to reflect the characteristics of the genotype of interest.


Generic Winter Wheat Growth Stages

	Growing Degree-Days:		Number of Leaves:	
	No Stress	Stressed	No Stress	Stressed
Seeding to Emergence	100 ●	150 ○	1.0 ○	1.5 ○
E to First Tiller	200 ●	200 ○	1.9 ○	1.9 ○
Jan 1 to Single Ridge	180 ●	175 ○	1.7 ○	1.7 ○
SR to Double Ridge	125 ●	120 ○	1.2 ○	1.2 ○
DR to Terminal Spikelet	150 ●	145 ○	1.4 ○	1.4 ○
TS to Jointing	105 ●	100 ○	1.0 ○	1.0 ○
J to Flag Leaf Complete	210 ●	160 ○	2.0 ○	1.5 ○
FLC to Heading	140 ●	130 ○	1.3 ○	1.3 ○
H to Anthesis Start	75 ●	65 ○	0.7 ○	0.7 ○
AS to Maturity	800 ●	640 ○	7.4 ○	5.9 ○
M to Harvest Ready	300 ●	175 ○	2.8 ○	1.6 ○

Variety: Generic

Figure 3. Growth stages screen for selected crop. The default parameters for a generic winter wheat plant are shown.

Figure 3 shows a key screen for the simulation model. This lists the entire crop specific developmental sequence and contains the parameters used in the simulation model. We base this screen on the approach of McMaster (1997, Fig. 4), and have developed sequences for winter and spring wheat, winter and spring barley

(*Hordeum vulgare* L.), maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), proso millet (*Panicum milaceum* L.), hay millet [*Setaria italica* (L.) P. Beauv.], several rangeland plants (or functional groups), and other species.

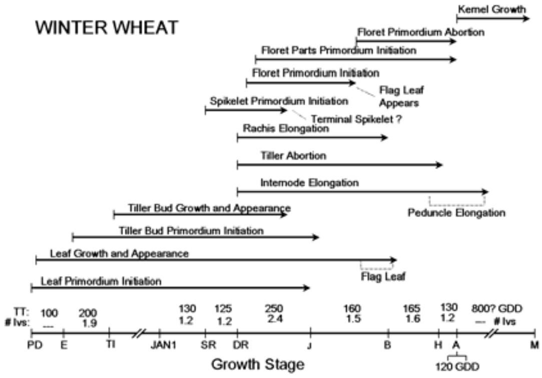


Figure 4. Developmental sequence for winter wheat. (Adapted from McMaster, 1997.)

5.3. Generating Plant Biomass

The radiation use efficiency (RUE) approach seems to work best under conditions where radiation tends to be a more limiting factor than water availability. In water-limiting environments, a variation often tried is called transpiration use efficiency (TUE), which is based on the ratio of biomass produced per unit of water transpired (Kemanian et al., 2005). It is not clear how the approach based on plant growth analysis compares to either the RUE or TUE approaches. Therefore, we will compare all three approaches for a limited number of crops (e.g., wheat, maize) for different environments to evaluate which approach works best in which environments. We also expect that when coupled with the more detailed phenology submodel discussed above we can change parameter values as appropriate for the growth stage of the plant.

5.4. Biomass Partitioning

Biomass partitioning is currently limited by insufficient detail in the phenological development of the plant. By improving the phenological submodel, more accurate simulation of biomass partitioning should be possible, and parameter values can be adjusted as appropriate by growth stage.

5.5. Root Growth

Three problems have been identified in this submodel: a) the start and ending of root growth and functioning is not adequately simulated, b) partitioning of daily generated biomass to roots is based on a static root/shoot ratio and no feedback on partitioning is considered for the resource that is limiting, and c) different root morphologies are not well accommodated.

By incorporating a more detailed phenology submodel as described above, the beginning and ending of root growth should be improved, and also partitioning of biomass to the roots should be enhanced by a clearer understanding of when they are growing and functioning. The root/shoot ratio approach also should be enhanced by altering the ratio based on resource limitions and stage of crop development. For instance, if water or N is limiting, a generic plant response is to allocate more resources to roots, and when light is limiting to allocate more to canopy growth. Last, because different species have different root morphologies, we have developed a submodel (currently in Java) whereby different root morphologies associated with different species are simulated. This is critical when more than one species is simulated, whether in the rangeland forage model, with intercropping, or with crop/weed competition situations. If only one species is simulated, as in a monocrop, then only one root morphology is selected. Root morphology also plays a critical role in determining water availability to the crop. Another possible improvement is to have a root "activity" function by layer that changes over time.

5.6. Stress Factors

A variety of approaches have been used to incorporate multiple stress factors. Liebig's Law of the Minimum, where only the most limiting factor is used to reduce the rate of processes, is the most straightforward. Physiologically it is most applicable when the level of the process is very limited, such as a single chemical reaction. However, as different processes are aggregated and scaled up (e.g., canopy LAI), then the concept that only one factor is limiting is less appropriate. Therefore, evaluating alternatives such as multiplying or adding the stress factors will be explored on select processes, although this requires a new stress response surface function for the approach largely due to the interaction of stress factors.

6. REFERENCES

Andales, A. A., Ahuja, L. R., and G. A. Peterson (2003), Evaluation of GPFARM for dryland cropping systems in eastern Colorado. *Agronomy Journal* 95: 1510-1524.

Andales, A. A., Derner, J. D., Bartling, P. N. S., Ahuja, L. R., Dunn, G. H., Hart, R. H., and J. D. Hanson (2005), Evaluation of GPFARM for simulation of forage production and cow-calf weights. *Rangeland Ecology and Management* 58: 247-255.

Arnold, J. G., Weltz, M.A., Alberts, E. E., and D. C. Flanagan (1995), Plant growth component. Chapter 8 in *USDA – Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation*, 8.1-8.41. NSERL Report No. 10. D. C. Flanagan, Nearing, M. A., and J. M. Laflen (eds.). West Lafayette, Ind: USDA-ARS National Soil Erosion Research Laboratory.

Ascough II, J. C., Hoag, D. L., McMaster, G. S., and W. M. Frasier (2002), Computer use and satisfaction by Great Plains producers: Implications for software developers. *Agronomy Journal* 94: 1263-1269.

Flanagan, D. C. and M. A. Nearing (eds.) (1995), *USDA – Water Erosion Prediction Project Hillslope Profile and Watershed Model Documentation*. NSERL Report No. 10. West Lafayette, Ind.: USDA-ARS National Soil Erosion Research Laboratory.

Kemanian, A. R., Stockle, C. O., and D. R. Huggins (2005), Transpiration-use efficiency of barley. *Agric. For Meterol.* 130: 1-11.

Kiniry, J. R., Williams, J. R., Gassman, P. W., and P. Debaeke (1992), A general process-oriented model for two competing plant species.

McMaster, G. S. (1997), Phenology, development, and growth of the wheat (*Triticum aestivum* L.) shoot apex: A review. *Advances In Agronomy* 59: 63-118.

McMaster, G.S. 2004. Simulating crop phenology. IN: T. Fischer et al. (Eds.), *New directions for a diverse planet:* Handbook and Abstracts for the 4th International Crop Science Congrress, Brisbane, Australia, 26 September - 1 October 2004. Web site www.regional.org.au/au/cs

McMaster, G. S., Ascough II, Dunn, G. H., Weltz, M. A., J. C., Shaffer, Palic, D. B., Vandenberg, B., Bartling, P., Edmunds, D., Hoag, D., and L. R. Ahuja. (2002), Application and testing of GPFARM: A farm and ranch decision support system for evaluating economic and environmental sustainability of agricultural enterprises. *Acta Horticulturae* 593: 171-177.

McMaster, G. S., Ascough II, J. C., Shaffer, M. J., Deer-Ascough, L. A., Byrne, P. F., Nielsen, D. C., Haley, S. D., Andales, A. A., and G. H. Dunn (2003), GPFARM plant model parameters: Complications of varieties and the genotype X environment interaction in wheat. *Transactions of American Society of Agricultural Engineers* 46: 1337-1346.

Monsi, M. and T. Saeki (1953), Uber den Lictaktor in den Pflanzengesell – Schaften und sein Bedeutung fur die Stoffproduktion. *Japan J. Botany* 14: 22-52.

Montieth, J. L. (1977), Climate and the efficiency of crop production in Britain. *Phil. Trans. Res. Soc. London B.* 281: 277-329.

Russell, G., Jarvis, P. G., and J. L. Montieth (1989), Absorption of radiation by canopies and stand growth. IN: Russell, G., Marshall, B., and P. G. Jarvis (eds.), *Plant Canopies: Their Growth, Form and Function*, Cambridge Univ. Press, Cambridge, pp 21-39.

Shaffer, M. J., Bartling, P. N. S., and J. C. Ascough II (2000), Object-oriented simulation of integrated whole farms: GPFARM framework. *Computers and Electronics in Agriculture* 28: 29-49.

Shaffer, M. J., Bartling, P. N. S., and G. S. McMaster (2004), GPFARM modeling of corn yield and residual soil nitrate-N. *Computers and Electronics in Agriculture* 43: 87-107.

Wagner, L. E. (1996), An overview of the wind erosion prediction system. Proc. Of International Conference on Air Pollution from Agricultural Operations, Feb. 7-9, 19996, Kansas City, Missouri, pp. 73-75.

Wilhelm, W. W., McMaster, G. S., Rickman, R. W., and B. Klepper (1993), Above-ground vegetative development and growth of winter wheat as influenced by nitrogen and water availability. *Ecological Modelling* 68: 183-203.

Williams, J. R., Jones, C. A., Kiniry, J. R., and D. A. Spanel (1989), The EPIC crop growth model. . *Transactions of American Society of Agricultural Engineers* 32: 497-511.