

Preliminary results of a UV-B effect incorporated GOSSYM model

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ABSTRACT

Field experiments and laboratory tests have shown multiple effects of enhanced ultraviolet-B (UV-B) radiation on cotton growth, development, and yield. Adverse effects include development of chlorotic and necrotic patches on leaves, reductions in total leaf area, plant height, photosynthesis, and yield. However, little work has been carried out to incorporate these experimental results into a simulation model and to estimate the effects of UV-B radiation under field conditions with varied environments and management practices. This study incorporates experimental results of UV-B effects on cotton crop into a cotton simulation model, GOSSYM, which is being used widely in various applications. In this work, first modules were modified to incorporate the effects of UV-B radiation on canopy photosynthesis, leaf area expansion, and stem and branch elongation. Then, the modified model was used to test the validity of model assumptions and algorithms on independent experimental data sets. Finally, preliminary studies were performed to simulate the effects of UV-B radiation in the field conditions at Stoneville, Mississippi using 30-year (1964-1993) climate data. Simulation results agreed well with experimental measurements, proving the validation of the model. Our results suggest that cotton lint yield declined with increased UV-B radiation. The reductions were 20% when UV-B irradiance was 12 kJ m⁻² under irrigated conditions. Similar reductions in yield were predicted at lower UV-B radiation (11 kJ m⁻²) under rain-fed conditions. The modified model will be useful to simulate the impacts of UV-B radiation on cotton growth and yield under current and future climatic conditions and to suggest management options to mitigate the adverse effects.

Key Words: UV-B radiation, cotton, GOSSYM model, crop model

1. INTRODUCTION

Observed depletion of stratospheric ozone in both high and middle latitude areas (Farman et al., 1985; Stolarski et al., 1992; Reinsel et al., 1994) raises concerns in scientific community of concomitant increases in UV-B radiation reaching the Earth's surface (Frederick and Snell, 1988; Scotto, 1988; Grant, 1988; Blumthaler and Ambach, 1990; Kerr and McElroy, 1993; Jaque, 1994; Herman et al., 1996; Madronich et al., 1998) and its detrimental effects on plants, human beings, and ecological communities (Smith et al., 1992; Madronich and Gruijl, 1993; Rozema et al., 1997; Caldwell et al., 1998; Longstreth et al., 1998; Kulandaivelu and Tevini, 2003; Flint et al., 2003; Kakani et al., 2003a; Bredahl et al., 2004). Experiments have shown that widely grown crops such as cotton, wheat, rice, soybean, corn, and sugarcane appear to be susceptible to enhanced UV-B radiation (Kakani et al., 2003b). Ecosystem level examinations have revealed a wide range of UV-B responses in terrestrial and marine communities, including decreases in plant growth, changes in populations of fungi, bacteria, viruses, phytoplankton, zooplankton, and invertebrates, changes in moss growth, and production of secondary metabolites (Flint et al., 2003; Clarke and Harris, 2003; Bassman, 2004). While interacting with other physical stressors such as high temperature and air pollutants, enhanced UV-B radiation will affect agricultural productivity and various goods and services of natural ecosystems. Experimental and modeling studies of UV-B effects on agriculture and its interactions with other stressors are valuable in risk assessment, agricultural practice, crop species selection, natural resource management, and in achieving sustainable development.

Cotton (*Gossypium hirsutum* L.) is a major fiber-producing and economic crop grown on over 32 Mha worldwide in both tropical and temperate regions and on over 5 Mha in 2004 in the United States (NASS-USDA, 2005). The crop is sensitive to variations of weather factors, such as temperature, atmospheric CO₂ concentration, soil moisture, and UV-B

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radiation (Reddy et al., 1997a; Reddy et al., 2002; Zhao et al., 2005). Field and growth chamber experiments have revealed a variety of morphological, anatomical, growth, and physiological responses of cotton plant to enhanced UV-B radiation and its interactions with elevated CO₂ concentration and high air temperature (Gao et al., 2003; Kakani et al., 2003a; Reddy et al., 2003; Zhao et al., 2003; Reddy et al., 2004; Zhao et al., 2004; Zhao et al., 2005). These include developments of chlorotic and necrotic patches on leaves, changes in plant structure and pigment, decreases in photosynthetic activity, and losses of yield, leaf area, and plant height. However, little work has been done to incorporate these experimental results into a simulation model, which can in turn be used to estimate comprehensive effects of UV-B radiation on cotton growth productivity across a wide range of environmental conditions and under varied management and cultural practices. A simulation model provides quantitative description of plant growth and development in response to soil and aerial environments and management practices. Simulation models also assist in decision making processes for policy makers and farm managers. Further, crop growth models are being coupled with climate models to study the interactions between regional climate and crop canopy dynamics to study the impacts of altered perturbations in climate on agricultural productivity (Dickinson et al., 1998; Izaurrealde et al., 2003; Luo et al., 2005; Challinor et al., 2005; Xu et al., 2005). The positive feedback mechanism between a dynamic simulation model and field or controlled experiments makes the model more valuable in the research to study crop growth processes and to investigate the impacts of agricultural practices, resource management, policy analysis, and production estimation ((McKinion et al., 1980; Lemmon, 1986; 1990; Bannayan, 2003; Dhungana, 2006).

The GOSSYM cotton growth model is a process-oriented dynamic simulation model that simulates the growth of cotton plant from emergence to yield, elucidating major physiological and morphogenetic processes and accounting for the primary physical and biochemical interrelationships in the soil-plant-atmosphere system (Baker et al., 1983; Boone et al., 1995). The model has been extensively validated with different data sets from Arizona and Mississippi (Fye et al., 1984; Reddy et al., 1985; Reddy and Baker, 1988) and has been used worldwide in a large variety of applications (Landivar et al., 1983a, 1983b; Lemmon, 1986; McKinion et al., 1989; Lemmon, 1990; Reddy, 1995; Gertsis et al., 1996, 1997; Reddy et al., 1997b, 2002; Watkins et al., 1998; McKinion et al., 2001; Bannayan, 2003). Some other cotton growth models, such as cotton2k (Marani, 2004) and qualitative simulation model (Plant et al., 1998), have been developed from GOSSYM. Its validity and usefulness have been approved both in research community and by application users.

However, GOSSYM model was developed in early 1980s (Baker et al., 1983) and was modified and improved in 1990s (Reddy et al., 1997b). The model and its variants simulate the responses of cotton growth to meteorological factors and physical and chemical processes in soil. Atmospheric factors include solar radiation, temperature, precipitation, wind speed, and CO₂ concentration. To our knowledge, little work has been carried out to incorporate the effects of UV-B radiation on cotton growth into a cotton growth model. Based on the extensive and comprehensive experiments conducted at the Mississippi Agricultural and Forestry Experiment Station at Mississippi State University, Mississippi State, Mississippi, USA using sunlit Soil-Plant-Atmosphere Research (SPAR) units, this study formulates the experimental results into proper parameterized algorithms and equations, incorporates them into the GOSSYM cotton growth model, validates the model with different experimental datasets, and assesses UV-B effects on cotton yield. Uncertainties of the simulation and future work directions are also discussed.

2. MATERIALS AND METHODS

Data, which are being used in this study to develop functional algorithms on the effects of UV-B radiation, were obtained by Reddy et al. (2003). For reader's convenience, we describe the methods and data collection concisely in this section. Published data are used for validation. GOSSYM cotton growth model is briefly introduced as well. Modifications and improvements on this model are presented in a later section.

2.1 Experimental details

Two experiments were conducted at the Agriculture and Forestry Experiment Station (33°28'N, 88°47'W) at Mississippi State University, Mississippi State, MS, United States of America, in 2001 using SPAR units (Reddy et al., 2003). The SPAR experiment facilities use solar radiation as the light source (Reddy, 2001). Each SPAR unit comprises a steel soil bin (1 m deep with a section of 2.0 m by 1.5 m) as a rooting medium for growing plants, a Plexiglas chamber to accommodate aerial plant parts, a heating and cooling system for temperature manipulation, and an environmental monitoring and control system to control and monitor the system and to collect data. Temperature, CO₂, soil moisture, irrigation, and continuous monitoring of important gas exchanges (CO₂) between plants and the environment are controlled with a designated computer, which can be programmed as required. Measurements are taken automatically by the computer.

Cotton cv. NuCOTTON 33B, a midseason Upland and commonly grown cotton variety, was seeded in both experiments. The cotton seeds were sown on 4 June in Experiment I and on 1 August for Experiment II in 2001. Three rows of five plants per row, with each 0.67 m apart, were sown in each SPAR unit. The rooting medium used was fine sand. Plants were irrigated three times a day with half-strength Hoagland's nutrient solution delivered at 8:00, 12:00, and 17:00 h local time with a computer-controlled drip system to provide optimal nutrient and water conditions for plant growth. Temperatures in both experiments were set at the constant level of 30/22 °C (day/night) during the whole experimental period. Artificial UV-B radiation was provided to the plants for 8 hours from 8:00 to 16:00 h local time every day soon after emergence until 43 days after emergence (DAE) in Experiment I and 66 DAE in Experiment II using UV-313 lamps (Q-Panel Company, Cleveland, OH) driven by 40 W dimming ballasts. The lamps were calibrated before the experiments, but not monitored during the experiments. UV-B treatments were 0, 4, 8, 12, and 16 kJ m⁻² day⁻¹ in Experiment I and 0, 8, and 16 kJ m⁻² day⁻¹ for Experiment II.

2.2 Measurements

Number of nodes, plant heights, and leaf area were measured every three days. Final harvest was carried out 43 DAE in Experiment I and 66 DAE in Experiment II. The plants were analyzed into different components, dried to constant weight, and weighed to determine the biomass of various plant components and total dry matter. Bolls and squares were counted at the end of the study in both the experiments. Canopy photosynthesis was measured using a mass balance approach as described by Reddy et al. (2003).

2.3 Other data

In addition to the aforementioned measurements in the experiments, data were collected from different resources for this study. Soil physical properties data from the database established by Ali et al. (2004) were used. Climate data (1964 to 1993) from the archives of Stoneville Weather Station were used for impact assessments.

2.4 The GOSSYM model

GOSSYM model was developed in early 1980s as a process level cotton growth and development dynamic simulation model (Baker et al., 1983). The model is dynamic because the main processes, such as photosynthesis, respiration, and growth, are driven by key environmental factors, including temperature, solar radiation, and nitrogen, and are controlled by limiting stressors, such as soil water content and nitrogen supply. It also responds to chemical growth regulators and CO₂ concentrations in the atmosphere. The model was implemented using FORTRAN 77/90 and was able to run on both Windows and Unix/Linux systems.

In order to enhance the modularity and readability and to facilitate the maintenance of the software, we redesigned and reconstructed the program. An abstracted flow chart diagram of the software is shown in Figure 1. The program starts with reading input data, including daily weather data, agricultural management practices, and soil properties. Before a simulation, variables need to be initialized. The central part of the software is the daily simulator. It computes the daily photosynthesis, growth, and development. Environmental factors, including temperature, solar radiation, soil water content and availability, as well as nitrogen supply, are all simulated on a daily basis. On each day, the program checks if this is the last day for the simulation. It stops and outputs simulation results when the last day reaches.

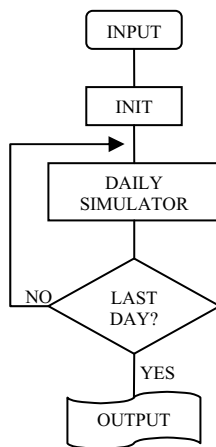


Figure 1 A schematic diagram of GOSSYM model

3. UV-B EFFECTS AND MODEL DEVELOPMENT

UV-B radiation may affect cotton growth and yield formation in various ways, such as fruit abscission (Zhao et al., 2005) and dry matter accumulation (Reddy et al., 2003), and these effects could be interacted with other environmental factors, including CO₂ concentration, temperature, and soil water supply (Zhao et al. 2003; Reddy et al., 2004). Appropriate algorithms of UV-B effects were developed (canopy photosynthesis, stem growth and leaf area expansion rate) and incorporated into the GOSSYM model.

3.1 UV-B indices for photosynthesis, plant height, leaf area, and dry matter

From the published results (Reddy et al., 2003), UV-B indices for several important growth and physiological processes were developed. These indices, ranging from 0 to 1, account for fractional limitation of those processes due to UV-B radiation with a value 0 when UV-B radiation is totally limiting (stopping) the process and 1 when it does not limit that process. Figure 2 shows the UV-B indices for leaf area expansion, stem growth, net canopy photosynthesis, and dry matter accumulation. Table 1 provides regression equations and parameters. The data and regression results presented in Figure 2 and Table 1 are from the work of Reddy et al. (2003) and they are given here for the readers' convenience.

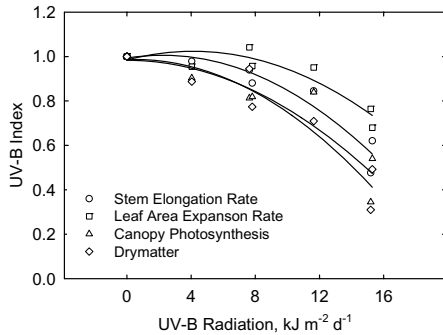


Figure 2 UV-B effects as measurements against regression lines (Reddy et al., 2003).

Table 1 Regression parameters and coefficients of UV-B indices for leaf area, stem elongation, photosynthesis, and dry matter accumulation ($I = 1 + ax + bx^2$, where I is the index and x is the UV-B dosage). Data used for the regression are the same as shown in Figure 2 (Reddy et al., 2003).

Plant process	a	b	r ²
Leaf area expansion	0.0157	-0.0022	0.86
Stem elongation	0.0101	-0.0025	0.93
Photosynthesis	-0.00038	-0.002	0.86
Dry matter accumulation	-0.00116	-0.0017	0.81

3.2 Model development

Figure 3 provides an abstracted flow chart of the daily simulator of the GOSSYM cotton growth model showing the basic organization of the model and program flow. Daily weather data are computed by the module CLYMAT. The SOIL module simulates the main soil processes, including soil water and soil nutrients. The effects of chemical growth regulators, such as PIX and PREP, are modeled by the module CHEM. The PNET module calculates net canopy photosynthesis. GROWTH module estimates the growth rates of plant organs. PLTMAP simulates the birth and abscission of all the organs such as leaves, squares and bolls. More detailed descriptions of the model can be found from the literature (Baker, et al., 1983; Fye, et al., 1984; McKinion, et al., 1989; Reddy et al., 1997a). The two modules, PNET and GROWTH, highlighted by a frame, are where we made modifications to incorporate the effects of UV-B radiation on the corresponding growth processes.

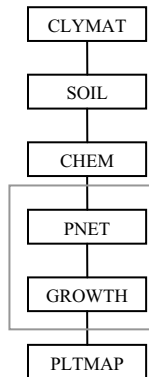


Figure 3 The abstracted diagram of the daily simulator.

In order to integrate the UV-B effects on cotton growth, three growth processes were modified with the corresponding UV-B indices. For the canopy photosynthesis, the daily potential net photosynthesis is multiplied by, among others, UV-B index, which is computed using UV-B radiation data and the regression equation given in Table 1, to calculate the corresponding actual photosynthetic rate. Daily potential leaf area expansion rate and daily stem elongation rate were reduced by UV-B radiation in the same way as photosynthesis processes.

These integrations of UV-B indices for canopy photosynthesis, leaf area expansion rate, and stem and branch growth account for most of the direct effects of UV-B on cotton growth (Reddy et al., 2003). Experimental data show that the enhanced UV-B radiation does not affect cotton development, including the major life-cycle reproductive events and leaf addition rate on the main stem. The boll abscission, reduction in dry matter, change in dry matter partitioning, and decrease in final yield are represented by the reduction in canopy photosynthesis.

3.3 Verification of the model

Experimental measurements in Experiment II were used to evaluate the model. For completeness and comparison, however, simulation results for Experiment I are also presented. In the simulations for both experiments, we assume that

no water and nitrogen stresses existed on the cotton growth during the experimental periods as described above. Therefore, we ignored the soil type and the initial condition of the soil. Although this may affect the simulation results of soil water and nitrogen dynamics as well as transpiration, it will not influence the simulation results of plant growth. Biological parameters for a midseason Upland cotton cultivar calibrated in previous studies were adopted since this was the cultivar used in the experiments. UV-B irradiances were inputs for the corresponding treatments. We assumed the current CO₂ level (360 ppm). We did not consider any chemical growth regulator applications in the simulations since there were no applications of these chemicals in the experiments.

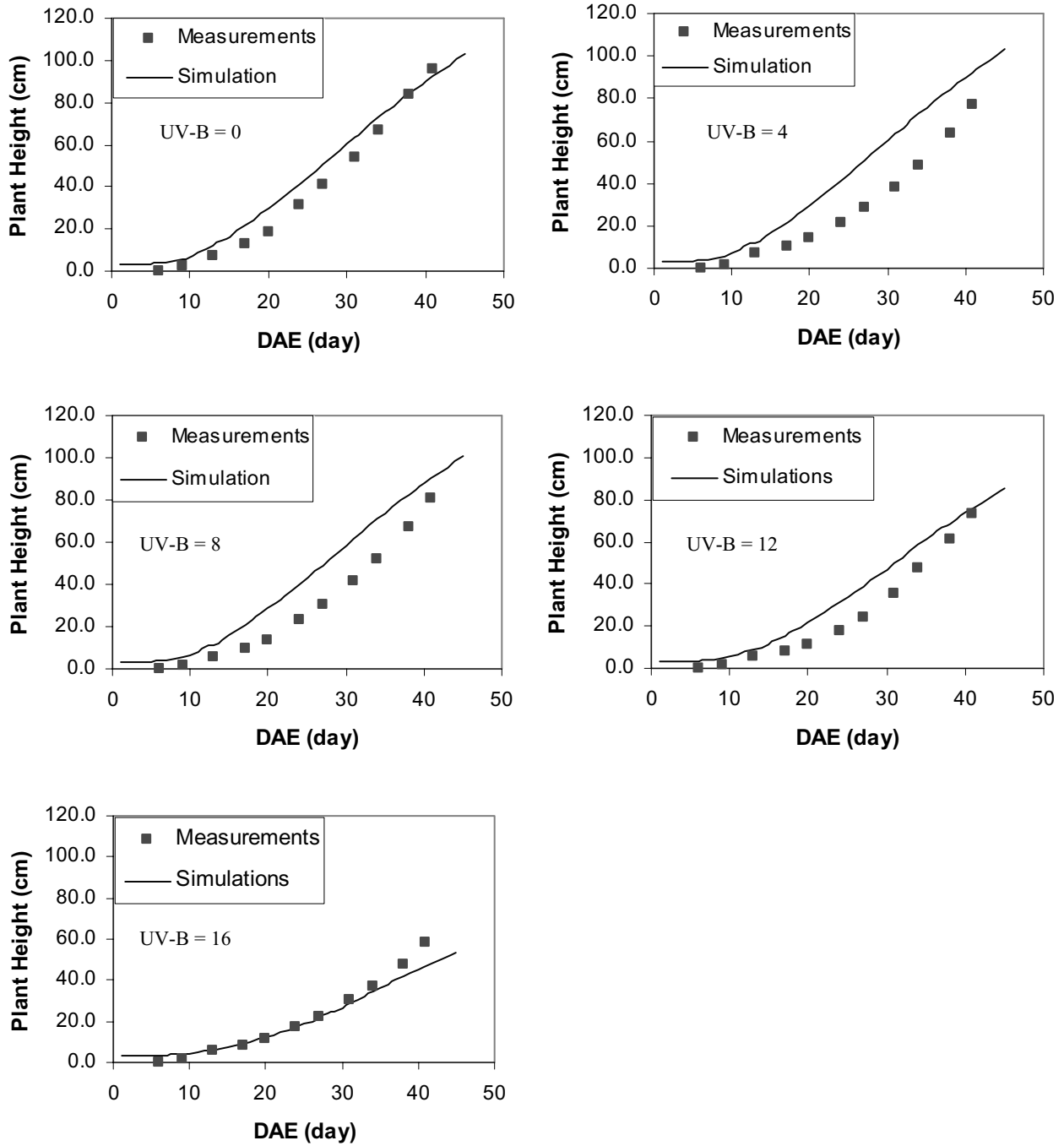


Figure 4. Measured and simulated cotton plant height under different UV-B treatments in Experiment I. DAE: days after emergence.

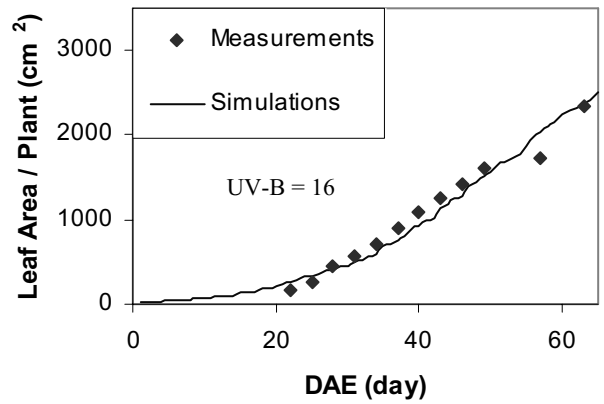
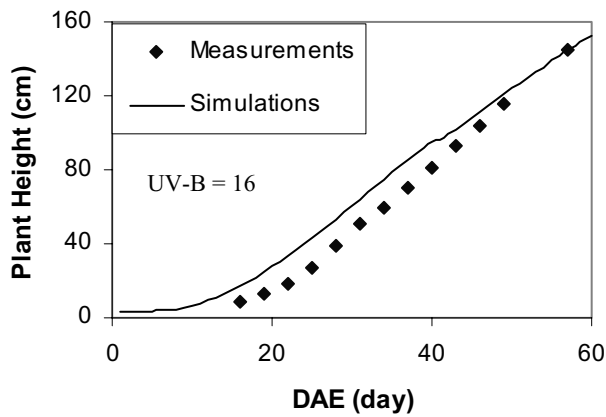
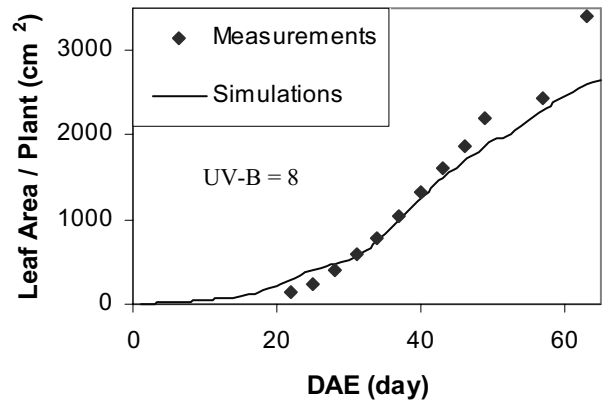
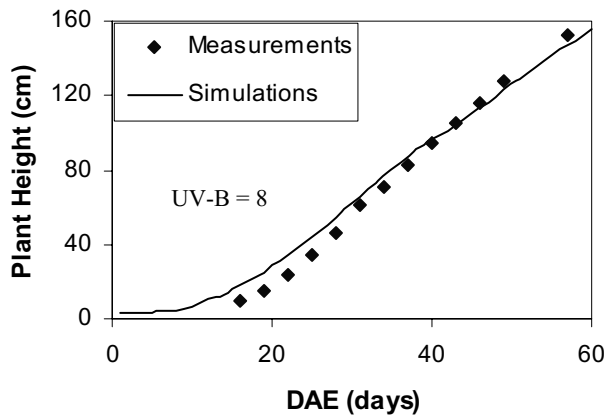
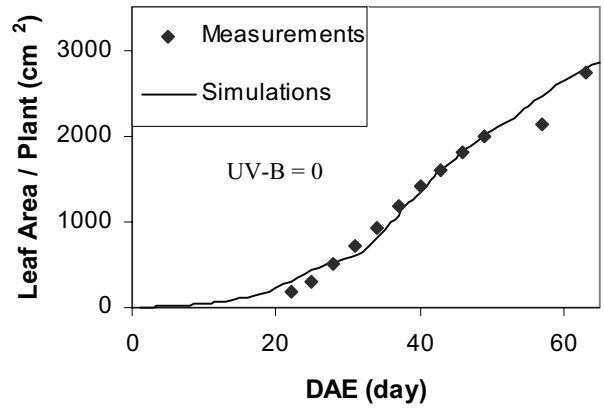
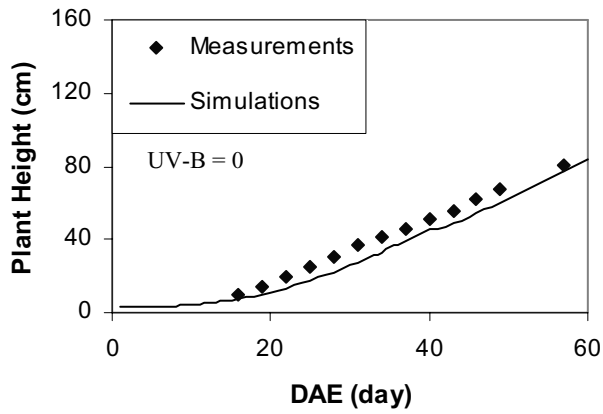


Figure 5. Measured and simulated cotton plant height under different UV-B treatments in Experiment II. **DAE:** days after emergence.

Figure 6. Measured and simulated cotton leaf area under different UV-B treatments in Experiment II. **DAE:** days after emergence.

Figure 4 shows the measured and simulated results of plant height at different UV-B treatments in Experiment I. The measurements and simulation results at different UV-B treatments in Experiment II are presented in Figures 5 for plant

height and leaf area development, respectively. From these figures, we can see that the simulated results agree well with the measurements (within 5% for most points) in both experiments for plants grown under different UV-B levels. These good agreements between measurements and simulations convince us that the model is satisfactory.

Note that for the plant height, the simulations are systematically higher than measurements in both Experiment I and II. This deviation may be attributed mainly to the simulation assumptions of optimal water and nitrogen supplies (no water and nitrogen stresses). Although irrigation and nitrogen fertilizer were provided regularly during the experiments, light water or nitrogen stresses might exist since the stem elongation was very sensitive to water and nitrogen supplies. However, this discrepancy will not affect the correctness of the model since prediction results of the model will be based on more realistic assumptions.

4. EFFECTS OF UV-B LEVEL ON COTTON YIELD

The verified and calibrated model described in the previous section is employed to simulate the effects of enhanced UV-B radiation levels on cotton yield in Stoneville, Mississippi under rain fed and irrigated conditions. The thirty years climate data, from 1964 to 1993, were used in the simulations. We used a midseason cultivar cv. NuCOTTN 33B and clay soil conditions. Nitrogen was properly provided for the simulation (as normally in farming practice). The simulation was conducted under two scenarios: rain fed and irrigated (no water stress). The average cotton lint yields and normalized yield to zero UV-B level are presented Figure 7 and Figure 8, respectively.

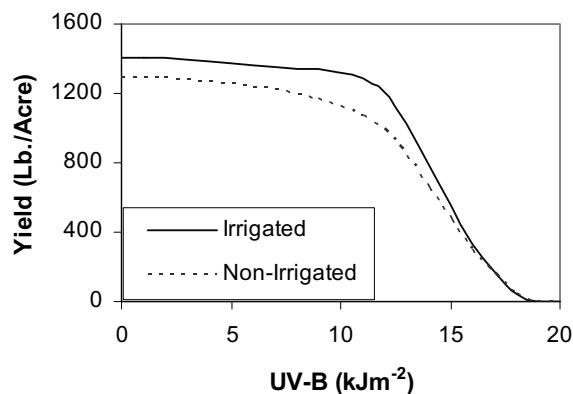


Figure 7. Simulated effects of UV-B radiation level on cotton lint yield at Stoneville, MS, USA. The thirty years climate data (1964-1993) were used in the simulation and the results were averaged over the thirty years in the figure.

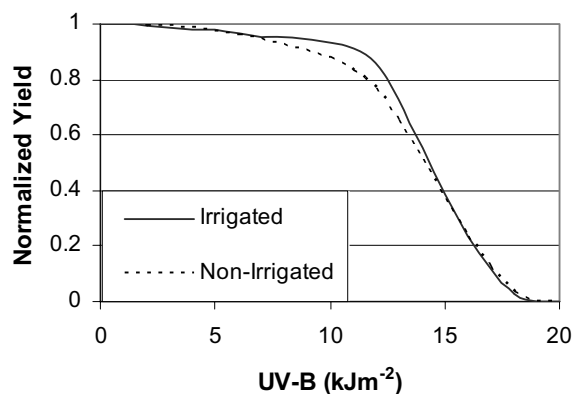


Figure 8. Simulated cotton lint yield as shown in Figure 7 normalized to that of zero UV-B radiation. In average, cotton lint yields were reduced by 20% at 12 kJ m⁻² for irrigated conditions. Similar reductions were predicted at 11 kJ m⁻² under rain fed conditions.

As shown in Figure 7, water stress existed under the natural climate conditions during the simulation period, which was responsible for a 10-20% reduction of the yield in average, provided the UV-B radiation is lower than 10 kJm⁻² day⁻¹. Under current climate condition, proper irrigation will most likely produce 10-20% more cotton lint yield in this area. The effects of UV-B radiation on cotton yield are nonlinear. When UV-B irradiance varied within 0-11 kJm⁻² day⁻¹, cotton yields decreased with UV-B radiation level gradually. Beyond this range, cotton yields dropped sharply. The UV-B radiation level of 11 kJm⁻² day⁻¹ can be considered as a critical value for cotton growth and yield productivity. The averaged yield was zero when UV-B irradiance exceeded 18 kJm⁻² day⁻¹. These results agree with the conclusion for leaf expansion by Reddy et al. (2003). Figure 8 shows the same results as in Figure 7, but the yields were normalized to that when no UV-B radiation was imposed (UV-B = 0). From this figure we can see the interactive effects of UV-B radiation with water stress. Within the range of 7-15 kJm⁻² day⁻¹, water stress aggravated the effects of UV-B radiation on cotton yield significantly (over 10% in average). When UV-B radiation is lower than 7 kJm⁻² day⁻¹, this joint effect is not considerable (less than 3% in average). Beyond 15 kJm⁻² day⁻¹, UV-B radiation is the major limiting factor to cotton yield. Irrigation will not improve the cotton growth and yield production under natural climate conditions. On an average, cotton yield declined by 20% when UV-B irradiance was 12 kJ m⁻² day⁻¹ under irrigated conditions. When UV-B radiation effects are combined with water stress, the 20% reduction in yield occurred at a lower UV-B level (11 kJ m⁻²

day⁻¹) showing both the mechanistic nature of the cotton simulation model and the interactive effects of UV-B radiation with water stress.

5. CONCLUSION AND FUTURE WORK

We have developed the quantitative UV-B indices for leaf area expansion, stem growth, net canopy photosynthesis, and dry matter accumulation of cotton using controlled environment facilities. These indices have been integrated into the GOSSYM cotton growth model into the respective subroutines of the program. The model was verified using independent experimental results. The model evaluation results showed a satisfactory agreement between measured and simulation results.

The verified model was then used to simulate the impacts of UV-B radiation on cotton yield in the field conditions under multi-stress conditions. The results showed a significant reduction in cotton yield when UV-B irradiance exceeded 12 kJ m⁻². Cotton yields declined by 20% at 12 kJ m⁻² of UV-B radiation under irrigated conditions. Similar reduction occurred at a lower UV-B radiation level (11 kJ m⁻²) under rain fed conditions. On an average using both management conditions, a 50% reduction in cotton lint yield would occur at UV-B irradiance of 14 kJ m⁻² which is projected to occur when stratospheric ozone declines by 30% (Madronich et al., 1998).

Due to the limitation of data, the evaluation of the model was limited to a small set of experimental and field data. Further experimental studies are needed to study interactive effects of UV-B with other environmental factors such as drought stress. In addition, cultivar responses to UV-B radiation should also be studied. Once the UV-B radiation effects are modeled correctly, then the model can be coupled with climate models to simulate the influence of altered changes in climate on cotton lint yield and to suggest mitigation strategies to overcome the negative impacts of UV-B on US cotton production under present and projected climates.

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