Cotton modeling: Advances and gaps in our ability to assess climate change, crop management, economic and environmental policy decisions

V.R. Reddy[1], K.R. Reddy[2], K. Sailaja[2], A.G.Richardson[2], V.G.Kakani[2] and D. Zhao[2]
[1] USDA-ARS, Alternate Crops and Systems Laboratory, BARC-West, Beltsville Maryland USA
[2] Department of Plant and Soil Sciences, Mississippi State University, Mississippi State, Mississippi USA
Correspondence author vreddy@asrr.arsusda.gov

ABSTRACT

Simulation models are useful tools that provide information about potential changes to production systems before committing time and resources. There are many potential uses of simulation models in providing solutions to many problems in research, crop management and policy. In this paper, we discuss GOSSYM, cotton (Gossypium hirsutum L.) simulation model, from its inception, development, validation, applications and future development needs. GOSSYM was released to USA farmers in 1984 and since then farmers, scientists, education specialists, extension personnel, and policy makers are using GOSSYM. GOSSYM is being continuously validated across the US Cotton Belt and also in several other countries like China, Israel, Greece and Spain as new information become available. GOSSYM has wide applications, both at regional level and farm level. At the regional level, it aids in policy decisions such as climate change impact analysis, yield decline assessment, insect damage assessment, tillage and erosion assessment and cultivar/genetics improvement research. At the farm level, it aids in pre-season and in-season decisions such as land lease/purchase, genotype selection, irrigation and nitrogen management, growth regulator and harvest-aid chemical applications. A study in Greece showed that GOSSYM decision-implemented fields produced 26-81% higher yields than farmer decision-implemented fields. In monetary terms, studies in the USA illustrated that farmers were benefited by about \$80-350 ha^{-1} when decisions by GOSSYM were implemented in farmer's fields. Scientists from National Center for Atmospheric Research, USA compared GOSSYM with other models like COTTAM and showed that GOSSYM was more realistic than any other models. GOSSYM has also educational applications and till date 57 Masters and Ph.D theses and dissertations were submitted to Mississippi State University, Mississippi State, Mississippi, USA with GOSSYM as a major component of research. These continuous assessments/applications of GOSSYM since 1980s identified some knowledge voids, which have been incorporated in the model and newer versions have been released. The model simulates most of the physiological and physical processes affecting cotton growth, development and yield. The model has proven potential for increasing profitability and is being used in the USA in commercial farm management. The GOSSYM model would be much more useful if the influence of nutrients other than carbon and nitrogen, UV-B radiation effects, fiber quality parameters as affected by environmental and cultural factors and severe weather factors such as hail and rain studied systematically are incorporated into the model.

Introduction

Cotton is the fifth most economically important crop in the world; the total harvested area being 5.2 Mha in the USA (USDA-NASS, 2002) and is grown on more than 34 Mha worldwide. Cotton, being indeterminate in growth habit, responds fairly well to changes in environment and management (Reddy, K.R. *et al*., 1997a; Gerik *et al*., 1998). Therefore, there is an increasing need for more efficient management of cotton production systems. Consideration of environmental issues relating to management decisions has necessitated the development of simulation models as additional management tools for farm managers. Models have many other uses, as a research tool, to support problem solving, in risk assessment, and for decision-making. They can guide researchers in prioritizing their research and integrating quantitative knowledge from different disciplines. Models can also be used as a framework for training. Furthermore, models can be used to extrapolate research findings over broad regions and extended time, because the models account for crop-environmental interactions. Using long-term weather data, yield probabilities can be simulated. About 15 cotton development models have been proposed and published (Jallas, 1998). Of all these, GOSSYM is the dynamic simulation model which is most widely and commonly used in the commercial agriculture to aid in crop management and policy decisions. In this paper, we bring together simulations from the experiments carried out by GOSSYM, and we present how GOSSYM was developed, calibrated, validated and utilized. We also show how crop models are used in technology transfer, including their use in combination with precision agriculture and other forms of new technologies. Application of GOSSYM along with the Geographic Information System (GIS), Global Positioning Systems (GPS) and related improvements in field equipment monitoring and delivering devices to agriculture production systems will generate information which has not been previously available.

Model development

The first cotton simulation model, SIMCOT (Duncan, 1972) was developed and was improved with the addition of RHIZOS, a simulator of soil growth and root processes and the combined model was called GOSSYM, an acronym from the words Gossypium and simulation. GOSSYM evolved as a dynamic simulation model and is being used in commercial agriculture to aid in crop management decisions. The model development, algorithms and applications have been described (Baker *et al.*, 1983; Mckinion *et al.*, 1989; Boone *et al*., 1993; Reddy K.R. *et al.*, 1997a, 2002a; Hodges *et al*., 1998).

Parallel to the development of GOSSYM, some scientists attempted to develop crop simulation models in different ways. Models such as OZCOT in Australia (Hearn, 1994), and some variants of GOSSYM were evolved for specific purposes. For example, CALGOS (Marani *et al.*, 1992) and ICEMM (Landivar, 1991) were developed for irrigated southwest and southern Texas, USA, respectively. Also, models/expert systems such as CALEX (Plant, 1989) and COTTAM (Jackson *et al.,* 1998) were developed for specific applications. A morphogenetic model COTCO2 (Wall *et al*., 1994) was developed for global change to simulate changes in atmospheric CO_2 concentrations, but it has never been tested in production environment. COTONS (Jallas *et al.*, 2000) a second descendant and another variant of GOSSYM is a three dimensional architectural extension of GOSSYM and is developed as a visualization model, but it is never tested on field. Recently, Cotton Production Model (CPM) was developed with object-oriented structure by the United States Department of Agriculture, Agricultural Research Service, Beltsville, Maryland, USA, but it is not validated to be useful commercially as a decision aid.

Among the various variants of GOSSYM and other cotton models studied, GOSSYM is being widely validated and is being used for on-farm research and policy decisions. GOSSYM accounts for carbon, nitrogen, and water in the plant and soil root-zone. It simulates crop responses to the environmental variables such as solar radiation, temperature, rain/irrigation, wind as well as variation in soil properties and cultural practices. The model estimates growth and development rates by calculating potential rates for the observed daily mean temperatures assuming other conditions are not limiting and then it corrects the potential rates by intensity of environmental stresses (Baker *et al*., 1983; Reddy K.R. *et al*., 1997a; Hodges *et al*., 1998). The model provides the user with information on plant size, growth stage, growth rate and the intensity of stress factors on a daily basis. Therefore, growers can predict the impact of select future weather scenarios to estimate yield and the impact of alternative cultural practices on crop maturity. GOSSYM provides a framework for interpreting the output from field experiments in different environments and can also be used to explore methods of improving crop management. The program flow and various discrete processes are organized in different sub-routines (For more details on the program structure and processes, see Hodges *et al*., 1998; Reddy K.R. *et al*., 2002a).

The heart of the model development resides in a suite of ten naturally lit plant growth chambers known as Soil-Plant-Atmosphere-Research (SPAR) units designed and constructed specifically to understand the basic mechanisms governing growth and development (Reddy K.R. *et al.*, 2001) of the crop in study. This facility allows experimentalists to design specific experiments to generate data that is useful in developing process-level crop models. Operating a SPAR facility to acquire model data is often more expedient and economical than field-plot experiments, as SPAR chambers allows the scientists to minimize many of the co-varying factors that occur in field experiments. The SPAR units are optimized for measurement of plant and canopy-level growth and developmental processes under precisely controlled, but naturally lit environmental conditions. The experiments are being conducted in environments that allow only the variable being tested to be limiting. Plants are being grown in well-watered sand and adequately fertilized with all known mineral nutrients (Reddy K.R. *et al*., 2001). Plants are also being grown in elevated CO_2 environments to enhance photosynthesis to avoid carbon deficits, and the plants are not subjected to disease or insect infestations. Thus, plants are grown at their potential rates and limited only by the variable being tested. Potential rates may be estimated from relationships developed in this manner and then corrected by stress factors known to occur in the natural environment. Several experiments were designed to generate data either to improve several growth and developmental processes or to develop new processes (Reddy K.R. *et al*., 1993, 1995, 1997a, 1999, 2001; Reddy, V.R., 1993, 1995).

Validation of the model

As the model is said to be an imitation of the real system, it is important to conduct extensive field validations to determine whether it is structurally sound and to assess the extent and limitations of its validity. The uniqueness of GOSSYM was its extensive testing across diverse environments and cultural practices. It was evaluated for its accuracy on overall yield predictions, as well as on the validity of major processes in the model. Validation aids in the continuous evolution of the model by providing feedback information from researchers testing it under new environments and also from farm managers using it under variable weather, soil and management conditions. The data used to validate GOSSYM was from the areas of the US Cotton Belt, and also from other cotton growing countries like China (Pan *et al*., 1994), Greece (Gertsis and Symenoksis, 1998) and Israel (Marani and Baker, 1978). The results of the validation process were used to refine the model and to guide the modelers for further experimentation to improve the model (Reddy K.R. *et al.*, 1995, 1997a, 1997b, 1999).

A validation study in Arizona, USA, suggested that the model needs some alterations in the maximum reduction of photosynthesis due to water stress to simulate an apparent hardening process in the cotton plants. The same study also helped to modify the growth rates of roots, plant height and leaves as affected by water stress (Marani *et al*., 1985). Several studies by Reddy V.R. *et al*. (1985) and Staggenborg *et al.* (1996) were used to validate the model. More farmers adopted the model, which led to a requirement for more precise prediction of growth and development. These studies also led to the development of cultivar-specific genetic coefficients for modern cultivars and extended GOSSYM use across a wider geographic area and genetic base. As innovative information becomes available, GOSSYM continues to evolve from these new concepts.

A successful model predicts crop growth even at places other than its origin. To validate this, GOSSYM was tested in several other cotton producing countries such as China (Pan *et al.*, 1994) and Greece (Gertsis and Symenoksis, 1998). An evaluation study in Greece has demonstrated the validity of GOSSYM as a tool for efficient cotton production with low input strategies. Some collaborative studies by the Cotton Research Institute, the Chinese Academy of Agricultural Sciences, Henan, Peoples Republic of China, and the Crop Simulation Research Unit, USDA-ARS at Mississippi State University, Mississippi State, Mississippi, USA were conducted. In China, Pan *et al*. (1994) showed that the model accurately predicted the key developmental stages within acceptable limits. Plant height and leaf area were accurately simulated, but the model failed to account for damage caused by cotton bollworm infestation during certain periods of the study. The modification of appropriate functions in GROWTH and PLTMAP subroutines to account for some local cultural practices was also necessary.

Validation of soil temperature subroutine of the model showed that TMPSOL of GOSSYM did not perform well under bare and cotton-cropped surface conditions in the field (Khorsandi and Whisler, 1996). This study led to incorporation of more mechanistic soil temperature subroutine of a soybean growth simulator, (GLYCIM). The resulting new soil temperature subroutine was called HEAT. Under bare surface conditions, HEAT under-predicted the average daily soil temperatures at all locations and depths (Khorsandi *et al.*, 1997). However, under cotton cropped surface conditions, HEAT calculated the soil temperature adequately, especially after canopy closure.

Carrying out a sensitivity analysis with GOSSYM can identify the most influential/sensitive parameters of the environment. With this analysis, optimal management strategies can be developed and implemented to meet the increase/decrease of yields in future climates. The most recent sensitivity analysis conducted by Richardson *et al.* (2003) is discussed here. This was conducted in a diverse range of locations in various states of the USA (Stoneville, Mississippi; Florence, South Carolina; Corpus Christi, Texas; Artesia, New Mexico; and Springfield, Illinois). GOSSYM was used to understand the climate parameter impacts on cotton growth, phenology and yield. Several environment variables such as carbon dioxide, temperature, precipitation and solar radiation were varied 'ceteris paribus'. In the future climates, these variables turned out to be the most influential parameters affecting yield and other yield-related parameters. Carbon dioxide increased yields reflecting enhanced photosynthesis and carbohydrate supply. Increasing temperature increased mainstem node number; decreased plant height and yield; and hastened the developmental events such as time to first square, time to first flower and time to first open boll (Figure 1). The temperature was varied from –12 °C (T_{avg} – 12 °C) to + 12 °C (T_{avg} + 12 °C) from the average temperature (T_{avg}). When the T_{avg} – 12 °C was increased to T_{avg}, the yields in warmer locations (Corpus Christi, Texas and Stoneville, Mississippi) increased or were unchanged, whereas yields in the cooler locations (Florence, South Carolina; Artesia, New Mexico; Springfield, Illinois) significantly increased. When the temperatures were further increased from T_{avg} to T_{avg} + 12 °C, yields at cooler locations were unaffected while yields at warmer locations were reduced. These results indicate that yield responses to increase/decrease in temperatures are location-specific. The results also show that, with present management practices and available cultivars, the present US Cotton Belt may shift to higher latitudes in future climates. The magnitude of this shift may however, be reduced by altering current management practices, or by developing new cultivars with improved heat/cold tolerance.

Model applications at regional level

The foremost useful application of crop simulation models is for policy management. Policy issues could range from global issues such as climate change impacts to field-level issues such as the effect of crop rotation strategies on long term changes in soil quality. World food production studies (Penning de Vries *et al*., 1995), agroecological zonation (Agarwal, 1993) and exploration of climate change impacts on crop production (Wolf, 1993) employed crop growth models. Boote *et al*. (1996) concluded that a number of policy uses have been made using crop models in the areas of climate change, water use, erosion, soil nutrients and pesticide use. GOSSYM as a tool for policy makers is discussed in the following subsections.

Climate change impact assessment

Climate change is an important policy topic because of its potential consequences and its inherent complexity. Policy makers are faced with the daunting task of adopting appropriate strategies to deal with the climate change issue. GOSSYM was used to understand the implications of climate change on cotton production, as cotton will be grown under much different environments in the future than present. In a study by Reddy K.R. *et al*. (2002b), thirty years (1964-1993) of cotton growth and yield at Stoneville, Mississippi, USA, were simulated using GOSSYM. There was a 54% increase in yield when the atmospheric CO_2 concentration was increased from 200 to 900 ml l^{-1} (Figure 2). The increase was only 10% when the CO_2 was increased from ambient to 540 ml l^{-1} showing that most of the effects of elevated CO_2 might have already occurred. However, yields declined by 9% when all the projected climate changes were included. GOSSYM was also used to study the effects of climate extremes on cotton growth and yield (Figure 3). The adverse impact of climate change on cotton production was relatively greater in a 'hot and dry' year (1980). However, in a 'cold and wet' year, climate change had a positive response. The simulations suggest that yield limitations to climate change may be mitigated by management practices by improving genotype tolerance to abiotic stresses.

Simulations with GOSSYM by scientists at the National Center for Atmosphere Research (NCAR) indicated that cotton yield increases with an increase in atmospheric CO_2 (Doherty *et al.*, 2003). A study of Mearns *et al*. (1999) from NCAR compared the results of climate change from another model of cotton, COTTAM with those of GOSSYM and they concluded that GOSSYM results were more realistic than COTTAM results. Doherty *et al*. (2003) examined the response of GOSSYM on two different spatial scales, 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, three climate scenarios were simulated. The first scenario simply examined the impact of climate change alone, which resulted in a 10% decrease in cotton yields in the southeastern USA (Alabama, Arkansas, northern Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina and Tennessee) with fine-scale scenario, but the coarse-scale model simulated a 4% increase in yields. With the climate change and elevated CO_2 case the fine-scale model showed a 5% increase whereas the coarse-scale model showed a 16% increase. Finally, when both the climate change, elevated CO_2 were combined with farming adaptations, such as planting crops earlier to take advantage of a longer growing season, the fine-scale model predicted a 26% increase and the coarse-scale model predicted a 36% increase.

There were some limitations in these studies. The future climate scenarios were established assuming the same natural daily variability in weather parameters as the present climate. This assumption arose from the nature of the future climate projection data generated by the RegCM which provided only monthly mean estimates of future changes in weather parameters. Thus, future research should be directed to attain daily estimates from the RegCM. Incorporation of this daily resolution input data into GOSSYM is expected to result in more realistic estimates.

Yield decline assessment analysis

GOSSYM was used to identify the causes of yield decline, which was observed throughout the Cotton Belt between 1960 and 1980, despite the introduction of better and improved varieties, effective pesticide applications and a continuous increase in atmospheric carbon dioxide concentrations (Meredith, 1987). Weather (Davis and Gallup, 1977; Orr *et al.*, 1982), increasing soil compaction (Brooks, 1977), increased nematode populations (Orr *et al*., 1982), soil herbicide accumulations (Hurst, 1977), untimely use of pesticides (Leigh, 1977), excess and/or limited nitrogen supply (Maples, 1977; Gerik *et al.*, 1998) and ozone levels (Reddy V.R. *et al.*, 1989) were all implicated as causative agents for the yield decline, but there was no comprehensive effort to determine the exact causes for the temporal yield decline because of the complexities of soil-plant-environment interactions and management practices. The National Cotton Council in 1984 assigned the GOSSYM group to investigate the causes of yield decline across the US Cotton Belt. GOSSYM was used to evaluate retrospectively, the influence of environmental conditions and cultural practices on cotton yields. The weather issue was analyzed first by taking weather, soil, and cultural input data at five locations across the US Cotton Belt for over a 20-year period (Reddy V.R. and Baker, 1990). The results of the simulation analysis showed that weather varied greatly among years and caused large fluctuations in yields. The model tracked yield variations fairly well, but over predicted yield by 20%, indicating that other yield-reducing factors were on play.

Brooks (1977) suggested that greater soil compaction caused by the increasing size and weight of farm equipment in the 1970's and 1980's compared with equipment used in earlier years, which may be the causative factor of yield decline. As in the previous yield-decline studies, weather, soil and cultural input data from six locations across the Cotton Belt were used in this analysis, but there were no consistent trends traceable to soil compaction at all locations. However, compaction effects were masked and complicated by weather and the effects varied from location to location. For example, prior to 1974, compaction was found to have a negative effect at Florence, South Carolina, but after annual in-row sub-soiling became a common cultural practice, this effect was alleviated. Soil compaction effects at Stoneville, Mississippi were generally detrimental, but they were often masked by weather according to the simulation analysis. In years with abundant water, wheel traffic compaction had little negative effect on yields, since shallow root systems could extract sufficient moisture for crop growth and yield (Whisler *et al.*, 1993).

The next issue addressed was herbicides. Reddy V.R. *et al*. (1987, 1990) identified and hypothesized two herbicide effects on cotton growth and development by affecting root pruning at various depths, and reduced root water and nutrient permeability. The simulation analysis indicated that both factors reduced cotton yields. They concluded that improper herbicide applications were one of the causative factors for cotton yield decline in the U.S. Cotton Belt.

Finally, the effects of changes in atmospheric ozone and carbon dioxide were evaluated (Reddy V.R. *et al.*, 1989). The photosynthetic subroutine was modified to accommodate the influence of ozone and atmospheric carbon dioxide levels (Miller *et al.*, 1998). The simulated effects of the two environmental factors on cotton yields varied among locations because of interactions of soil, crop, atmospheric variables and nutrient levels. Under well-fertilized conditions, it was found that the increase in atmospheric carbon dioxide from 1960 to 1985 would have increased lint yields by 10%. 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. This study demonstrated that a physiologically, physically and mechanistically based model such as GOSSYM was the only available tool that can be used to study the effects of such environmental factors on crop growth and yield, but the affected physiological processes in the model must be appropriately modeled for each variable tested.

Tillage, erosion and cropping system studies

The GOSSYM model has been used to evaluate the effects of soil erosion and erosion-related activities on cotton lint yields (Whisler *et al*., 1986) based on which policy decisions can be made. According to Whisler *et al.* (1993), GOSSYM could be used to show the interaction of soils and weather on crop yields. The model has been used to investigate the effects of simulated tillage and wheel traffic on cotton growth and yield (Whisler *et al.*, 1986, 1993). The soil compaction due to wheel traffic and subsequent loosening of the soil surface due to cultivation can change the root distribution patterns and water and nutrient extraction patterns, especially in lighter, sandy textured soils. In looking at overall effects of wheel traffic compaction, there were no consistent trends. The interacting effects of weather that varied from location to location masked compaction trends. The erosion and tillage studies could only be conducted in a meaningful and quantitative way by using a process-level model such as GOSSYM. The soil profile, 1 m deep, used in the simulation, was assumed to have a traffic pan 170 to 240 mm below the soil surface and that the surface soil was eroded by 50 or 100 mm. Weather for a relatively dry year, 1980, and wet year, 1982, were used and compared. For the dry year, 50 mm of erosion reduced simulated yield by 9%, and 100 mm of erosion reduced yield by 19%. For the wet year, the maximum yield reduction was only 2%. For a 0.3 m deep profile of the same soil, but where the traffic pan was reformed each year at 170-240 mm below the soil surface, the reductions in yield were greater. On the shallower soil, the predicted yield was reduced 32% in a dry year, and increased erosion further reduced the yield another 10 to 20%. In a wet year, simulated yields on the shallower soil were only reduced by 14%, but more erosion further reduced the yields 20 to 40%.

Results from a study (Reddy K.C. *et al*., 2000) where GOSSYM predictions were compared for different management systems showed that GOSSYM could not simulate accurately the effects of conservation tillage and poultry litter on soil moisture conservation and nutrient supply. This shows that GOSSYM, in its current version will not be able to provide reliable growth data for the RUSLE (Revised Universal Soil Loss Equation) model to predict soil erosion in conservation tillage systems with poultry litter as an N source. Thus, additional algorithms are needed for GOSSYM to predict cotton growth parameters used as input data into the RUSLE model.

Insect damage assessment

GOSSYM has the capability to determine the need for insect control or recommend the best control strategy. This is accomplished by an input of plant maps that reflect the location and degree of fruit loss caused by insects. Effective integration of such an insect expert system with a physiologically-based cotton model such as GOSSYM can potentially improve the management decisions made by cotton farm managers. Validation of GOSSYM against a commercial cotton crop grown in 1976 (Baker *et al*., 1993) revealed that a 32% yield loss occurred due to lygus (*Lygus lineolaris*) damage to squares and to fruiting branch development at the eighth and ninth nodes on the plant. Along with lygus, over 20 species of Arthropods attack cotton Beltwide. In the Mississippi Delta, the estimated average cost of insecticides use was \$131 ha^{-1} (Mississippi Cooperative Extension Service, 1990).

A rule-based wholistic insect management expert system (rbWHIMS) was designed to integrate with GOSSYM and it provided information to the user for determining pesticide management strategies (Olsen and Wagner, 1992). This aids as a decision making tool which describes arthropod induced losses to field crops. This system uses an insect scouting methodology for plant growth stages, and pest sampling by species and population levels. Output includes recommendations for pest control including timing of pesticide application or non-application, and when to observe the field for future management strategies.

Cultivar/genetics improvement research

There are several opportunities for improving crop performance and productivity through optimization of cultural practices, plant breeding and new technological developments including biotechnology. Recently, a number of plant breeders have envisioned models as tools for predicting the effects and economic benefits of various genetic combinations. Breeders are also interested in predicting the responses of particular genotypes to specified niche environments and how the crop can be best managed to maximize yields (Landivar *et al*., 1983a, 1983b)

GOSSYM was used to answer the persistent question of why the okra leaf-type cotton performs poorly compared to normal leaf-type of cotton even though it produces more bolls per plant. GOSSYM was used to analyze the inconsistencies in lint yield of okra leaf-type cotton by varying nitrogen application rates and plant carbohydrate supply (Landiver *et al*., 1983a). Higher irrigation and nitrogen supply to the plant are required in order to supply sufficient carbohydrates to maintain the fruit load on okra leaf-type cotton. Increased carbohydrate supply through increased photosynthetic efficiency also retained a higher percentage of fruits at all N application rates, which suggests that photosynthesis is the critical known limiting factor in okra leaf-type cotton.

Specific leaf weight (SLW) has been used as a criterion to select for improved photosynthetic performance in crops (Barnes *et al.*, 1969; Dornhoff and Shibles, 1970; Kerby *et al*., 1980). The GOSSYM model was used in the selection of physiological characters for yield improvement (Landivar *et al*., 1983b) and to determine whether SLW can be used to predict higher photosynthetic efficiency. In this study, an increase in lint yield of 54% was obtained by increasing the photosynthesis by 30%, if adequate N and water were available. Increased SLW did not improve crop yield as most of the assimilates produced were simply utilized for increasing the leaf thickness. Thus, increased photosynthesis is a superior yield selection criteria compared to specific leaf weight.

Educational applications

GOSSYM is a useful tool of education, serving as an aid for teaching of crop and soil management, and also in helping students and commercial users to develop a 'system' of thinking that enables them to appreciate their specialty as part of a larger system. At universities, the GOSSYM model is used to create a better understanding of environmental plant and crop physiology concepts. Since 1979 there were 22 accepted Masters and Ph. D theses and dissertations on GOSSYM by researchers from different disciplines at Mississippi State University, Mississippi State, U.S. Improvements in crop model performance along with the ability to graphically present the changes in plant growth and development makes the model an indispensable classroom-teaching tool (Reddy K.R. *et al*., 2002a). On the farm, GOSSYM is already in use educating farmers on how to improve crop productivity and providing crop consultants with valuable information on how to reap rich harvests. GOSSYM has served as the template for some subsequent ARS crop growth models such as melons, soybean, corn, wheat, rice and potato (http://www.ars.usda.gov/is/pr/2002). As more is learnt, the possibilities and opportunities for model applications to provide solutions as well as insight into the physical and physiological problems associated with crop responses to the environment appear limitless.

Model applications at farm level

Pre-season and in-season decisions

GOSSYM is used in both tactical and strategic farm management decisions. Tactical management refers to the within the season decision-making process; whereas strategic management refers to decisions made before the cropping season begins. The model provides a quick and straightforward assessment of the plant at many levels of detail, as desired by the user. Producers in different USA cotton growing regions use GOSSYM with different objectives. These objectives include yield and/or profit maximization, minimization of risk, minimization of plant stress, minimization of length of growing period, optimization of the use of plant growth regulators and crop termination. Evidently, several of these objectives are an indirect way of maximizing the yield or profit. Published information shows that farmers used GOSSYM extensively as a tool for on-farm management decisions. Timely decisions are the key to successful harvest. An analysis of GOSSYM usage by farmers across the US Cotton Belt was conducted by a group of independent scientists (Ladewig and Powell, 1989; Ladewig and Thomas, 1992). The survey revealed that the majority of farmers used the GOSSYM model as a decision support system for determining crop termination, nitrogen utilization, and irrigation practices. On average, users of GOSSYM earned \$80.00 ha^{-1} more compared to users who did not use any simulation models. McKinion *et al.* (1989) reported that benefits of using GOSSYM as a management tool were \$100-350 ha^{-1}.

A pilot test conducted in 1985 on the Mitchner farm (Mississippi, USA) is a realistic experience of the GOSSYM application in decision-making. GOSSYM predicted an increase in cotton lint yield of 224 kg ha^{-1} with an additional 56 kg (N) ha^{-1}, but the farmer could apply only 22 kg (N) ha^{-1}. Cotton was picked both by hand and machine, the hand picked area showed a net increase in yield by about 202 kg ha^{-1} of cotton lint, while the machine picked area recorded a 129 kg ha^{-1} increase in lint yield. The difference between the hand picked and machine harvested yield is attributable to losses in mechanical harvest. The additional economic value of the machine picked cotton was about \$161 ha^{-1}, where the cost of fertilizer was \$10 and the application cost of fertilizer was \$15. This led to a net profit of \$135 ha^{-1} on this 2700 ha farm. Similarly, in a study by Gertsis *et al.* (1997), "GOSSYM-managed" plots, where crop management practices were varied as per the predictions of GOSSYM, showed higher yields than "farmer-managed" plots in Greece. GOSSYM-managed plots yielded 26-81% more than farmer-managed plots in Greece.

Irrigation and nitrogen management

Timely irrigation and maintaining soil fertility are important in sustaining cotton productivity and profitability. Cotton plants are sensitive to both water stress and reduction in nitrogen supply caused by water stress (Reddy K.R. *et al*., 1997a; Gerik *et al*., 1998). GOSSYM simulates soil water and nitrogen present in the two-dimensional array of soil cells. Water and nitrogen uptake are calculated in cells containing roots. GOSSYM calculates daily evaporation (E), transpiration (T), and evapo-transpiration (ET) using subroutines as modified from the algorithms of Ritchie (1972). These values (E, T and ET) and plant water demand are calculated from potential ET rates, canopy light interception, and soil water content. A study by Staggenborg *et al*. (1996) showed that GOSSYM underestimated E by 18%, due to overestimation of LAI, thus reducing incident radiation at the soil surface. However, the simulated ET over the entire crop duration of 102 d was within 10% at the end of the measuring period, despite overestimation of LAI. However, GOSSYM can still be used to assess water use by the cotton crop, and as a tool for scheduling irrigation in a semi-arid region, provided the current algorithms used to calculate potential ET are modified to include air humidity.

Crop simulation models that include soil processes are the only tools that simultaneously integrate the interacting soil, water, plant, and weather factors, which determine soil-N availability and current and future N needs. Wanjura and McMichael (1989) used simulation analysis instead of costly field experimentation to study the impact of N fertilization on cotton productivity. Adoption of the model for on-farm use required simulations of the optimum nitrogen supply under specific sets of farm conditions (soil, weather and cultivar). A survey of GOSSYM users (Albers *et al.*, 1992) found that 76% of the farmers who used the model changed their N-management practices. Stevens *et al.* (1996) validated the nitrogen dynamics in cotton crops. The GOSSYM simulated lint yields on the Loring soil (fine-silty, mixed, thermic Typic Fragiudalfs) were greatest with 90 kg ha^{-1}. The study revealed that GOSSYM simulated responses to N fertilizer were similar to actual data, but were lower over the whole range of applied N. GOSSYM was unable to accurately simulate the mineralization and immobilization processes or ammonia-volatilization losses from the soil or the plants (Boone *et al.*, 1993), and hence overestimated soil N availability by 10-30 kg N ha^{-1}, overestimated fertilizer N recovery, and underestimated cotton yield and over predicted the fertilizer N recovery by plants. Thus, improving algorithms relating to processes that control N dynamics of the plant and soil system is essential to enhance the model simulations and its wider utility.

Excessive N application in farmlands is a major cause of eutrophication of ground water and is also an unnecessary cost for the farmer. Hunt *et al.* (1998) reported that the GOSSYM model could be used to avoid excessive N fertilizer applications on cotton farms. They conducted a study to determine if seed yields or excess N application were affected by the timing of N applications via buried microirrigation tubing, tubing spacing or peanut rotation. Rotation did not have any effect on the measured parameters. GOSSYM management did not improve seed yield, but it did reduce the N (fertilizer N–seed N) to <20 kg ha^{-1} yr^{-1}. Hence, GOSSYM may be used to tailor the fertilizer needs of individual fields.

Growth regulator and crop termination chemical applications

Mepiquat chloride (MC), a plant growth regulator used in cotton production, acts a tool to the grower to manipulate a proper balance between vegetative and reproductive growth (York, 1983a, 1983b; Reddy V.R. *et al*., 1990). MC suppresses excessive plant growth by decreasing plant height, number of nodes, fruiting and vegetative branch lengths, and leaf area. The on-farm success of GOSSYM is attributed to continuous development and upgrading of the model as new information becomes available. An example is the development of a sub-routine dealing with MC (Reddy V.R. 1993; Reddy K.R. *et al*., 1995). The initial MC subroutine was developed with a single rate of MC applied to flowering cotton plants (Reddy V.R. 1993). This model has not worked satisfactorily in all growing conditions and over a range of MC application rates (Reddy K.R. *et al*., 1995). The new MC subroutine was developed from leaf expansion, stem elongation, and photosynthetic rate data of plants containing different MC concentrations in the tissues The model with the new subroutine predicted with greater accuracy and the model also performed well with data sets from a wide range of environmental conditions, a variety of cultural practices, and diverse genetic resources (Figure 4). The data sets comprised both single and multiple MC application rates applied on different dates during the growing season.

GOSSYM was also used to determine the optimum MC application strategy. Watkins *et al.* (1998) evaluated 12 different MC application strategies for two different soil types (Bosket sandy loam and Dundee silty clay loam) and three different weather scenarios (normal, cold-wet, and hot-dry) in the Mississippi Delta using the GOSSYM management system. The simulations revealed quantitatively what most growers knew intuitively, but could not predict, a priori. The soil type and weather conditions determine the type of MC application strategy that should be used as opposed to using a blanket MC application strategy for all weather conditions.

Reddy VR (1995) developed a model for ethephon and integrated with GOSSYM to be used for crop termination decisions. Improper dosage or time of application of ethephon, a crop termination and harvest-aid chemical can drastically reduce cotton lint yield and quality. The model provides the users an insight on time, rate and amount of ethephon and other crop termination chemicals for end of the season harvest decisions.

Precision agriculture management

Precision farming/agriculture aims to improve crop production efficiency and reduce environmental contamination by adjusting production inputs (for example - seed, fertilizer and pesticide) to the specific conditions within each area of the field. The multidisciplinary field of precision farming requires expertise in remote sensing, geographic information systems, global positioning system and crop modeling. Currently, efforts to integrate these systems into a single unit for planning and improving the efficiency of cotton production systems are being investigated. McCauley (1999) used GOSSYM integrated with GRASS, a geographic information system, to produce spatially variable outputs. Inputs to the model were collected from a 3.9 ha cotton field. Soil nitrate, a primary driver for fertilizer recommendations was sampled on a 15.2 m regular grid for depths to 150 mm and on a 30.5 m rectangular grid at six 150 mm depth intervals (down to 900 mm). GOSSYM was used to simulate the application of these recommendations and predicted spatially variable yield and residual nitrogen. This study concluded that crop simulations and geographic information systems are a valuable combination of precision farming and planning variable rate applications. Simulations from this study indicated that excessive fertilization, while potentially damaging to the environment, might also have negative impacts on yield. This conclusion illustrates one of the advantages of precision farming, especially in fields with high variability of soil properties.

In a recent study, McKinion *et al.* (2001) combined the GOSSYM system with the Arc View GIS software. It was used to evaluate nitrogen and water stress experiments on cotton conducted during 1997 on the Kenneth Hood Farm in Bolivar County, Mississippi, USA. The total actual N applied was 160 kg N ha^{-1}. The amount of irrigation water applied was 83 mm in three applications. During the crop growth period of May to October of 1997, a total of 754 mm of rainfall was also received. The entire selected area for the study was divided into grids containing 1 ha areas and 88 simulations were carried out which were based on the variation in soil types. A whole field simulation based on the summation of the above simulations predicted an average yield of 1,133 kg ha^{-1}, higher by 4.3%, compared with grower's actual yield of 1,084 kg ha^{-1}. The precision agricultural system (GOSSYM + Arc View GIS) recommended nitrogen application rates from 7.8 to 199 kg (N) ha^{-1}. Further evaluation is needed for the higher rate of 199 kg ha^{-1}, while the remaining rates of 16.8 to 108 kg (N) ha^{-1} were reasonable. The irrigation totals ranged from 0 to 176 mm of water. The recommended number of irrigations varied from one to seven. Obviously, growers will not be able to apply water on a per hectare basis as addressed in this analysis, but the numbers are included here to show the range in variability with just having soil type information as a variable. The yield predictions were shown as differences between the precision agriculture optimized yield and the yield predicted using the grower's actual cultural practices. The negative yield differences obtained show that the expert system is not infallible. One reason may be that surface and nutrient movement are not accounted for in the model. When an event like this occurs, the user should conduct manual simulations to determine if improvements can be made or an appropriate interpretation of the problem can be obtained. The predicted yield improvement using the precision agriculture tool showed that the grower could expect an increase of 286 kg ha^{-1} (0.51 bales per acre) for this field even with the few negative results.

Another valuable tool in precision agriculture is remote sensing which may also be combined with crop modeling. The agricultural research community is currently engaged in identifying cotton plant spectral reflectance signals associated with growth and development stages (Reddy K.R. *et al.*, 2003a), nutrient and water status of cotton plants. Studies conducted so far using spectral reflectance have attempted to identify plant responses to different stresses by using plant chlorophyll content as the primary indicator (Tarpley *et al.*, 2001; Read *et al.*, 2002). Sensors can also be developed to predict cotton nutrient and water status under field conditions. Information from remote sensing may then be combined with crop model predictions of yield response for real-time in-season crop management.

Deficiencies and future development needs

In this paper, we tried to put forth how GOSSYM evolved as a potential tool in research, crop management and in policy decision-making processes. Despite concerns about the difficulty in validation of crop models, GOSSYM was tested widely in diverse environments. Researchers made use of this model in conducting hypothetical studies, and also comparing simulation results with their experimental results. The validation and testing of the model in diverse environments provided knowledge voids that led to further improvement of the model. Examples were cited from the literature and case studies were presented. Along with considerable potential of crop modeling, there can also be misrepresentation, misuse and misunderstanding of the tools. Both the developers and users should be aware of the limitations and their possible misuse.

Although GOSSYM includes the effects of extreme temperatures and of water and nutrient stresses on many physiological processes and yield, the model is far from complete. Factors or limitations of the model concern are nutrients other than carbon and nitrogen, as well as damages caused by herbicides, pests, and extreme weather events such as hail and winds. Many of the model applications discussed involve an assessment of risk. Thus, it is worthwhile to say that risk and uncertainty are inherent in agriculture. The model for now lacks the capability to predict fiber quality, an economic component of the crop, as affected by environmental and management factors. Functional fiber quality algorithms need to be incorporated into the model that can provide both in-season management decisions for a better end-of the season fiber quality assessment at the mill. Studies at Mississippi State University are in progress to incorporate the effects of UV-B radiation into this physiologically-based model (Reddy *et al.*, 2003b). Furthermore, the model needs to be integrated with several other technologies such as GIS and remote sensing for site-specific crop management.

Acknowledgements

We thank Drs. Soo Kim, Genhua Niu, Mike Williams and Frank Whisler for their valuable suggestions. Part of this research was supported by the National Aeronautical and Space Administration–funded Remote Sensing Technology Center at Mississippi State University. Contribution from the USDA-ARS and the Department of Plant and Soil Sciences, Mississippi State University, Mississippi Agricultural and Forestry Experiment Station, Paper no. PS 10330.

References

- Agarwal, P.K. (1993). Agro-ecological zoning using crop growth simulation models: characterization of wheat environments in India. In: Systems Approaches for Sustainable Agricultural Development (ed. Penning de Vries, F.W.T.), Kluwer Academic Publishers, Netherlands, pp. 97-109.
- Albers, D.W., Mobley, J. and Tracy, P.W. (1992). Evaluation of GOSSYM-COMAX in Missouri 1987-1991. *In* Proceedings of Beltwide Cotton Conference (eds. Herber, D.J. and Ritcher, D.A.), National Cotton Council, Memphis, Tennessee, USA, pp. 1350-1351.
- Baker, D.N., Lambert, J.R. and McKinion, J.M. (1983). GOSSYM: a simulator of cotton crop growth and yield. South Carolina Agricultural Experimental Station Technical Bulletin No. 1089, Clemson, South Carolina, USA.
- Baker, D.N., Reddy, V.R., McKinion, J.M. and Whisler, F.D. (1993). An analysis of the impact of lygus on cotton. *Computers and Electronics in Agriculture*, **8**: 147-161.
- Barnes, D.K., Pearce, R.B., Carlson, G.E., Hart, R.H. and Hanson, C.H. (1969). Specific leaf weight differences in alfalfa associated with variety and plant age. *Crop Science*, **9**: 421-423.
- Boone, M.Y.L., Porter, D.O. and McKinion, J.M. (1993). Calibration of GOSSYM: theory and practice. *Computers and Electronics in Agriculture,* **9**: 193-203.
- Boote, K.J., Jones, J.W. and Pickering, N.B. (1996). Potential uses and limitations of crop models. *Agronomy Journal*, **88**: 704-716.
- Brooks, O.L. (1977). Effects of soil environment on cotton yields. *In* Proceedings of Beltwide Cotton Conference (eds. Herber, D.J. and Ritcher, D.A.), National Cotton Council, Memphis, Tennessee, USA, pp. 68-69.
- Davis, D.R. and Gallup, J. (1977). Have weather patterns changed and affected cotton yields? *In* Proceedings of Beltwide Cotton Production Conference (eds. Herber, D.J. and Ritcher, D.A.), National Cotton Council, Memphis, Tennessee, USA, pp. 70-71.
- Doherty, R.M., Mearns, L.O., Reddy, K.R., Downton, M. and Daniel, L.M. (2003). Impacts of spatial scale climate scenarios on simulated cotton production in the southeastern USA. *Climatic Change*, **60**: 99-129.
- Dornhoff, G.M. and Shibles, R.M. (1970). Varietal differences in net photosynthesis of soybean leaves. *Crop Science*, **10**: 42-45.
- Duncan, W.G. (1972). SIMCOT: A simulator of cotton growth and yield. *In* Proceedings of a Workshop on Tree Growth, Dynamics and Modeling, Duke University, North Carolina, USA, pp. 115-118.
- Gerik, T.J., Oosterhuis, D.M. and Torbet, H.A. (1998). Managing cotton nitrogen supply. *Advances in Agronomy*, **64**: 115-147.
- Gertsis, A.C. and Symeonakis, A.G. (1998). Efficient cotton production in Greece with the use of GOSSYM – a cotton crop simulation model. *Acta Horticulturae*, **476**: 307-312.
- Gertsis, A.C., Stella, G.S., Papathanasiou, G. and Symeonokis, A. (1997). Use of GOSSYM-A cotton growth simulation model to manage low input production system in Greece. *In* Proceedings of First European Conference for Information Technology in Agriculture (eds. Kure, H., Thysen, I. and Kristensen, A.R.) Copenhagen, Denmark, pp. 359-362.
- Hearn, A.B. (1994). OZCOT: a simulation model for cotton crop and management. *Agricultural Systems*, **44**: 257-259.
- Hodges, H.F., Whisler, F.D., Bridges, S.M., Reddy, K.R. and McKinion, J.M. (1998). Simulation in crop management: GOSSYM/COMAX. *In* Agricultural Systems Modeling and Simulation (eds. Peart, R.M. and Curry, R.B.), Marcel Decker Inc., New York, USA, pp. 235-281.
- Hunt, P.G., Bauer, P.J., Camp, C.R. and Matheny, T. (1998). A Nitrogen accumulation in cotton grown continuously or in rotation with peanut using subsurface microirrigation and GOSSYM/COMAX management. *Crop Science*, **38**: 410-415.
- Hurst, H.R. (1977). Are herbicides cutting yields? *In* Proceedings of Beltwide Cotton Production Re-

search Conference (eds. Herber, D. J. and Ritcher, D. A.), National Cotton Council, Memphis, Tennessee, USA, pp. 61-63.

- Jackson, B.S., Arkin, G.F. and Hearn, A.B. (1998). The cotton simulation model "COTTAM" Fruiting model calibration and testing. *Transactions of the ASAE*, **31**: 846-854.
- Jallas, F. (1998). Improved model based decision support by modeling cotton variability and using evolutionary algorithms. Ph. D thesis, Mississippi State University, Mississippi State, Mississippi, USA.
- Jallas, E., Cretenet, M., Turner, S., Sesquira, R. and Martin, P. (2000). COTONS release 2.0.3, CIRAD, BP 5035, Montpelliar, France.
- Kerby, T.A., Buxton, D.R. and Matsuda, K. (1980). Carbon source-sink relationships with narrow-row cotton canopies. *Crop Science*, **20**: 208-213.
- Khorsandi, F. and Whisler, F.D. (1996). Validation of the soil-temperature model of GOSSYM-COMAX. *Agricultural Systems*, **51**: 131-146.
- Khorsandi, F., Boone, M.Y.L., Weerakkody, G. and Whisler, F.D. (1997). Validation of the soil temperature subroutine HEAT in the cotton simulation model GOSSYM. *Agronomy Journal*, **89**: 415-420.
- Ladewig, A.M. and Thomas, J.K. (1992). A Follow-Up Evaluation of the GOSSYM/COMAX Cotton Program, Texas Agricultural Extension services College Station, Texas, USA, p. 47.
- Ladewig, H. and Powell, E.T. (1989). An Assessment of GOSSYM/COMAX as a Decision System in the U.S. Cotton Industry, Texas Agricultural Extension. Services College Station, Texas, USA, p. 51.
- Landivar, J.A. (1991). Physiological characteristics affecting the performance of cotton cultivars in different environments. *In* Proceedings of Beltwide Cotton Research Conference (eds. Herber, D.J. and Ritcher, D.A.), National Cotton Council of America, Memphis, Tennessee, pp. 97-99.
- Landivar, J.A., Baker, D.N. and Jenkins, J.N. (1983a). Application of GOSSYM to genetic feasibility studies: I. Analyses of fruit abscission and yield in okra-leaf cottons. *Crop Science*, **23**: 497-504.
- Landivar, J.A., Baker, D.N. and Jenkins, J.N. (1983b). Application of GOSSYM to genetic feasibility studies: II. Analyses of increasing photosynthesis, specific leaf weight and longevity of leaves in cotton. *Crop Science*, **23**: 504-510.
- Leigh, T.F. (1977). Insecticides and cotton yield. *In* Proceedings of Beltwide Cotton Conference (eds. Herber, D.J. and Ritcher, D.A.), National Cotton Council, Memphis, Tennessee, USA, pp. 63-65.
- Maples, R. (1977). Are we using too much fertilizer? *In* Proceedings of Beltwide Cotton Conference (eds. Herber, D.J. and Ritcher, D.A.), National Cotton Council, Memphis, Tennessee, USA, pp. 65-68.
- Marani, A. and Baker, D.N. (1978). Development of predictive dynamic simulation model for growth and yield of Acala cotton. Science report to US-Israel Binational Science Foundation.
- Marani, A., Cardon, G.E. and Phene, C.J. (1992). CALGOS: a version of GOSSYM adapted for irrigated cotton. I. Drip irrigation, soil water transport and root growth. *In* Proceedings Beltwide Cotton Conference (eds. Herber, D.J. and Ritcher, D.A.), National Cotton Council, Memphis, Tennessee, pp. 1352-1357.
- Marani, A., Baker, D.N., Reddy, V.R. and McKinion, J.M. (1985). Effect of water stress on canopy senescence and carbon exchange rates in cotton. *Crop Science*, **25**: 798-802.
- McCauley, J.D. (1999). Simulation of cotton production for precision farming. *Precision Agriculture,* **1**: 81-94.
- McKinion, J.M., Jenkins, J.N., Akins, D., Turner, J.L., Willers, E., Jallas, E. and Whisler, F.D. (2001). Analysis of a precision agriculture approach to cotton production. *Computers and Electronics in Agriculture,* **32**: 213-228.
- McKinion, J.M., Baker, D.N., Whisler, F.D. and Lambert, J.R. (1989). Application of the GOSSYM/COMAX system to cotton crop management. *Agricultural Systems*, **31**: 55-65.
- Mearns, L., Katz, R., Adams, R., McCarl, B., Easterling, W. and Carbone, G. (1999). Sensitivity analysis of the effect of changes in mean and variability of climate on crop production and regional economic in the Southeastern US. Project Final Report, National Center for Environmental Research, Boulder, Colorado, USA.
- Meredith, W.R. (1987). Final report of the cotton foundation yield and productivity study. *In* Proceedings of Beltwide Cotton Conference (eds. Herber, D.J. and Ritcher, D.A.), National Cotton Council, Memphis, Tennessee, USA, pp. 33-37.
- Miller, J.E., Patterson, R.P., Heagle, A.S., Pursely, W.A. and Heck, W.W. (1998). Growth of cotton under chronic ozone stress at two levels of soil moisture. *Journal of Environmental Quality*, **17**: 635-643.
- Mississippi Cooperative Extension Service (MCES). 1990. Farm management Handbook, MCES, Mississippi State, Mississippi, USA.
- Olson, R.L. and Wagner, T.L. (1992). WHIMS: a knowledge-based system for cotton pest management. *Artificial Intelligence Applications*, **6**: 41-58.
- Orr, C.C., Robinson, A.F., Heald, C.M., Veech, J.A. and Carter, W.W. (1982). Estimating cotton losses to nematodes. *In* Proceedings of Beltwide Cotton Conference (eds. Herber, D.J. and Ritcher, D.A.), National Cotton Council, Memphis, Tennessee, USA, pp. 22.
- Pan, X., Deng, S. and McKinion, J.M. (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, 7p.
- Penning de Vries, F.W.T., Van Kuelan, H. and Rabbinge, R. (1995). Natural resources and limits of food production in 2040. *In* Ecological Approaches for Sustainable Land Use and Food Production. (ed. Bouma, J.), Kluwer Academic Publishers, The Netherlands, pp. 65-87.

- Plant, R.E. (1989). An integrated decision support system for agricultural management. *Agricultural Systems*, **29**: 49-66.
- Read, J.J., Tarpley, L., McKinion, J.M. and Reddy, K.R. (2002). Narrow-waveband reflectance ratios for remote estimation of nitrogen stress in cotton canopies. *Journal of Environmental Quality*, **31**: 1442-1452.
- Reddy, K.C., Nyakatawa, E.Z. and Reddy, K.R. (2000). Predicting cotton growth and yield parameters under different management systems using the GOSSYM model. *In* Proceedings of the International Agricultural Engineering Conference (eds. Salokhe, V.M. and Hussein, M.B.), Bangkok, Thailand, pp. 543-549.
- Reddy, K.R., Zhao, D., Kakani, V.G., Read, J.J. and Sailaja, K. (2003a). Estimating cotton growth and developmental parameters through remote sensing. *In* Proceedings of SPIE: Ecosystems Dynamics, Agricultural Remote Sensing and Modeling, and Site-Specific Agriculture (eds. Wei Gao and David Shaw), SPIE, Bellingham, WA, USA, Vol. 5153 pp. 277-288.
- Reddy, K.R., Kakani, V.G., Zhao, D., Mohammed, A.R. and Gao, W. (2003b). Cotton Responses to Ultraviolet-B Radiation: Experimentation and algorithm development. *Agricultural and Forest Meteorology*, **120**: 249-266.
- Reddy, K.R., Kakani, V.G., McKinion, J.M. and Baker, D.N. (2002a). Applications of a cotton simulation model, GOSSYM, for crop management, Economic and Policy decisions. *In* Agricultural Systems - Models in Field Research and Technology Transfer (eds. Ahuja, L.R., Ma, L. and Howell, T.A.), Lewis Publishers, Boca Raton, New York, USA, pp. 33-54.
- Reddy, K.R., Doma, P.R., Mearns, L.O., Boone, M.Y.L., Hodges, H.F., Richardson, A.G. and Kakani, V.G. (2002b). Simulating the impacts of climate change on cotton production in the Mississippi Delta. *Climate Research*, **22**: 271-281.
- Reddy, K.R., Hodges, H.F., Read, J.J., McKinion, J.M., Baker, J.T., Tarpley, L. and Reddy, V.R. (2001). Soil-plant-atmosphere research (SPAR) facility: A tool for plant research and modeling. *Biotronics*, **30**: 1-24.
- Reddy, K.R., Davidonis, G.H., Johnson, A.S. and Vinyard, B.T. (1999). Temperature regime and carbon dioxide enrichment alter cotton boll development and fiber properties. *Agronomy Journal,* **91**: 851-858.
- Reddy, K.R., Hodges, H.F. and McKinion, J.M. (1997a). Crop modeling and applications: a cotton example. *Advances in Agronomy,* **59**: 225-290.
- Reddy, K.R., Hodges, H.F. and McKinion, J.M. (1997b). Modeling temperature effects on cotton internode and leaf growth. *Crop Science,* **37**: 503-509.
- Reddy, K.R., Boone, M.Y.L., Reddy, A.R., Hodges, H.F., Turner, S. and McKinion, J.M. (1995). Developing and validating a model for a plant growth regulator. *Agronomy Journal,* **87**: 1100-1105.
- Reddy, K.R., Hodges, H.F. and McKinion, J.M. (1993). A temperature model for cotton phenology. *Biotronics*, **2**: 47-59.
- 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 interactions in cotton. *Computers and Electronics in Agriculture*, **13**: 27-35.
- Reddy, V.R. and Baker, D.N. (1990). Application of GOSSYM to analysis of the effects of weather on cotton yields. *Agricultural Systems*, **32**: 83-95.
- Reddy, V.R., Baker, D.N., Whisler, F.D. and McKinion, J.M. (1990). Analysis of the effects of herbicides on cotton yield trends. *Agricultural Systems*, **33**: 347-359.
- Reddy, V.R., Baker, D.N. and McKinion, J.M. (1989). Analysis of the effects of atmospheric carbon dioxide and ozone on cotton yield trends. *Journal of Environmental Quality*, **18**: 427-432.
- Reddy, V.R., Baker, D.N., Whisler, F.D. and Fye, R.E. (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., Baker, D.N. and Jenkins, J.N. (1985). Validation of GOSSYM: Part II – Mississippi conditions, *Agricultural Systems*, **17**: 133-154.
- Richardson, A.G., Reddy, K.R. and Boone, M.L. (2003). Sensitivity analysis of climate change impacts on cotton production using the GOSSYM crop model. *Biotronics*, **32**: 1-24
- Ritchie, J.T. (1972). Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Research*, **8**: 1204-1213.
- Staggenborg, S.A., Lascano, R.J. and Krieg, D.R. (1996). Determining cotton water use in a semiarid climate with the GOSSYM cotton simulation model. *Agronomy Journal*, **88**: 740-745.
- Stevens, W.E., Varco, J.J. and Johnson, J.R. (1996). Evaluating cotton nitrogen dynamics in the GOSSYM simulation model. *Agronomy Journal*, **88**: 127-132.
- Tarpley, L., Reddy, K.R. and Sassenrath-Cole, G.F. (2000). Reflectance indices with precision and accuracy in predicting cotton leaf nitrogen concentration. *Crop Science*, **40**: 1814-1819.
- USDA-NASS, (2002). Crop Production Report, National Agricultural Statistics Service (NASS), Agricultural Statistics Board. United States Department of Agriculture (USDA), Washington, D.C., USA, p. 4.
- Wall, G.W., Amthor, J.S. and Kimball, B.A. (1994). COTCO2: a cotton growth simulation model for global change. *Agricultural and Forest Meteorology,* **70**: 289-352.
- Wanjura, D.F. and McMichael, B.L. (1989). Simulation analysis of nitrogen application strategies for cotton. *Transactions of ASAE*, **32**: 627-632.
- Watkins, K.B., Lu, Y.C. and Reddy, V.R. (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., Reddy, V.R., Baker, D.N. and McKinion, J.M. (1993). Analysis of effects of soil compaction on cotton yield trends. *Agricultural Systems*, **42**: 199-207.
- Whisler, F.D., Acock, B., Baker, D.N., Fye, R.E., Hodges, H.F., Lambert, J.R., Lemmon, H.E., McKinion, J.M. and Reddy, V.R. (1986). Crop simulation models in agronomic systems. *Advances in Agronomy*, **40**: 142-208.
- Wolf, J. (1993). Effects of climate change on wheat production potential in the European Community. *European Journal of Agronomy*, **2**: 281-292.
- York, A.C. (1983a). Cotton cultivar response to mepiquat chloride. *Agronomy Journal*, **75**: 663-667.
- York, A.C. (1983b). Response of cotton to mepiquat chloride with varying N rates and plant populations. *Agronomy Journal, 75*: 667-672.

Figure 1. *Sensitivity analysis of temperature effects on (a) plant height, (b) mainstem nodes, (c) yield, (d) days to first square, (e) days to first bloom and (f) days to first open boll at different locations in USA (Stoneville, Mississippi; Corpus Christi, Texas; Springfield, Illinois; Florence, South Carolina; Artesia, New Mexico) (Source: Richardson* et al.*, 2003).*

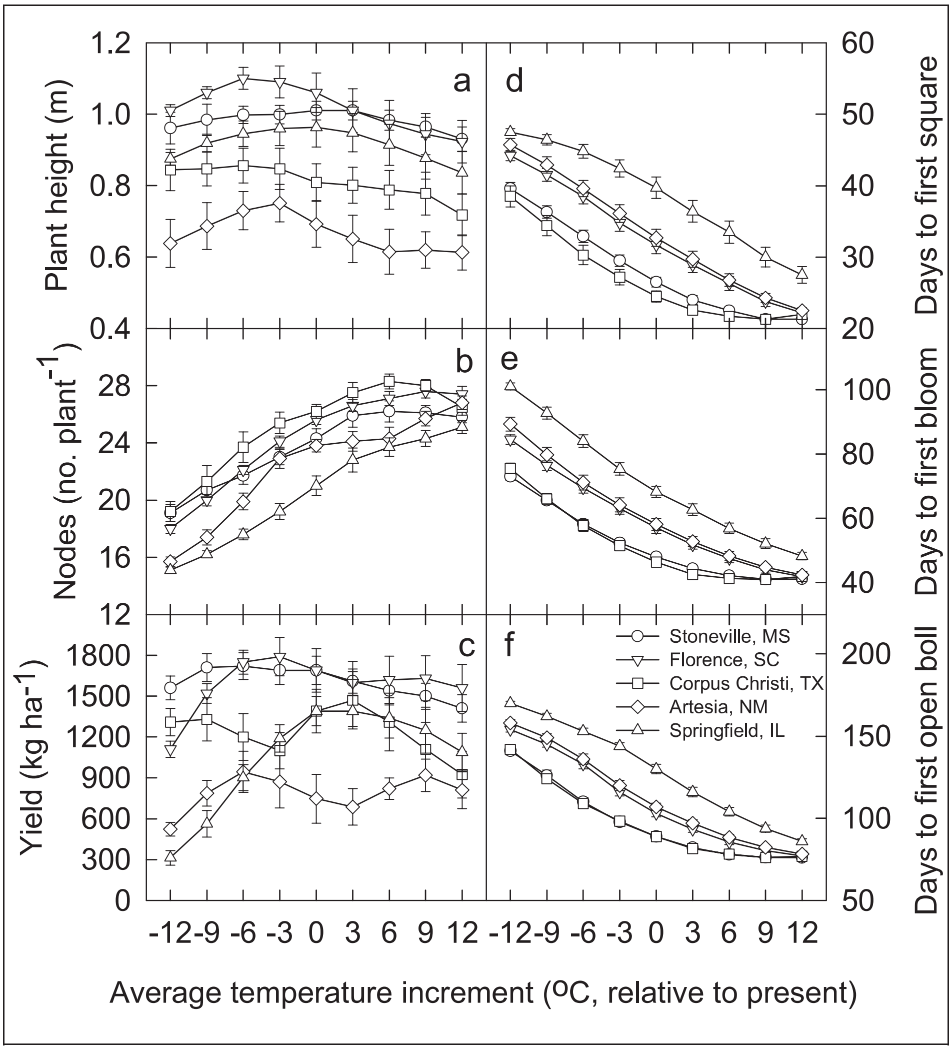

Figure 2. Cotton response climate change: Simulated lint yield response to carbon dioxide enrichment. The data are means of 30-year simulations (1964-1993) (Source: Reddy K.R. et al., 2002b).

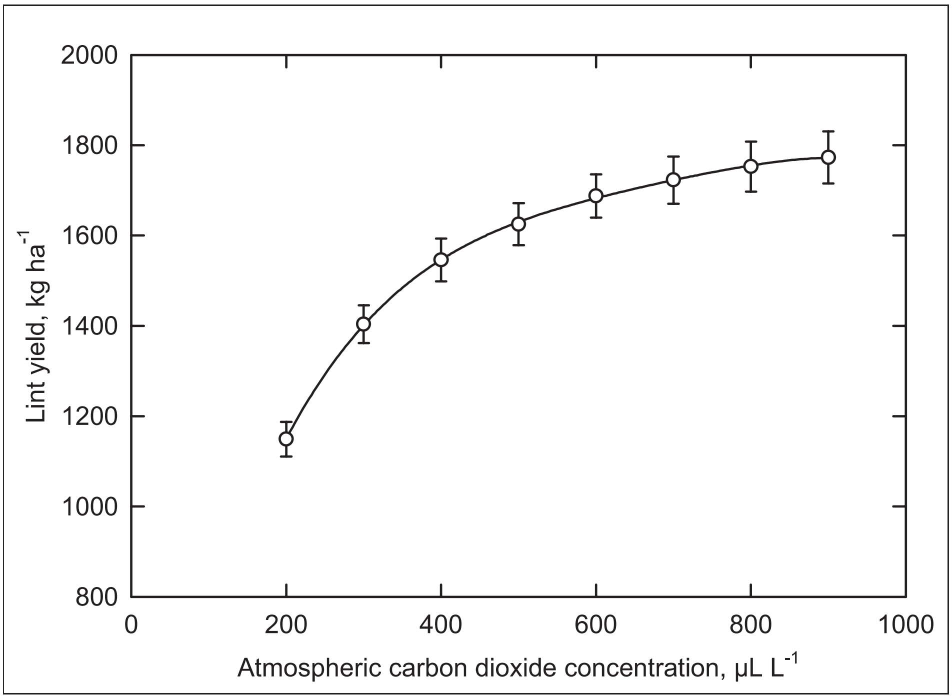

Figure 3. Cotton response to climate change: Simulated yields for different years with varying weather patterns; current weather with ambient CO_2, current weather with elevated CO_2, and future weather with elevated CO_2 (Source: Reddy K.R. et al., 2002b)

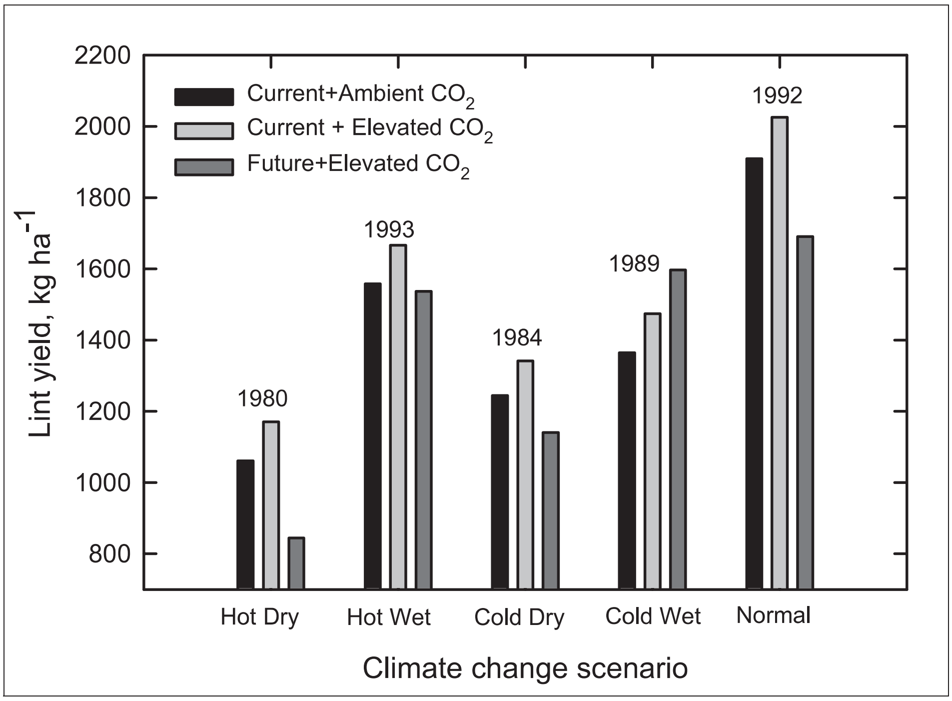

Figure 4.
Comparison of observed and simulated (A) plant height, (B) mainstem nodes, (C) lint yield using the new MC routine in GOSSYM. The data collected from plants grown on various soil types, weather conditions, and management practices across the US Cotton Belt. (Source: Reddy K.R. et al., 1995).