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Impact of enhanced ultraviolet-B irradiance on cotton growth, development, yield, and qualities under field conditions

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Abstract

The stratospheric ozone depletion and enhanced solar ultraviolet-B (UV-B) irradiance may have adverse impacts on the productivity of agricultural crops. The effect of UV-B enhancements on agricultural crops includes reduction in yield, alteration in species competition, decrease in photosynthetic activity, susceptibility to disease, and changes in structure and pigmentation. Many studies have examined the influence of supplemental UV-B irradiance on different crops, but the effect of UV-B irradiance on cotton (*Gossypium hirsutum* L.) crops has received little attention. Cotton is one of the most versatile of all the crops. It is a major fiber crop of the world and a major source of trade and economy in many countries. In this study, we provide quantitative examination of the effects of elevated UV-B irradiance on cotton plant (Sukang 103). The tested cotton crop was grown under natural and four regimes of supplemental UV-B irradiance in the field. With UV-B irradiance increased 9.5% throughout the growing season, the negative impacts on cotton growth included reductions in height of 14%, in leaf area of 29%, and in total biomass of 34%. Fiber quality was reduced and economic yield dropped 72%; an economic coefficient was reduced 58%. A brief discussion is included on how the impacts on cotton contrast with impacts that have been observed in other studies on other plants, including trees.

Keywords: Ultraviolet-B (UV-B) radiation; Cotton; Yield; Qualities

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1. Introduction

One component of global climate change is the loss of stratospheric ozone, which has prompted recent efforts in assessing the potential damage to vegetation due to enhanced levels of ultraviolet-B (UV-B, 280–320 nm) radiation (World Meteorological Organization, 1989; Grant, 1990; Bornman, 1991; Nunez et al., 1994; Caldwell et al., 1998; Madronich et al., 1998). Satellite measurements have shown expansion of stratospheric ozone losses from over the poles of our planet into temperate regions, and ground-level measurements have detected significant UV-B increases (Kerr and McElroy, 1993). Elevated UV-B levels caused by reduced stratospheric ozone are expected to continue well into the 21st century (Madronich et al., 1998; Weatherhead et al., 2000) and many observers expect to see additional evidence of increased ground-level UV-B in mid-latitudes as monitoring networks improve.

Many biological responses to UV exposure are far greater at the shorter wavelengths. Thus, even relatively small increments of UV-B radiation can lead to substantial biological effects (Madronich et al., 1998).

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Though only a small portion of the total solar electromagnetic spectrum, UV-B has a disproportionately large photobiological effect, largely because it is readily absorbed by important macromolecules such as proteins and nucleic acids. In general, plant responses include increased accumulation of flavonoids, increased leaf thickness, increased reflectance of leaves, reductions in growth, and direct damage to photosynthetic mechanisms (Bornman, 1991). Plant species and varieties differ greatly in their response, with the response generally dependent on the ratio of UV-B to UV-A (Teramura, 1983; Tevini and Teramura, 1989; Middleton and Teramura, 1994). Some species show sensitivity to present levels of UV-B irradiance (Bogenrieder and Klein, 1982), while others are apparently unaffected by rather massive UV-B enhancements (Becwar et al., 1982). One-third to one-half of all plant species tested are deleteriously affected by UV-B levels "above ambient" (Sullivan, 1992). A substantial number of studies have been conducted that have evaluated the potential consequences of an increase in UV-B radiation on many plants (Tevini et al., 1981; Teramura et al., 1990; Miller et al., 1994; Caldwell et al., 1998; Correia et al., 1998, 1999; Li et al., 2000, Searles et al., 2001), but we have a rather limited understanding of the role that UV-B radiation plays in controlling cotton growth, development, yield and quality. Searles et al. (2001) searched for "all suitable published studies" with field-based measurements of UV-B influences on vascular plants and found no studies on cotton. The cotton crop is important for natural fiber and is among the main cash crops used in textile, light, food, chemical, medical, and national defense industries. Thus, it is very important to characterize the effects of enhanced UV-B irradiance on cotton plants.

This paper describes field experiments to test the growth and physiological responses of cotton (*Gossypium hirsutum* L.) to enhanced UV-B radiation. The paper provides an assessment of the impact of enhanced UV-B radiation on cotton growth, development, yield, and qualities.

2. Materials and methods

The experimental field was established in the agro-meteorological research station of Nanjing Institute of Meteorology, in Nanjing, China (32.14°N, 118.42°E). A cotton variety, Sukang 103, was evaluated under supplemental UV-B irradiance during the cotton-growing season of 1998. Plants were seeded on Julian day 92, 1998 and were grown in the experimental field with a density of 75,000 plants/ha and the soil fertility at a normal level.

Supplemental UV-B irradiance treatments were applied to three plots of the experimental cotton field through the whole growing season until the harvest. The treatments were two supplemental UV-B treatments, designated as UV_1 and UV_2, and a control treatment described as Ck. The supplemental UV-B treatments UV_1 and UV_2 averaged 4.8 and 9.5%, respectively more UV-B irradiance than the natural UV-B irradiance received by the Ck treatment. Artificial UV-B irradiance was supplied by broadband, "Black-light" lamps with the spectral range of 280–400 nm. Polyester plastic films (0.13 mm-thick Koadcel TA 401) were used to exclude the portion of UV-A (wavelength $>$ 320 nm). The films were changed weekly to ensure uniformity of UV-B transmission. The lamps were oriented perpendicular to the plant rows and suspended above the plants. Lamps were fitted with 50 mm-wide mini-reflectors and manually adjusted for time and height control. Total daily photosynthetic active radiation (400–700 nm) under the lamp fixtures was about 90% of that above the lamps. The lamps were suspended from wires stretched between steel poles at both ends of the planted rows. Supplemental irradiation was provided daily at a constant rate during the day for 8 h centered around the solar noon. For the Ck treatment, lamps were filtered with 0.13 mm thick polyester (spectrally equivalent to Mylar Type S) plastic films that absorb essentially all radiation below 320 nm, so plants beneath these lamps received only natural levels of UV-B. The UV-B irradiance was adjusted monthly to allow for seasonal changes in ambient UV-B. The different UV-B treatments were obtained by varying the distance between the lamps and the top of the plants. The height of the lamps above the plants was adjusted weekly to maintain constant lamp-to-plant distances as the plants grew.

Biological sampling was performed nine times during the growing season in a 1 m^2 area of each tested plot for measuring the height of plant, leaf area, the weight of fresh and dry plants, and changes in chlorophyll content. The net assimilation and relative growth rates were also calculated.

Another three UV-B treatments were designed to test the effect of enhanced UV-B irradiance on cotton qualities. The control treatment was the Ck treatment as described above. The two other supplemental UV-B irradiance treatments, UV_3 and UV_4, were only provided during the critical growing stages that most affect the cotton qualities. UV_3 treatment was applied during the square (flower bud) stage (Julian day 197–216) and UV_4 treatment covered the boll-forming stage (Julian days 223–242). Both UV_3 and UV_4 treatments provided 9.5% more UV-B irradiance than the Ck treatment during the test periods.

In this cotton qualities experiment, samples of the cotton from 10 plants were harvested six times at 5-day intervals from Julian days 258 to 283 for all three treatments. Cotton is a main material for the textile industry. The quality of cotton determines the quality of fabric and price of cotton products. There are many parameters that can be measured to test cotton qualities. They include the cotton types, the gin turnout of unginned cotton, the grade of lint cotton (toughness and maturity of fibers), the length, moisture content and impurities of cotton. International Cotton Trade requires that at least the cotton fiber thinness, toughness and sugar content must be tested to decide the cotton quality. To quantify the effect of enhanced UV-B irradiance on cotton qualities, the following important parameters were examined: M value (the number of μg/in. fiber), P_{si} value (toughness of a bunch of fibers), and sugar content at each harvest.

All data are presented as means of the six samples. For estimating significant differences of the means, a t-test with $\alpha = 0.05$ and 0.01 was performed and presented in tables.

3. Results and discussion

3.1. Effect of enhanced UV-B radiation on cotton growth

The cotton plants showed a range of growth responses to supplemental UV-B irradiance during the growing season. Plant height was reduced by supplemental UV-B irradiance (Fig. 1). At the boll-forming stage, plant height under UV_2 treatment was 86% of that under the Ck treatment and the height under UV_1 treatment was 95% of that under the Ck treatment. The reduction of cotton plant height increased with increased UV-B irradiance. The effects of the

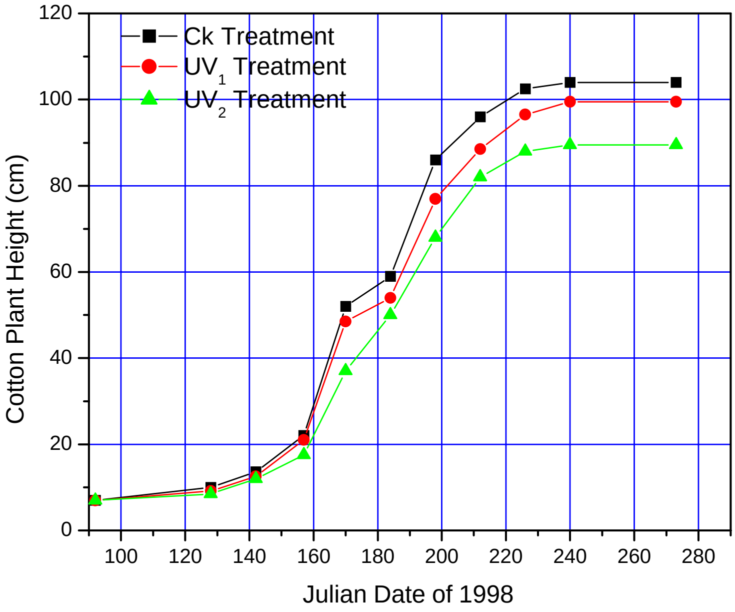

Fig. 1. The change of cotton plant height under different UV-B treatment.

Table 1
The comparisons of cotton growth under different UV-B treatments

UV-B treatments	Plant height (cm, %)	Leaf area (cm^2 per plant, %)	NAR (g m^2 per day, %)	RGR (10^{-2} g per day, %)	Biomass (g per plant, %)	Economic yield (g per plant, %)	Economic coefficient (%)
Ck	104 (100)	3709.2 (100)	8.3 (100)	6.8 (100)	167.8 (100)	67.8 (100)	40.41 (100)
UV$_1$	99.5 (95)**	3000.2 (80.9)*	5.2 (62.7)	4.8 (70.6)	147.8 (88.1)*	47 (69.3)	31.97 (79.1)
UV$_2$	89.5 (86)**	2625.8 (70.8)*	4.8 (57.8)	4.4 (64.7)	110.3 (65.7)*	18.7 (27.6)	16.95 (41.9)

The first four observations were taken in the boll-forming stage and the rest in the harvesting stage.
* Significantly different at 99% level of confidence.
** Significantly different at 95% level of confidence.

supplemental UV-B irradiance on plant height were different in different growth stages. No obvious differences in cotton plant height were detected at the seedling period. Significant reductions in plant height were observed at the higher supplemental UV-B irradiance from the date of button appearance, i.e. 75 days after the seedling stage. Plant height differences were larger during the vegetative stages and showed greater UV-B sensitivity in the early development stage of cotton growth. Reduction of plant height by UV-B radiaiton was also observed in wheat, cucumber, wild oats, sunflower (Tevini and Teramura, 1989), soybean (Sullivan et al., 1994), rice (Dai et al., 1992; Barnes et al., 1993). A photooxidative destruction of the phytohormone indole acetic acid might contribute to UV-B-induced reductions of plant height (Mark and Tevini, 1996).

Leaf area decreased significantly under both supplemental treatments compared with that under the Ck treatment. Under the UV$_2$ treatment a 30% reduction of leaf area was observed, while the UV$_1$ treatment caused a 20% reduction of leaf area (Table 1) compared to the Ck treatment. A significant reduction in leaf area for plants such as soybean (Teramura and Murali, 1986), sunflower (Tevini and Teramura, 1989) and cucumber (Tevini and Teramura, 1989) has also been reported. The result of measurements of leaf area at different heights along a transverse section through the cotton crop showed leaf area index (LAI) decreased from upper to lower leaf layers under both supplemental UV-B treatments. The greater decrease of LAI at the lower level than upper level was observed during the flowering and boll-filling stages. The center of the leaf layer distribution was shifted upward and the number of leaves at the lower levels decreased. Under the supplemental UV-B, the existing leaves at the lower levels aged more rapidly than the upper leaves (Table 2) apparently because they were the earlier-born leaves and the supplemental UV-B irradiance sped up the aging process.

Reports of past studies showed that the supplemental UV-B irradiance has an adverse effect on physiological processes of plants including the reduction of photosynthetic efficiency, decrease of leaf stomatal conductance and transpiration rate (Krupa and Kickert, 1989; Staaij et al., 1990; Zheng et al., 1996a; Yan et al., 1997). The Net Assimilation Rate (NAR) and the Relative Growth Rate (RGR) were observed to decrease with the supplemental UV-B irradiance in this study (Table 1). Compared with the Ck treatment, the NAR and RGR decreased 38 and 30%, respectively under the UV$_1$ treatment and 42 and 35% under the UV$_2$ treatment.

Averaged over the whole plant, the chlorophyll content of cotton leaves was reduced with increased UV-B irradiance (Table 3). We found that most of

Table 2
The effect of different UV-B treatments on the distribution of leaf area

UV-B treatments	Total LAI	Upper layer LAI	vs. Ck (%)	Middle layer LAI	vs. Ck (%)	Lower layer LAI	vs. Ck (%)
Ck	4.19	2.06	49.15	1.24	29.59	0.895	21.36
UV$_1$	2.16*	0.72	33.33	1.06	49.07	0.38	17.59
UV$_2$	2.00*	1.16	58	0.83	41.5	0.017	0.85

* Significantly different at 99% level of confidence.

Table 3
The change of the chlorophyll content of the cotton under different UV-B treatments

UV-B treatments	Chlorophyll content (weighted means, mg/g)	Upper layer (mg/g)	Middle layer (mg/g)	Lower layer (mg /g)
Ck	280.2	303.9	367.6	236.1
UV_1	275.2	216.4	294.8	280.9
UV_2	253.3	325.9	163.2	

the chlorophyll content reduction occurred during the middle-to-late growing periods. The reduction of the chlorophyll content was not obvious during the early growing periods but the measurements of the chlorophyll content at three plant levels with different UV-B treatments still showed that the enhanced UV-B treatments accelerated the chlorophyll decomposition. This probably contributed to the leaf aging in the early growing stages (Zheng et al., 1996a). Enhanced UV-B irradiance has a negative effect on the photosynthetic efficiency because of the decreased stomatal conductance of plant leaves, which permits less CO_2 to go into the plants (Zheng et al., 1996a). The results in this experiment also demonstrated that the reduction of the chlorophyll content under enhanced UV-B was another reason that the photosynthetic efficiency was lower.

3.2. *Effect of enhanced UV-B radiation on cotton yield*

Since the enhanced UV-B irradiance caused the reduction of plant height, leaf area, and assimilation rate, the cotton biomass, dry matter weight, and yield were in turn influenced (Table 1).

Ziska and Teramura (1992) and Barnes et al. (1993) reported that supplemental UV-B caused a decrease in dry matter weight in rice. Sullivan and Teramura (1994) found supplemental UV-B caused reduction in total biomass of seeding loblolly pines (*Pinus taeda* L.). In contrast, Petropoulou et al. (1995) found that supplemental UV-B radiation during a period of drought stress was beneficial for seedlings of pine (*Pinus pinea* L. and *Pinus halepensis* Mill.) by increasing dry weight compared to a control without the

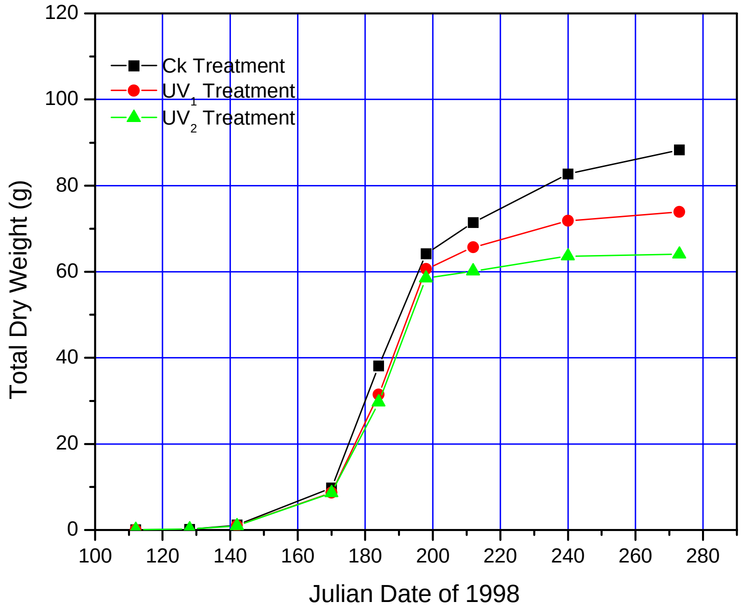

Fig. 2. The variation of cotton dry matter weight under UV-B treatments.

Table 4
Changes of cotton qualities under different UV-B irradiance treatments

	Harvest dates					
	15 September	20 September	25 September	30 September	5 October	10 October
Square stage						
P_{si} value						
UV_3	89.1*	85.9**	89.8*	84.6*	83.1**	79.2**
Ck	90.2	91.7	95.7	86.6	88.6	87.0
Diff.	−1.1	−5.8	−5.9	−2.0	−5.5	−7.8
M value						
UV_3	4.4*	4.8*	4.8*	4.8*	4.8*	4.7*
Ck	4.9	5.0	5.2	4.9	4.8	4.4
Diff.	−0.5	−0.2	−0.4	−0.1	0	0.3
Sugar content						
UV_3	1.0	1.1	1.1	1.4	1.0	1.3
Ck	1.1	1.1	1.0	1.2	1.0	2.2
Diff.	−0.1	0	0.1	0.2	0	−0.9
15 September	20 September	25 September	30 September	10 October		
Boll-forming stage						
P_{si} value						
UV_4	88.9**	86.6*	86.0*	83.4*	80.6*	
Ck	99.2	87.1	80.2	85.9	81.4	
Diff.	−10.3	−0.5	+5.8	−2.5	−0.8	
M value						
UV_4	4.5*	4.3*	4.6*	4.7*		
Ck	4.8	4.7	5.1	4.4		
Diff.	−0.3	−0.4	−0.5	0.3		
Sugar content						
UV_4	1.0	1.1	1.2	1.3	1.8	
Ck	1.0	1.2	1.0	1.2	2.1	
Diff.	0	−0.1	0.2	0.1	−0.3	

* Significantly different at 99% level of confidence.
** Significantly different at 95% level of confidence.

UV-B supplement. Krupa and Kickert (1989) summarized studies of UV-B effects on dry weight for a large variety of different plants; the effects ranged from negative to negligible to positive, and sometimes effects differed for a species in different studies.

The measurement results in this study showed that the enhanced UV-B irradiance caused a significant reduction of the dry matter accumulation. The dry matter accumulation decreased with the increased UV-B irradiance (Fig. 2). The decreased leaf and canopy photosynthesis contributed to the reduction of dry matter accumulation. By the last measurement period of the growing season, the dry matter weight of cotton was decreased 16.3% under UV_1 treatment and 27.5% under UV_2 treatment compared to Ck treatment. The effect of enhanced UV-B irradiance on the dry matter weight increased as the growth and development of cotton continued, but was different from phase to phase. Throughout the seedling stage, there were no significant differences in dry matter weight among the Ck, UV_1 and UV_2 treatments, but the difference increased when the boll-forming stage started. We detected a significant difference in dry matter weight among treatments at the square-appearance stage. Apparently, this tested cotton plant can tolerate a certain level of UV-B irradiation during the seedling stage. Influence on the dry matter weight might occur sooner if more enhanced UV-B irradiance was used.

The supplemental UV-B irradiance had an adverse effect on the cotton economic yield (unginned cotton) in this experiment. With increased UV-B irradiance the cotton biomass and economic coefficient (economic yield divided by biomass) declined significantly (Table 1). The economic coefficient under the UV_2 treatment was 41.9% of that under the Ck treatment. The enhanced UV-B irradiance had more effect on economic yield than cotton biomass, which indicated the reproductive growth and development and the reproductive organs were affected by the enhanced UV-B irradiance to a great extent. Similar results were reported for other crops (Zheng et al., 1996b; Yan et al., 1997).

3.3. *Effect of enhanced UV-B radiation on cotton qualities*

The results of the measurements are presented in Table 4. Both P_{si} and M values decreased significantly in both supplemental UV-B treatments (UV_3 and UV_4 treatments) compared with those in the Ck treatment. The cotton qualities were degraded in both supplemental UV-B treatments. There was no significant difference in the sugar content between the supplemental UV-B treatments and Ck treatment in this experiment. The level of cotton quality degradation caused by UV_3 and UV_4 treatments was similar. Both square stage and boll-forming stage were critical to cotton quality and the supplemental UV-B irradiance used in these two stages contributed to degradation of cotton quality in this experiment.

4. Conclusions

The cotton plant variety, Sukang 103, was evaluated under supplemental UV-B irradiances that provided 4.8% (UV_1) and 9.5% (UV_2) more irradiance than a control treatment. The supplemental UV-B irradiance had an adverse effect on the cotton growth, development, yield and qualities. Under the UV_1 and UV_2 treatments, respectively, we found reductions in the cotton plant height of 5 and 14%, in leaf area of 19 and 29%, and 1.8 and 9.6% in chlorophyll content. The photosynthetic efficiency decreased with increased UV-B irradiance. Reductions of the cotton plant total biomass of 12 and 34% resulted with the UV_1 and UV_2 treatments, and economic yield was reduced 31 and 72%. Enhanced UV-B irradiance in either square stage or boll-forming stages degraded the cotton qualities. Thus, the cotton variety tested in this experiment appeared to be highly susceptible to damage from increased UV-B irradiance. This study only selected one cotton variety. It is of great interest to investigate the impact of increased UV-B irradiance on other varieties of cotton plants using the same experiment so that the varieties could be compared under the same weather conditions.

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