Cotton Modeling for Climate Change, on-farm Decision Support and Policy Decisions

Reddy, V. R.[1], Y. Yang[2], K. R. Reddy[3], D. J. Timlin[1] and D. H. Fleisher[1]

[1]USDA-ARS, Crop Systems and Global Change Lab., Beltsville, MD 20705, USA
[2]Wye Research and Education Center, University of Maryland, Queenstown, MD, USA
[3]Mississippi State University, Department of Plant and Soil Sci., Mississippi State, MS 39762, USA
Email: VR.Reddy@ARS.USDA.GOV

Keywords: GOSSYM, decision support system, technology transfer, precision agriculture, global climate change

EXTENDED ABSTRACT

Crop simulation models are valuable tools that scientists can use in testing hypotheses. Models also are used to identify the areas where knowledge is lacking, indicating the need for future research activities. In addition, models are being used as decision support systems at the farm level to optimize resource management. The cotton simulation model, GOSSYM, is a mechanistic process level model which simulates cotton growth, development and yield and has been used for over 20 years as an on-farm decision support tool by cotton growers and consultants resulting in increased profits to cotton producers. By optimizing the inputs such as chemical fertilizers, insecticides, plant growth regulators and harvest-aid chemicals, the model not only contributes to increased yields but also helps to decrease environmental contamination. The use and application of the model in research management, yield forecasting, and farm management is reviewed. Also, the application of GOSSYM on the impacts of projected climate change on cotton production is reviewed. Suggested mitigation options to be used in the future higher atmospheric carbon dioxide concentrations and warmer temperatures are presented.

1. INTRODUCTION

Decision support systems (DSS) are computer systems that assist the user in complex problem solving or decision-making. The DSS is very helpful in learning more about crop's responses to environmental factors, and in complying with governmental regulations. Furthermore, the ability to compare the probable outcomes of different decisions can help a producer make more informed decisions and reduce risk in the face of future uncertainties.

One of the major reasons to develop and to apply crop model-based DSS in farm management is to increase profit and manage resources. The complexity of agricultural production systems demands a DSS that is capable of systematically accounting for the variations in these factors. In crop growth simulation models, current knowledge of plant growth and development from various disciplines, such as crop physiology, agrometeorology, soil science and agronomy is integrated in a coherent, quantitative and process-oriented manner. After proper validation, the models may be used to predict the effects of changes in environment and management on crop growth, development and final yield. These models offer great potential for numerous improvements in crop production efficiency and crop management, and in policy decision.

Cotton, produced in over 76 countries covering more than 32 million ha across a wide range of environmental conditions, is the world's leading textile fiber plant that forms a vital part of global as well as domestic agriculture. The USA is the world's largest cotton exporter. In year 2002, the total harvested area in the USA was 5.2 million ha (USDA-NASS, 2002). To compete at the global market place, growers have to optimize inputs and maximize yields and profits. Therefore, there is need for a model-based DSS which can improve the management efficiency of cotton production systems. About 15 cotton development models have been proposed and published (Jallas, 1998). Of all these models, GOSSYM is the most widely and commonly used in commercial agriculture to aid in water and nitrogen management as well as for timing harvest operation (Baker et al., 1983). GOSSYM was also combined with an expert system called COMAX (Lemmon, 1986).

2. BRIEF HISTORY OF THE DEVELOPMENT AND VALIDATION OF GOSSYM-COMAX MODEL

GOSSYM is a mass balance dynamic simulation model that accounts for carbon, nitrogen, and water in the plant and soil root-zone. The model

considers environmental variables such as solar radiation, temperature, rain/irrigation, wind as well as variation in soil properties and cultural practices as inputs, and simulates crop response to changes in environmental conditions and management inputs. It estimates potential growth and development rates for the observed daily temperature by assuming that other conditions are not limiting, and then it corrects the potential rate by intensity of environmental stresses (Baker et al., 1983; Reddy et al. 1997). Since the model can provide a user the information on plant size and growth stage as well as growth rate and the intensity of the stress factors, one can use the model to determine yield estimates and the impact of alternative cultural practices on yield of the crop by assuming certain future weather conditions.

GOSSYM has been extensively validated with data that represents a wide range of environmental conditions and cultural practices (Reddy and Baker, 1988; Reddy et al., 1995, 2002a; Reddy and Boone, 2002). The validation data for GOSSYM were from areas of the USA cotton belt, and also from other cotton growing countries such as China (Pan et al., 1994) and Greece (Gertsis and Symeonakis, 1998). The model has been continuously updated as new information becomes available. Reddy and Bonne (2002) implemented the phytomer concept for plant height and leaf area development simulation. The effect of nitrogen and water stress, the influence of plant growth regulators on leaf development were also implemented (Reddy et al., 1995, 1997). Recently, the effects of UV-B radiation on canopy photosynthesis, leaf area expansion, and stem and branch elongation were incorporated in the model (Reddy et al., 2003; Wang et al., 2006).

3. GOSSYM/COMAX IN FARM MANAGEMENT

The application of GOSSYM in farm management started as a pilot program on two farms in 1984. By late 1987, with the help of the State Cotton Specialist for the Mississippi Cooperative Extension Service and the National Cotton Council, USA, the model was delivered to 70 cotton farms in several states in the Midsouth. Primarily due to the continuous success in research and on-farm testing conducted in different parts of U.S. and other parts of the world, the model was adopted by over 100 producers in 12 states by 1990. Extension specialists and consultants served an additional 200 to 300 producers (Ladewig and Thomas, 1992). According to a survey conducted by Ladewig and Powell (1989) and Ladeweig and Thomas (1992), the majority of the producers used

the GOSSYM model as a decision support system for determining crop termination, nitrogen utilization, and irrigation practices in efforts to maximize profit, minimize risk and optimize input. Users of GOSSYM earned $80 more per hectare on average compared with producers who did not use any simulation models.

3.1. Irrigation and Nitrogen Management

The cotton crop is sensitive to both water and nitrogen stresses (Reddy et al., 1997). Timely irrigation and maintaining soil fertility is therefore very crucial in sustaining cotton productivity and profitability.

GOSSYM is capable of simulating the dynamics of soil water and nitrogen as well as water and nitrogen uptake. In the model, plant water demand in terms of evapotranspiration (ET), which is defined as the sum of evaporation (E) and transpiration (T), are calculated from canopy light interception and soil water content. Staggenborg et al (1996) modified the potential ET calculation in GOSSYM so as to include relative humidity in the simulation. With this modification, the model simulation could be used to assess cotton water status, and as a tool for irrigation management in semiarid regions.

Kim et al. (2006) studied different water management strategies with GOSSYM using environmental, cultural, and experimental data of cotton trials in California and Texas. Model simulations identified both critical and non-critical timings of irrigation, and determined water use efficiency under different water management strategies. Their study revealed that GOSSYM is a useful tool for testing viable water management regimes of cotton production systems without extensive investments in time and resources for experimental investigations.

GOSSYM includes simulation of soil processes, hence it is capable of integrating the interacting soil, water, plant, and weather factors, which in turn determine soil-N availability and current and future N demands. The model was used to determine appropriate N application strategies on cotton farms. In a survey of GOSSYM users (Albers et al., 1992), it was found that 76% of the producers who used the model changed their N-management practices. The following example demonstrates the benefit of using GOSSYM in N-management at farm level. In a pilot test conducted in 1985 on Mitchner farm, Sumner (Mississippi), GOSSYM suggested that the producer apply an additional 56 kg (N) ha^{-1} and predicted an increase in cotton lint yield of 224 kg ha^{-1}. The producer,

who had not planned to apply any fertilizer, applied 22 kg (N) ha^{-1}. Cotton was picked both by hand and machine. The hand-picked area showed a net increase of 202 kg ha^{-1} in lint yield, while the lint yield in the machine picked area increased by 129 kg ha^{-1}. Losses in mechanical harvest were assumed to have caused the difference between the hand-picked and machine-harvested yield (Reddy et al., 2002a).

3.2. Growth Regulator/Crop Terminator Application Management

One key reason for the success of GOSSYM on farm-management is the continuous development and upgrading of the model as new information becomes available. An example is the development of a subroutine in GOSSYM to simulate the effect of the application of mepiquat chloride (MC). MC is a plant growth regulator that has been used by cotton growers in manipulating the balance between vegetative and reproductive growth in cotton plants (Reddy et al., 1990). Initially the MC subroutine in GOSSYM could only simulate the effect of a single rate of MC applied on flowering cotton plants, and was not able to deal with changes in growing conditions or MC application rates (Reddy, 1993). Reddy et al. (1995) studied the relationship between MC concentration in tissue and leaf expansion, stem elongation, and photosynthetic rates, and developed a new MC subroutine. The new subroutine simulated effect of MC with greater accuracy and was able to deal with changes in environmental conditions, cultural practices and genetic resources.

With the new MC subroutine, GOSSYM was used in determining the optimum MC application strategies. Simulations conducted using two different soil types and three different weather scenarios in the Mississippi Delta (Watkins et al., 1998) quantitatively revealed the relationship between weather conditions, soil type and MC application strategy. The growers also knew from experience that they should not use a blanket MC application strategy for all weather conditions, but without the help of GOSSYM, they could not predict the proper strategy *a priori*.

Ethephon is a crop termination and harvest-aid chemical. Improper dosage or time of ethephon application can drastically reduce cotton lint yield and quality. Reddy (1995) developed a subroutine for ethephon in GOSSYM. With the subroutine, the model provided the users helpful information on time, rate and amount of ethephon and other crop termination chemicals for end of the season harvest decisions. With these enhancements, the model can be used for a whole host of harvest aid chemicals to defoliate and to schedule harvest time.

4. MODEL APPLICATIONS AT REGIONAL LEVEL

4.1 Yield Decline Assessment Analysis

It was observed that despite the introduction of better and improved varieties, effective pesticide applications and continued increases in atmospheric CO_2 concentrations, cotton yields had declined slightly from 1960 to 1980 (Meredith, 1987). Scientists suspected different reasons such as weather (Orr et al., 1982), increasing soil compactions (Brooks, 1977), untimely use of pesticides (Leigh, 1977), excess and/or limited nitrogen supply (Gerik et al., 1998), and rising atmosphere ozone levels (Reddy et al., 1989) might have contributed to the decline in cotton yield. However, because of the complex interactions among soil, plant and atmosphere, and the variations in site-specific management practices, there was no comprehensive effort to determine the exact causes.

GOSSYM was used to evaluate the influence of environmental conditions and cultural practices on cotton yields retrospectively. In a study, weather, soil and cultural input data at five locations across the U.S. Cotton Belt for over 20 years were collected for analysis (Reddy and Baker, 1990). The effect of changes in weather was analyzed first. Simulations indicated that large variations in weather from year to year caused large fluctuation in yield. The model was able to track the variations in yield quite well, but it over predicted yield by 20%, indicating that there were some other factors that were reducing cotton yield. Weather therefore was ruled out as a yield-decline factor.

Addressing the issue of herbicides, Reddy et al. (1987) demonstrated how the response of cotton to herbicide damage could be simulated with GOSSYM model. A series of simulations were carried out to study the effect of root growth inhibition and reduction in the permeability of roots to water and nutrients on cotton growth, development and lint yield. The analysis showed that if herbicides were applied improperly, cotton root growth would be reduced, resulting in water and nutritional shortages and lower yields. The effect of root damage caused by herbicides on cotton yield trend was also simulated using the above mentioned 20-year data with GOSSYM (Reddy et al., 1990). Simulations showed that the reduction in root growth decreased uptake of water and nitrogen by the cotton crop. The simulated adverse effects of herbicides on lint yield varied

among locations and the lint yield decrease ranged from 14 kg ha^{-1} to 137 kg ha^{-1}. From these analyses, it was concluded that improper applications of herbicides was one of the causative factors for the cotton yield decline from 1960 to 1980 at all locations across the U. S. Cotton Belt.

Analysis conducted by Whisler et al. (1993) indicated that there were no consistent trends traceable to soil compaction at all locations. Compaction effects not only varied from location to location, but were also masked and complicated by variations in weather. According to the simulation analysis, soil compaction effects in Stoneville, Mississippi, were generally detrimental, but they were often masked by weather. In Florence, South Carolina, soil compaction was found to have a negative effect before 1974. But after annual in-row sub-soiling became a common cultural practice, the negative effect was alleviated. It was also found that wheel traffic compaction had little negative effects in years with abundant water, since shallow root systems were able to extract sufficient moisture for crop growth and yield.

The effects of changes in atmospheric ozone and carbon dioxide were also evaluated by modifying the photosynthetic module in GOSSYM to accommodate the influence of rising ozone and atmospheric carbon dioxide levels (Reddy et al., 1989). Because of the interaction of soil, crop and atmospheric variables, the simulated effects of the two environmental factors on cotton yields varied among locations. The simulations revealed that the increase in atmospheric carbon dioxide from 1960 to 1985 would have increased lint yield by 10%. However, the inclusion of 23 years of summertime surface mean ozone concentrations along with the increased carbon dioxide concentrations showed a 17% decrease in the corresponding simulated mean lint yield in California, but not in other locations where ozone concentrations were lower.

4.2. Tillage and Erosion Studies

The studies on erosion and tillage could only be conducted in a meaningful and quantitative way by using a process-level model such as GOSSYM. Whisler et al. (1986) used the model to evaluate the effects of soil erosion and erosion-related activities on cotton lint yields. In the study, the 1-m deep soil profile was assumed to have a traffic pan 170 to 240 mm below the soil surface and the surface soil was eroded by 50 or 100 mm. Weather data in 1980 (dry year) and 1982 (wet year) were used in the simulations. For the dry year, 50 mm of erosion reduced the simulated yield by 9%, and 100 mm erosion reduced simulated yield by 19%.

For the wet year, the maximum simulated yield was only reduced by 2%. If the soil profile was 0.3 m deep, but the traffic pan was reformed each year at 17- 240 mm below soil surface, the reductions in yield were greater. In a dry year, the predicted yield reduction was 32%, and increased erosion further reduced the yield by another 10 to 12%. In a wet year, reduction in simulated yield was only 14%, but yield was further reduced by 20 to 40% with more erosion.

Whisler et al. (1986) also reported that the interacting effects of weather that varied from location to location masked compaction trends. For the Norwood silt clay soil at College Station, TX, wheel traffic may have enhanced yields by changing the root/shoot partitioning in response to water stress. In other areas and soils, such as the Dundee silt loam of the Mississippi Delta, it appears that compaction generally reduced yields. These analyses proved that that GOSSYM could be used to study the interaction of soils and weather on crop yields.

5. FUTURE CLIMATE SCENARIOS

Crop models have been proved to be valuable tools in predicting the effects of future climate change on agriculture. Doherty et al. (2003) examined the response of GOSSYM on a coarse-scale global climate model (GCM) (180 by 186 mile grids) and a fine-scale regional climate model (RegCM) (31 by 30 mile grids). Using these two models, GOSSYM simulations were conducted with three climate scenarios. In the first scenario, the effect of temperature change alone was studied. With the RegCM model, GOSSYM predicted a 10% decrease in cotton yield in the southeastern USA (AL, AR, northern FL, GA, LA, MS, North CA, SC and TN). But with the GCM model, the simulated cotton yields increased by 4%. In the second scenario, both temperature change and elevated CO_2 were considered in the simulations. The fine-scale model predicted a 5% increase whereas the coarse-scale model showed a 16% increase. When both the climate change and elevated CO_2 were combined with alternative management practices, such as earlier planting, the simulated yield by the fine-scale model increased by 26% and the coarse-scale model predicted a 36% increase.

In a study conducted in a diverse range of locations in various states of the USA (Stoneville, MS; Florence, SC; Corpus Christi, TX; Artesia, NM; and Springfield, IL), GOSSYM was used to simulate the climate impacts on cotton growth, phenology and yield (Richardson et al., 2003). In the simulations, temperature was varied from –12

^{o}C (T_{avg} - 12 ^{o}C) to + 12 ^{o}C ($T_{avg\ +}$ 12 ^{o}C) from the average temperature (T_{avg}). When temperature increased from T_{avg} - 12 ^{o}C to T_{avg}, the yield in warm locations, such as Corpus Christi, TX and Stoneville, MS, increased or were unchanged, whereas yield at cooler locations (e.g. Florence, SC; Artesia, NM; Springfield, IL) increased significantly. When temperature further increased from T_{avg} to $T_{avg\ +}$ 12 ^{o}C, yields at cooler locations did not change while yield at warmer locations decreased. These results reveal that yield responses to change in temperatures are location-specific. With present management practices and available cultivars, the present US Cotton Belt may shift to higher latitudes in future climates. However, the magnitude of this shift may be reduced by altering current management practices or by breeding cultivars with enhanced tolerance to heat/cold.

GOSSYM simulations conducted with increased atmospheric CO_2 showed that at sufficient soil N levels, an increase of 10% of cotton lint yield would occur under predicted atmospheric CO_2 concentrations of 540 $\mu L\ L^{-1}$. At Stoneville, MS, with current practices, the crop could not take advantage of the increased CO_2 due to N stress (Reddy and Baker, 1990). Results from 30-year simulation studies (Reddy et al., 2002b) indicated that increases in CO_2 concentration had a positive effect on cotton production (Figure 1). At Stoneville, Mississippi, cotton lint yield increased by 54% with increase in CO_2 concentration from 200 $\mu L\ L^{-1}$ to 900 $\mu L\ L^{-1}$. When the CO_2 only increased from ambient to 540 $\mu L\ L^{-1}$, the increase was only 10%. Since the current atmospheric CO_2 concentration is already close to 380 $\mu L\ L^{-1}$, it maybe safe to assume that most of the effect of elevated CO_2 might have already occurred. When all the projected climate changes were included in the simulations, the predicted yield was reduced by an average of 9%. The decrease was relatively greater in a 'hot and dry' year. In a 'cold and wet' year, changes in climate increased the yield (Figure 2). In the cotton growing Delta region of Mississippi, an increase in CO_2 concentration with increased air temperature averaging 4 ^{o}C is predicted in future climate scenarios. Increased temperature reduced the crop-growing period by 11 days. Also, a decrease in number of days with temperatures less than 15 ^{o}C increased the number of growing days available per season in the future climate. These studies also indicated that altering management practices such as early planting and providing irrigation, and adopting genotypes with better tolerance to abiotic stress could mitigate the negative impact on yield caused by climate change.
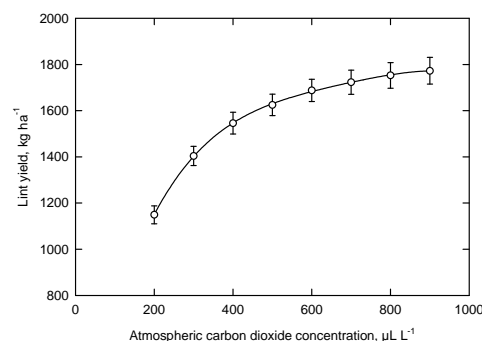
Figure 1. Cotton response to climate change: simulated lint yield response to CO_2 enrichment. The data are means of 30-year simulations for Stoneville, MS (From Reddy et al., 2002b).
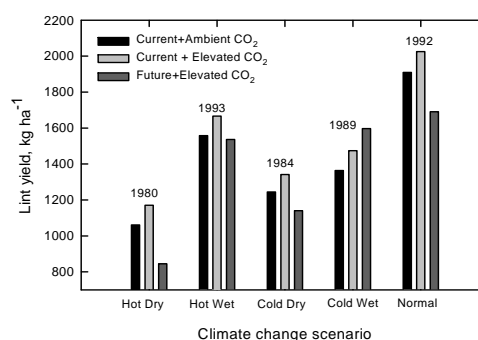
Figure 2. Cotton response to climate change: simulated yields for different years with various weather patterns including current weather with ambient CO_2, current weather with elevated CO_2, and future weather with elevated CO_2 (From Reddy et al., 2002b).

6. CONCLUSION

In this paper, we bring together simulations from the experiments carried out using GOSSYM, and we present how GOSSYM was developed, calibrated, validated and utilized. We also show how crop models are applied in DSS to help in research, crop management and in policy decision-making processes.

It is worthwhile pointing out that along with the considerable potential of crop modeling, there can also be misrepresentation, misuse and misunderstanding of the tools. Both the developers and users of the crop models should be aware of the limitations and their possible misuse. Even though the effects of extreme temperatures and of water and nitrogen stress on many physiological process and yield can now can be simulated by

GOSSYM, the model is far from complete. Stresses caused by nutrients other than nitrogen, damages caused by herbicides, pests, and extreme weather events such as hail and winds are not yet included in the model. The model for now is not capable of predicting fiber quality, which is an important economic component of the crop, as affected by environmental factors and management practices. Algorithms concerning fiber quality need to be implemented into GOSSYM so as to provide in-season management strategies that result in better end-of-season fiber quality assessment at the mill.

7. AKNOWLEDGEMENTS

8. REFRENCES

Albers, D.W., J. Mobley and P.W. Tracy (1992), Evaluation of GOSSYM-COMAX in Missouri 1987-1991. In Proc. Beltwide Cotton Conf., National Cotton Council, Memphis, TN, pp. 1350-1351.

Baker, D.N., J.R. Lambert and J.M. McKinion (1983), GOSSYM: a simulator of cotton crop growth and yield, South Carolina Agriculture Experiment Station Technical Bulletin, No. 1089, Clemson, SC.

Brooks, O.L. (1977), Effects of soil environment on cotton yields. In Proc. Beltwide Prod. Mech. Conf., Atlanta, GA, January 10-13, 1977, National Cotton Council, Memphis, TN, pp. 68-69.

Doherty, R.M., L.O. Mearns, K.R. Reddy, M. Downton, and L.M. Daniel (2003), Spatial scale effects of climate scenarios on simulated cotton production in the Southeastern U.S.A. *Climatic Change*, 60, 99-129.

Gerik, T.J., D.M. Oosterhuis and H.A. Torbet (1998), Managing cotton nitrogen supply, *Advances in Agronomy*, 64, 115-147.

Gertsis, A.C. and A.G. Symeonakis (1998), Efficient cotton production in Greece with the use of GOSSYM - a cotton crop simulation model, *Acta Horticulturae*, 476, 307-312.

Jallas, F. (1998), Improved model based decision support by modeling cotton variability and using evolutioany algorithms. Ph.D. Thesis, Mississippi State University, Mississippi State, MS.

Kim, S-H, Y. Yang, D.J. Timlin, K.R. Reddy, D.H. Fleisher and V.R. Reddy (2006), Application of GOSSYM for water management in cotton production. In 36th Biological Systems Simulation Conference, April 11-13, 2006, Fort Collins, Colorado, pp 39.

Ladewig, A.M. and E.T. Powell (1989), An assessment of GOSSYM/COMAX as a decision system in the U.S. cotton industry, Texas Extension Service, College Station, TX, 51 pp.

Ladewig, A.M. and J.K. Thomas (1992), A follow-up evaluation of the GOSSYM/COMAX cotton program. Texas Agric. Extn. Ser., College Station, TX, 47 pp.

Leigh, T. F. (1977), Insecticides and cotton yield. In Proc. Beltwide Cotton Prod. Res. Conf., Atlanta, GA, January 10-13, 1977. National Cotton Council, Memphis, TN, pp. 63-65.

Lemmon, H.E. (1986), COMAX: An expert system for cotton crop management, *Science*, 223, 9-33.

Meredith, W.R., Jr. (1987), Final report of the cotton foundation yield and productivity study. In Proc. Beltwide Cotton Prod.. Conf., Dallas, TX, January 4-8, 1987. National Cotton Council, Memphis, TN, pp. 33-37.

Orr, C.C., A.F. Robinson, C. M. Heald. J.A. Veech, and W.W. Carter (1982), Estimating cotton losses to nematodes. In Proc. Beltwide Cotton Production Research Conference, Las Vegas, NV, 22.

Pan, X., Deng, S., and J.M. McKinion (1994), Modification of GOSSYM for predicting the behavior of cotton production systems in China. Report submitted to Cotton Research Institute, Chinese Academy of Agricultural Sciences, Anyang, Henan, Peoples Republic of China, p. 7.

Prashant, R. D. (2000), Simulating the impacts of climate change on cotton production in Mississippi Delta, MS Thesis, Mississippi State University, Mississippi State, MS.

Reddy, V.R., D.N. Baker, F.D. Whisler and R.E. Fye (1987), Application of GOSSYM to

yield decline in cotton: I. Systems analysis of effects of herbicides on growth, development, and yield, *Agronomy Journal*, 79, 42-47.

Reddy, V.R. and D.N. Baker (1988), Estimation of parameters for the cotton simulation model GOSSYM: cultivar differences. *Agricultural Systems*, 26, 111-122.

Reddy, V.R., D.N. Baker and J.M. McKinion (1989), Analysis of effects of atmospheric carbon dioxide and ozone on cotton yield trends, *Journal of Environment Quality*, 19, 427-432.

Reddy, V.R. and D.N. Baker (1990), Application of GOSSYM to analysis of the effects of weather on cotton yields, *Agricultural Systems*, 32, 83-95.

Reddy, V.R., D.N. Baker, F.D. Whisler and J.M. Mckinion (1990), Analysis of the effects of herbicides on cotton yield trends, *Agricultural Systems*, 33:347-359.

Reddy, V.R. (1993), Modeling mepiquat chloride – temperature interactions in cotton: the model, *Computers and Electronics in Agriculture*, 8, 227 - 236.

Reddy, V.R. (1995), Modeling ethephon – temperature interaction in cotton. *Computers and Electronics in Agriculture*, 13, 27-35.

Reddy, K.R., M.Y.L. Boone, V.R. Reddy, H.F. Hodges, S. Turner and J.M. McKinion (1995), Developing and validating a model for a plant growth regulator, *Agronomy Journal*, 87, 1100-1105.

Reddy, K.R., H.F. Hodges and J.M. McKinion (1997), Crop modeling and application: a cotton example, *Advances in Agronomy*, 59, 225-290.

Reddy, K.R., and M.Y.L. Boone (2002), Modeling and validating cotton leaf area development and stem elongation, *Acta Horticulturae*, 593, 193-199.

Reddy, K.R., V.G. Kakani, J.M. McKinion and D.N. Baker (2002a), Application of a cotton simulation model, GOSSYM, for crop management, economic, and policy decisions. In Agricultural System Models: Field Research and Technology Transfer. Eds. L.R. Ahuja, L. Ma and T.A. Howell. Lewis Publishers.

Reddy, K.R., P.R. Doma, L.O. Mearns, H.F. Hodges A.G. Richardson, M.Y.L. Boone and V.G. Kakani (2002b), Simulating the impacts of climate change on cotton production in the Mississippi delta, *Climate Research*, 22, 271-281.

Reddy, K.R., V.G. Kakani, D. Zhao, A.R. Mohammed and W. Gao (2003), Cotton responses to ultraviolet-B radiation: experimentation and algorithm development, *Agricultural and Forest Meteorology*, 120, 249-265.

Richardson, A.G., K.R. Reddy, and M.L. Boone (2003), Sensitivity analysis of climate change impacts on cotton production using the GOSSYM crop model, *Biotronics*, 32, 1-24.

Staggenborg, S.A., R.J. Lascano and D.R. Krieg (1996), Determining cotton water use in a semiarid climate with the GOSSYM cotton simulation model, *Agronomy Journal*, 88, 740-745.

USDA-NASS (2002), Crop production report. National Agricultural Statistics Service (NASS). Agricultural Statistics Board. United States Department of Agriculture (USDA), Washington, D. C., USA. pp. 4.

Wang, X. W. Gao, K.R. Reddy, J. Slusser, and M. Xu (2006), Preliminary results of a UV-B effect incorporated GOSSYM model. In Remote Sensing and Modeling of Ecosystems for Sustainability III, eds. Gao, W. and S. L. Ustin, Proc. of SPIE Vol. 6298, 62980O-1.

Watkins, K.B., Y.C. Lu, and V.R. Reddy (1998), An economic evaluation of alternative pix application strategies for cotton production using GOSSYM/COMAX, *Computers and Electronics in Agriculture*, 20, 251-262.

Whisler, F.D., B. Acock, D.N. Baker, R.E. Fye, H.F. Hodges, J.R. Lambert, H.E. Lemmon, J.M. McKinion, V.R. Reddy (1986), Crop simulation models in agronomic systems, *Advances in Agronomy*, 40, 142-208.

Whisler, F.D., B. Acock, D.N. Baker, R.E. Fye, H.F. Hodges, and V.R. Reddy (1993), Analysis of the effects of soil compaction on cotton yield trends, *Agricultural Systems*, 4, 199-207.