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Modulated increased UV-B radiation affects crop growth and grain yield and quality of maize in the field

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Abstract

Current research on the effect of increased UV-B radiation on crop production has been limited to exposing plants to improbable UV-B dose or growth condition. The objective of this study was to test the effects of short-term modulated increased UV-B radiation on maize (*Zea may*s L.) growth, grain yield, and quality under field conditions for three years. A modulated irradiance system was used to maintain UV-B radiation at 30% above the ambient level and was applied daily between the elongation and silking stages of maize. The result indicated that increased UV-B radiation adversely affected maize growth and yield, especially on plant height when UV-B was enhanced at the elongation stage and on yield when UV-B was enhanced near the silking stage. Yield reduction that induced by enhanced UV-B radiation was associated with reductions in number of kernels per row and kernel mass. Protein content of grains was increased with enhanced UV-B radiation, but oil and starch contents were not affected. This study confirmed the sensitivity of maize to increased UV-B radiation under the field condition, and contributed to understand the full negative and positive effects of increased UV-B radiation on crop production.

Additional key words: growth; maize; quality; UV-B radiation; yield.

Introduction

The amount of solar UV-B radiation (280–320 nm) reaching the Earth's surface has increased as a result of ozone depletion by anthropogenic gases in last 50 years (UNEP 2002). The increased UV-B radiation can widely influence plant physiology, morphology, growth, and development (Caldwell and Flint 1994, Kakani *et al.* 2003, Wargent *et al.* 2011). Although the Montreal Protocol has succeeded in controlling most of the ozone depleting substances, ozone depleting substance already in atmosphere are long-lived, recovery cannot be immediate, and present projections estimate a return to pre1980 levels by 2050 to 2075 (UNEP 2008). In addition, the uncertain interaction effect of the ozone layer and other climate changes factors will delay the recovery (UNEP 2012). Therefore, it remains necessary to investigate the effects of elevated UV-B radiation on various aspects of crop production, continuously.

UV-B radiation has a great influence on crop physiology, morphology, growth, yield and quality (Santos *et al.* 1993, Correia *et al.* 1998, Wargent *et al.* 2011). Kakani *et al.* (2003) analyzed about 129 studies of 35 crop species published since 1975, and almost half of these studies confirmed a decrease in crop yield and biomass by increased UV-B radiation treatment, the other half studies showed that enhanced UV-B radiation did not affect yield, and a few studies showed that enhanced UV-B radiation increased yield. These different responses varied in crops and study conditions.

However, most previous studies were conducted either in growth chambers or greenhouses under fairly high UV-B radiation levels, which were likely to be unusual in the future climate change (Kakani *et al.* 2003). Furthermore, even when realistic levels of UV-B were used in simulating ozone reduction, the quantity of PAR (photosynthetically active radiation) and UV-A irradiance in the growth chamber and greenhouse were lower than in the ambient radiance. It has been demonstrated the importance of PAR: UV-A:UV-B ratio in mediating plant

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Abbreviations: PAR − photosynthetically active radiation; UV-A − ultraviolet-A radiation; UV-B − ultraviolet-B radiation.
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response (Caldwell *et al*. 1994, Allen *et al*. 1999). Therefore, in growth chamber, an unnatural spectral balance of radiation and unusual high levels of UV-B may change crop sensitivity to UV-B radiation substantially and exaggerat the UV-B damage in these previous researches (Flint *et al*. 2003, Kakani *et al*. 2003).

From available reports, only 15% of studies on UV-B radiation were conducted under field conditions (Kakani *et al*. 2003, Xu and Qiu 2007, Wang *et al.* 2009). A field experiment could provide the realistic intensity of PAR and UV-A. However, most field studies used a 'square-wave' UV-B irradiation system, *i.e.* a constant supplementary irradiance for a specified period of time with lamps producing constant supplementary UV-B (Li *et al.* 1998, Yao *et al*. 2006, Wang *et al*. 2009). The UV-B quantity was calculated from a chosen O_3 depletion scenario, for a particular day of the year and assuming cloud-free conditions. The supplementary UV-B irradiance in many of these field experiments represented a significantly larger O_3 depletion scenario than stated (Allen *et al*. 1999, Flint *et al*. 2003). Firstly, there was an overestimation by the model commonly used for calculating supplementary UV-B for a given O_3 depletion, especially under cloudy conditions, and secondly, there was no adjustment of supplementary UV-B levels when the ambient UV-B irradiance changed with time of the day and day of the season. Without adjustment of supplementary UV-B, the ratio of UV-B to PAR and UV-A was larger and more variable than typically under nature conditions.

Caldwell and Flint (1994) suggested a modulated UV-B irradiance supply system, which could provide designated supplementary irradiance proportional to that of natural sunlight, avoid the problems by continual monitoring of an ambient UV-B radiation, and adjust supplementary irradiance accordingly. The modulated system ensures that realistic UV-B:PAR:UV-A ratios are maintained as conditions change during the day and season. Using the modulated UV-B irradiance supply system may provide the most accurate data for prediction of crop responses to enhanced UV-B radiation (Fiscus and Booker 1995, Kakani *et al*. 2003). It is essential to perform more field studies with modulated UV-B irradiance supply system to evaluate the effects of enhanced UV-B radiation on crops.

Maize is the third most important crop worldwide and is sensitive to increased UV-B radiation (Santos *et al.* 1998, Correia *et al*. 1998, 2005). However, in these researches, the experiment was conducted either in the growth chamber (Santos *et al.* 1998), or supplied a constant UV-B radiation (Correia *et al.* 1998), or exaggerated increased UV-B radiation dose (Correia *et al.* 2000, 2005). Therefore, the effects of enhanced UV-B radiation on maize might be exaggerated. In this study, the effects of enhanced UV-B radiation on maize growth and grain yield and quality was evaluated in the field condition under ambient and supplementary modulated UV-B radiation for three years, consecutively.

Materials and methods

Experimental site: This study was conducted in suburban Beijing (40º02´N, 116º10´E) at the experimental station of China Agricultural University during 2005, 2006, and 2007. Average annual temperature is 13.2°C, with the average maximum temperature of 27.9°C occurring in July. Average annual rainfall of about 585 mm is distributed with 80% falling from June to September. During the experimental period, total rainfall was 539 mm for 2005, 468 mm for 2006 and 483 mm for 2007. The soil at the experimental site was a sandy-loam, and the soil pH was 6.4, with each 1 kg of soil containing 2.4% organic carbon, 0.2 g P_2O_5, 0.15 g K_2O and 1 g total N in 2005. The normal sowing date for maize is in the middle of April and harvesting date is in the late September.

Maize planting and management: Seeds of maize (var. Nongda 108, hybrid cultivar) was sown on 25 April 2005, 27 April 2006, and 23 April 2007 at an intra-row spacing of 0.30 m and inter-row spacing of 0.60 m for a population of 56,000 plants ha^{-1}. The plot size is 30 m^2 (5 × 6 m), rows were oriented in the east-west direction to minimize shading during UV-B radiation treatment. Fertilizer was applied at 100 kg(P_2O_5) ha^{-1}, 160 kg(K_2O) ha^{-1} and 100 kg(N) ha^{-1} before sowing and was incorporated with a plough. A 100 kg(N) ha^{-1} was further applied when maize had 7–9 leaves. Plants were irrigated as necessary to avoid water stress. Weeds were controlled manually. Maize was harvested on 28 September 2005, 2 October 2006, and 5 October 2007.

UV-B treatment: The experiment consisted of 6 treatments arranged in a completely randomized design with 4 replicates, including an untreated control and 5 UV-B treatments during a 4-week period between the elongation and silking stages (50% ear appeared silking). Four UV-B treatments (T1, T2, T3, and T4) were applied for 1 week. T1, T2, T3 and T4 started at day 0, 7, 14, and 21 of the experiment, respectively. The other UV-B treatment (T5) was exposed to increased UV-B radiation for 4 weeks, which began at day 0 and finished at day 28 of the experiment (Table 1). The UV-B treatment periods were 3 June–2 July 2005, 7 June–6 July 2006, and 4 June–3 July 2007, respectively.

UV-B radiation was supplied by UV-B lamp tubes (tube length 1.2 m, *Beijing Electronic Resource Inc*., Beijing, China) held in individual frames directly over the plant rows. Each replication included 9 plants that were grown under three UV-B tubes, respectively. To avoid a mutual influence of UV-tubes in the same replicate, the tube was arranged in rows with interval of 1.2 m. A buffer of two rows was around every replicate plot to minimize border effects, and the distance between tubes or UV-B treated and control plants was 1.2 m in the same row.

The tube radiation was filtered with 0.13-mm-thick cellulose diacetate membrane (transmission down to 290 nm), and the membrane was changed once a week. Changes in UV-B levels were measured using a UV-B radiometer (*Model 720, Beijing Normal Univ. Optronics Factory*, Beijing, China) (Wang *et al*. 2010). The supplementary UV-B level was controlled through manually adjusting the distances between the tube and the top of the plant canopy, and maintained at 30% above the ambient UV-B light. Lamps were switched on when the ambient UV-B irradiations exceeded 15 µW cm^{-2} and were switched off when UV-B fell below 15 µW cm^{-2}. The UV-B radiation was adjusted once every 30 min between 08:00 and 17:00 h during the treatment day.

Plant measurements: Maize was harvested on 28 September 2005, 2 October 2006, and 5 October 2007, when grains were completely mature. All of the 9 plants from each replicate were harvested and the plant and ear heights (from the ground surface to the base of the ear), ear length, number of rows per ear, number of kernels per row, mass of 100 kernels were measured.

Grain quality analysis: Maize grain protein, oil, and starch contents were analyzed by near infrared reflectance spectroscopy (NIRS) (Jiang *et al.* 2007). Maize for quality analysis was moisture-equilibrated in dry-seal vacuum desiccators for 2 weeks at water contents below 14%. The spectra of intact samples (40 g) were scanned by NIRS (*VECTOR 22/N Fourier Transform Near Infrared Spectrometer; Bruker*; Germany), and protein, oil, and starch contents were calculated.

Data analysis: An analysis of variance was performed using *SAS 8.0* (*SAS Inst. Inc.*, Cary, NC, USA), and *Tukey*'s multiple range tests were used to compare treatment means. The interaction between UV-B treatment and years was also analyzed. Multiple correlations between grain yield and yield components was analyzed by stepwise regression.

Results

Effect of increased UV-B radiation on plant and ear heights: Plant and ear heights were affected by increased UV-B radiation, which varied with a year (Table 1). Maize height decreased after 4 weeks (T5) of exposure to supplementary (30%) UV-B radiation. The height decreased by 14.3% in 2005, 5.5% in 2006, and 4.5% in 2007. In 2005, 1 week of UV-B exposure decreased plant height by 9.0 and 7.9% at T1 and T2, but did not affect plant height at T3 and T4. Plant height in 2006 was not affected by 1-week exposure to UV-B radiation. Plant height in 2007 was reduced by 2.6% at T1. Thus, enhanced UV-B radiation reduced plant height more when provided at the elongation stage than at the near silking stage. Enhanced UV-B radiation for 4 weeks (T5) decreased ear height by 8.9% in 2005 and 8.4% in 2007. Nodes per shoot were not affected by increased UV-B radiation (data not shown). There was no significant interaction between the year and UV-B radiation treatment on plant and ear height.

Effect of increased UV-B radiation on grain yield and yield components: Grain yield decreased when maize was exposed to 4 weeks (T5) of supplemental UV-B radiation by 14.6% in 2005, 18.2% in 2006, and 16.8% in 2007 (Table 2). One week of exposure to enhanced UV-B radiation in 2005 did not affect grain yield but affected grain yield in 2006 in every treatment. Grain yield in 2007 was reduced by 1 week of enhanced UV-B only at the T4 stage. Ear length varied form year to year at averaging 19.9 cm in 2005, 17.6 cm in 2006, and 18.7 cm in 2007, but ear length within a year was not affected by enhanced UV-B radiation (data not shown). Each maize ear had averaged 16 rows of kernels in each year, which was not affected by enhanced UV-B treatment (data not shown). Kernels number per row decreased when maize was exposed to 4 weeks (T5) of supplementary UV-B radiation by 7.3% in 2005, 12.1% in 2006, and 5.1% in 2007. One week of enhanced exposure to UV-B radiation did not affect kernels number per row in 2005 and 2007 but decreased kernels per row in the 2006 at T1 and T4 stage. Exposure to enhanced UV-B radiation for a week (T1, T2, T3, T4) did not affect kernel mass of 100 kernels. The mass of 100 kernels decreased by 8.9% in 2005 and 9.1% in 2007 when exposed to T5 for four weeks. There were no significant interaction between the year and UV-B radiation treatment on grain yield, kernels number per row and mass of 100 kermels. The relationship between grain yield and number of rows per ear (X_1), kernels per row (X_2) and 100 kernels mass (X_3) was: Yield = $-9.81 + 0.29\ X_2 + 0.30\ X_3$ ($r = 0.78$. $p<0.01$; $r_2 = 0.68$, $p<0.01$; $r_3 = 0.10$, $p<0.01$).

Effect of increased UV-B radiation on grain quality: Grain protein content varied by year within control, which has the lowest content of 9.3% in 2006, and the highest content of 10.3% in 2007 (Table 3). Enhanced UV-B radiation increased the grain protein content in each year. Grain protein contents were increased by 4-week treatment (T5) by 0.4% in 2005, 0.5% in 2006, and 0.4% in 2007 compared with control. In 2005, enhanced UV-B radiation at stages T3 and T4 increased protein contents by 0.4% and 0.5%, respectively. Similar

Table 1. The plant- and ear height of maize in response to increased UV-B radiation treatment. The values are means of 4 replicates ± SD. Each replicate includes 9 plants. Means within a column for each year followed by *different letters* are significantly different. * – significant at $P<0.05$; ** – significant at $P<0.01$; NS – not significant. T1, T2, T3, T4 – 1-week treatment; T5 – 4-week treatment.

Year	Time of UV-B exposure	Plant height [cm]	Ear height [cm]
2005	Control	278.8 ± 7.2^{a}	135.0 ± 6.9^{a}
	T1: 3–10 June	253.8 ± 5.7^{b}	127.0 ± 5.4^{ab}
	T2: 11–17 June	257.2 ± 6.8^{b}	123.6 ± 7.4^{b}
	T3: 18–25 June	269.2 ± 6.9^{a}	129.2 ± 8.0^{ab}
	T4: 25 June – 2 July	275.8 ± 10.6^{a}	132.2 ± 7.8^{ab}
	T5: 3 June – 2 July	239.0 ± 7.9^{c}	123.2 ± 8.2^{b}
2006	Control	252.7 ± 2.2^{a}	102.0 ± 1.0^{a}
	T1: 7–14 June	247.0 ± 5.0^{ab}	103.0 ±1.7^{a}
	T2: 15–21 June	252.3 ± 6.4^{a}	106.7 ± 5.0^{a}
	T3: 22–29 June	247.7 ± 4.8^{ab}	103.7 ± 4.5^{a}
	T4: 30 June – 6 July	247.0 ± 5.4^{ab}	101.3 ± 2.3^{a}
	T5: 7 June – 6 July	239.0 ± 5.4^{b}	102.3 ± 2.1^{a}
2007	Control	267.4 ± 1.8^{a}	118.0 ± 6.5^{a}
	T1: 4–11 June	259.6 ± 3.8^{b}	109.0 ± 5.9^{bc}
	T2: 12– 8 June	260.8 ± 2.9^{ab}	115.6 ± 5.1^{ab}
	T3: 19–26 June	262.0 ± 6.2^{ab}	115.4 ± 6.3^{ab}
	T4: 27 June – 3 July	262.6 ± 7.8^{ab}	110.8 ± 4.2^{abc}
	T5: 4 June – 3 July	255.4 ± 7.8^{b}	107.8 ± 6.0^{c}
Analysis of variance			
	Year	**	**
	UV-B	**	*
	Year × UV-B	NS	NS

Table 2. The yield and yield parameters of maize in response to increased UV-B radiation treatment. The values are means of 4 replicates ± SD. Means within a column for each year followed by *different letters* are significantly different. * – significant at $P<0.05$; ** – significant at $p<0.01$; NS – not significant. T1, T2, T3, T4 – 1-week treatment; T5 – 4-week treatment.

Year	Time of UV-B exposure	Yield [g m^{-2}]	Kernels per row	Mass of 100 kernels [g]
2005	Control	1,226 ± 49^{a}	41.4 ± 0.9^{a}	33.4 ± 1.7^{a}
	T1: 3–10 June	1,092 ± 268^{ab}	40.2 ± 2.3^{ab}	32.9 ± 0.9^{a}
	T2: 11–17 June	1,193 ± 46^{ab}	40.2 ± 1.7^{ab}	33.2 ± 2.1^{a}
	T3: 18–25 June	1,159 ± 21^{ab}	39.9 ± 1.7^{ab}	32.4 ± 1.6^{ab}
	T4: 25 June – 2 July	1,126 ± 19^{ab}	39.6 ± 1.8^{ab}	31.6 ± 0.6^{ab}
	T5: 3 June – 2 July	1,047 ± 35^{b}	37.8 ± 0.5^{b}	30.4 ± 0.8^{b}
2006	Control	963 ± 25^{a}	33.1 ± 0.8^{a}	32.4 ± 1.0^{a}
	T1: 7–14 June	806 ± 29^{bc}	29.4 ± 2.1^{b}	30.7 ± 1.8^{a}
	T2: 15–21 June	851 ± 42^{b}	31.0 ± 1.4^{ab}	30.7 ± 3.1^{a}
	T3: 22–29 June	862 ± 42^{b}	30.9 ± 2.5^{ab}	31.2 ± 0.9^{a}
	T4: 30 June – 6 July	812 ± 43^{bc}	29.8 ± 0.9^{b}	30.4 ± 1.4^{a}
	T5: 7 June – 6 July	787 ± 19^{c}	29.4 ± 1.1^{b}	29.7 ± 1.3^{a}
2007	Control	1,271 ± 76^{a}	39.4 ± 0.6^{a}	33.1 ± 2.1^{a}
	T1: 4– 1 June	1,165 ± 63^{ab}	38.2 ± 0.5^{ab}	31.7 ± 0.5^{ab}
	T2: 12–18 June	1,142 ± 83^{ab}	38.9 ± 2.4^{a}	32.1 ± 1.8^{ab}
	T3: 19– 6 June	1,137 ± 208^{ab}	38.1 ± 0.9^{ab}	32.9 ± 2.5^{a}
	T4: 27 June – 3 July	1,120 ± 79^{b}	38.6 ± 1.7^{a}	31.4 ± 1.9^{ab}
	T5: 4 June – 3 July	1,058 ± 115^{b}	36.7 ± 1.3^{b}	30.1 ± 1.5^{b}
Analysis of variance				
	Year	**	**	NS
	UV-B	**	**	**
	Year × UV-B	NS	NS	NS

Table 3. The contents of protein, oil and starch in maize in response to increased UV-B radiation treatment. The values are means of 4 replicates ± SD. Means within a column for each year followed by *different letters* are significantly different. * – significant at $P<0.05$; ** – significant at $P<0.01$; NS – not significant. T1, T2, T3, T4 – 1-week treatment; T5 – 4-week treatment.

Year	Time of UV-B exposure	Protein [%]	Oil [%]	Starch [%]
2005	Control	9.8 ± 0.3^{b}	4.5 ± 0.2^{a}	69.8 ± 0.3^{a}
	T1: 3–10 June	10.0 ± 0.1^{ab}	4.6 ± 0.5^{a}	69.4 ± 0.2^{a}
	T2: 11–17 June	10.1 ± 0.3^{ab}	4.5 ± 0.4^{a}	69.4 ± 0.2^{a}
	T3: 18–25 June	10.2 ± 0.2^{a}	4.5 ± 0.2^{a}	69.2 ± 0.6^{a}
	T4: 25 June – 2 July	10.3 ± 0.2^{a}	4.6 ± 0.1^{a}	69.3 ± 0.3^{a}
	T5: 3 June – 2 July	10.2 ± 0.1^{a}	4.3 ± 0.4^{a}	69.1 ± 0.6^{a}
2006	Control	9.3 ± 0.4^{c}	4.7 ± 0.6^{a}	69.8 ± 1.0^{a}
	T1: 7–14 June	9.5 ± 0.2^{bc}	5.3 ± 0.5^{a}	69.3 ± 0.3^{ab}
	T2: 15–21 June	9.5 ± 0.2^{bc}	4.6 ± 0.3^{a}	69.4 ± 1.1^{ab}
	T3: 22–29 June	10.0 ± 0.3^{a}	5.4 ± 0.7^{a}	68.2 ± 0.7^{b}
	T4: 30 June – 6 July	9.9 ± 0.1^{ab}	5.0 ± 0.2^{a}	68.9 ± 0.5^{ab}
	T5: 7 June – 6 July	9.8 ± 0.1^{ab}	4.8 ± 0.1^{a}	68.7 ± 0.2^{ab}
2007	Control	10.3 ± 0.2^{b}	4.3 ± 0.4^{a}	69.7 ± 0.3^{a}
	T1: 4–11 June	$10. 5 \pm 0.1^{ab}$	4.0 ± 0.8^{a}	69.5 ± 0.2^{a}
	T2: 12–18 June	10.6 ± 0.4^{ab}	4.1 ± 0.5^{a}	69.3 ± 0.6^{a}
	T3: 19– 6 June	10.4 ± 0.1^{ab}	3.7 ± 0.4^{a}	70.1 ± 0.6^{a}
	T4: 27 June – 3 July	10.6 ± 0.2^{ab}	4.3 ± 0.2^{a}	69.8 ± 0.3^{a}
	T5: 4 June – 3 July	10.7 ± 0.2^{a}	3.9 ± 0.7^{a}	69.4 ± 1.1^{a}
Analysis of variance				
	Year	**	**	NS
	UV-B	**	NS	NS
	Year × UV-B	NS	NS	NS

increase was found in 2006, when the grain protein content was increased by 0.7% at T3 and 0.6% at T4 stages. There were no effects of enhanced radiation on the oil and starch contents. No interaction between the years and UV-B radiation treatment on grain protein, oil and starch contents was observed.

Discussion

The elevated UV-B radiation, supplied by the modulated system, affected maize growth, yield, and grain quality. Previous reports indicated that maize was sensitive to UV-B radiation in growth chamber or field by the constant UV-B supplementary system (Santos *et al*. 1993, Correia *et al*. 1998, 2000, 2005; Gao *et al*. 2004). Here, we confirmed that even a short-term period (1–4 weeks) of increased UV-B radiation in the field affected maize growth during some critical developmental stages. Using modulated UV-B irradiation supply system can provide more accurate data for prediction of crop responses to enhanced UV-B radiation than previous research.

Reductions in maize height under increased UV-B radiation were observed (Table 1), which concurs with many previous reports, in several species (Zu *et al*. 2004, Yao *et al*. 2006, Xu and Qiu 2007). Mark and Tevini (1997) reported that 30% of increased UV-B radiation caused a 35% reduction in maize shoot height after 18 d of UV-B treatment. Correia *et al*. (2000) also found that maize height decreased with UV-B radiation simulating 20% ozone depletion. Pal *et al*. (1997) found that exclusion of UV-B radiation from the normal solar spectrum resulted in increased maize shoot height. In this study, although we used low UV-B radiation dose and short-term treatment, we also observed that enhanced UV-B radiation had the greatest adverse effects on plant height, especially when UV-B was enhanced during the stem-elongation stage (Table 1). This agreed with previous reports that the greatest sensitivity to UV-B radiation was found at the early development stage, and it showed more significant effects on plant height at the vegetative than reproductive and maturation stages (Mark and Tevini 1997, Correia *et al*. 1998, 2000). The ear height was also decreased, which was accompanied with the decrease of plant height. We observed that the number of nodes did not change, so the decreased height was due to the reduction in internode length, which agreed with reports for wheat (Li *et al*. 1998) and soybean (Li *et al*. 2002). Previous researches suggested that plant height reduction was due to photo-oxidative destruction of the phytohormone, indole acetic acid, followed by reduced cell wall extensibility (Ros and Tevini 1995, Correia *et al*. 2000).

There is little information on effects of increased

UV-B radiation on yield of field-grown maize and the few available reports showed that increased UV-B radiation decreased maize yield. In these researches, the supplementary UV-B radiation dose was higher, and UV-B treatment time was longer than this study (Santos *et al*. 1998, Correia *et al*. 1998, 2005). Short-term exposure to increased UV-B radiation at critical crop stages significantly decreased maize yield (Table 2). The most critical period for yield determination for maize is from 2 weeks before and 2–3 weeks after silking (Pandey *et al*. 2000). The number of kernels per row was closely associated with maize yield, and it varied markedly with stress (Andrade *et al*. 1999). In our study, the grain yield reduction was associated with the reduction of kernels number per row (r = 0.68, p<0.01). Previous research also indicated that increased UV-B radiation decreased the pollen germination rate and tube length *in vitro* and its fertilization ability in the field (Wang *et al*. 2010).

Many studies published so far have focused on the effects of UV-B radiation on cereal crops, but far less attention has been paid to changes in grain quality. In contrast to a previous report (Gao *et al*. 2004), our results showed that enhanced UV-B radiation increased protein content but did not affect oil and starch contents of maize grain. The crude protein concentration in brown rice (*Oryza sativa* L.) was significantly increased by supplementary UV-B radiation during flowering-ripening stage (Zhang *et al*. 2003). Zu *et al*. (2004) reported that the protein and total amino acid contents of five wheat cultivars were increased under enhanced UV-B radiation. Xu and Qiu (2007) reported that enhanced UV-B radiation tended to increase the crude protein and amylose concentration of super high-yield hybrid rice. However, the underlying mechanism of changes in grain quality is not clear yet.

The effects of UV-B radiation were constant across the growing seasons with the modulated lamp system in this study. Modulation of lamp output during UV-B supplementation has clear advantages, because supplementary irradiance is proportional to the natural sunlight on experiment site. This supplementary technique is much more realistic and ecologically relevant than an unmodulated system, especially under cloudy conditions. However, another important concern for UV-B dosimetry studies is the unequal change in intensity of wavelengths in UV-B spectra (280–325 nm). Ozone absorbs more at lower wavelengths (< 300 nm) of the UV-B spectra, so ozone depletion would significantly increase the intensity at low wavelengths (Kakani *et al*. 2003). Therefore, future studies in evaluating UV-B effects on plants should not only focus on realistic PAR, UV-A and UV-B levels, but also account for spectral differences.

In this study, significant correlation between the yield and plant height (r = 0.75, p<0.01) was shown, but UV-B radiation had a greater effect on plant height at elongation stage and had more effect on yield near the silking stage. Increased the UV-B radiation always have adverse effects on the plant height, however, in maize production, the decreased plant and ear height can decrease lodging risk, which can help enhance plant density for getting high yield. Thus, more field studies are needed to elucidate which effects and mechanisms are involved in the observed growth reduction due to enhanced UV-B radiation, and also what can be done to minimize these negative effects and utilize the available effects.

References

Allen, D.J., Nogués, S., Morrison, J.I.L. *et al*.: A thirty percent increased in UV-B has no impact on photosynthesis in well-watered and droughted pea plants in the field. – Global Change Biol. **5**: 235-244, 1999.

Andrade, F.H., Vega, C., Uhart, S. *et al*.: Kernel number determination in maize. – Crop Sci. **39**: 453-459, 1999.

Caldwell, M.M., Flint, S.D.: Stratospheric ozone reduction, solar UV-B radiation and terrestrial ecosystems. – Climatic Change **28**: 375-394, 1994.

Caldwell, M.M., Flint, S.D., Searles, P.S.: Spectral balance and UV-B sensitivity of soybean: a field experiment. – Plant Cell Environ. **17**: 267-276, 1994.

Correia, C.M., Areal, E.L.V., Torres-Pereira, M.S., Torres-Pereira, J.M.G.: Intraspecific variation in sensitivity to ultraviolet-B radiation in maize grown under field condition. I. Growth and morphological aspects. – Field Crops Res. **59**: 81-89, 1998.

Correia, C.M., Coutinho, J.F., Björn, L.O., Torres-Pereira, J.M.G.: Ultraviolet-B radiation and nitrogen effects on growth and yield of maize under Mediterranean field conditions. – Eur. J. Agron. **12**: 117-125, 2000.

Correia, C.M., Pereira, J.M.M., Coutinho, J.F. *et al*.: Ultraviolet-B radiation and nitrogen affect the photosynthesis of maize: a Mediterranean field study. – Eur. J. Agron. **22**: 337-347, 2005.

Fiscus, E.L, Booker, F.L.: Is increased UV-B a threat to crop photosynthesis and productivity? – Photosynth. Res. **43**: 81-92, 1995.

Flint, S.D., Ryel, R.J., Caldwell, M.M.: Ecosystem UV-B experiment in terrestrial communities: a review of recent finding and methodologies. – Agr. Forest Meteorol. **120**: 177-189, 2003.

Gao, W., Zheng, YF., Slusser, G.M., Heisler, R.H., Grant, F.H., Xu, J.Q., He, D.L.: Effects of supplementary ultraviolet-B irradiance on maize yield and qualities: A field experiment. – Photochem. Photobiol. **80**: 127-131, 2004.

Jiang, H.Y., Zhu, Y.J. Wei, L.M. *et al*.: Analysis of protein, starch and oil contents of single intact kernels by near infrared reflectance spectroscopy (NIRS) in maize (*Zea mays* L.). – Plant Breeding **126**: 492-497, 2007.

Kakani, V.G., Reddy, K.R., Zhao, D., Sailaja, K.: Field crop response to ultraviolet-B radiation: a review. – Agr. Forest Meteorol. **120**: 191-218, 2003.

Li, Y., Yue, M., Wang, X.: Effects of enhanced ultraviolet-B radiation on crop structure, growth and yield components of spring wheat under field conditions. – Field Crops Res. **57**: 253-263, 1998.

Li, Y., Zu, Y., Chen, J., Chen, H.: Intraspecific response in crops growth and yield of 20 soybean cultivars to enhanced ultraviolet-B radiation under field conditions. – Field Crops Res. **78**: 1-8, 2002.

Mark, U., Tevini, M.: Effects of solar ultraviolet-B radiation, temperature and CO_2 on growth and physiology of sunflower and maize seedlings. – Plant Ecol. **128**: 225-234, 1997.

Pal, M., Sharma, A., Abrol, Y.P., Sengupta, U.K.: Exclusion of UV-B radiation from normal solar spectrum on the growth of mung bean and maize. – Agr. Ecosyst. Environ. **61**: 29-34, 1997.

Pandey, R.K., Maranville, J.W., Admou, A.: Deficit irrigation and nitrogen effects on maize in a Sahelian environment I. Grain yield and yield components. – Agr. Water Manage. **46**: 1-13, 2000.

Ros, J., Tevini, M.: Interaction of UV-radiation and IAA during growth of seedling and hypocotyl segments of sunflower. – J. Plant Physiol. **146**: 295-302, 1995.

Santos, I., Almeida, J.M., Salema, R.: Plants of Zea mays L. developed under enhanced UV-B radiation. I. Some ultrastructural and biochemical aspects. – J. Plant Physiol. **141**: 450-456, 1993.

Santos, A., Almeida, J.M., Santos, I., Salema, R.: Biochemical and ultrastructural changes in pollen of *Zea mays* L. grown under enhanced UV-B radiation. – Ann. Bot. **82**: 641-645, 1998.

UNEP.: Executive summary. Final of UNEP/WMO scientific assessment of ozone depletion: 2002. Prepared by the scientific assessment panel of the Montreal protocol on substances that deplete the ozone layer. UNEP, Nairobi (released 23 August 2002), 2002.

UNEP.: Environmental effects of ozone depletion and its interactions with climate change: Progress report, 2007. – Photochem. Photobiol. Sci. **7**: 15-27, 2008.

UNEP.: Environmental effects of ozone depletion and its interactions with climate change: progress report, 2011. – Photochem. Photobiol. .Sci. **11**: 13-27, 2012.

Wang, S.Y., Wang, K., , Zhao, Y.L., Xin, Y.J.: Effects of enhanced solar UV-B radiation on the effective photosynthetic leaf area and milking phase of oat under natural field condition in Qing Tibetan Plateau. – Spectrosc. Spect. Anal. **29**: 1378-1381, 2009.

Wang S., Xie, B., Yin, L., Duan, L., Li, Z., Eneji, A.E., Tsuji, W., Tsunekawa, A.: Increased UV-B radiation affects the viability, reactive oxygen species accumulation and antioxidant enzyme activities in maize (*Zea mays* L.) pollen. – Photochem. Photobiol. **86**: 110-116, 2010.

Wargent, J.J., Elfadly, E.M., Moore, J.P., Paul, N.D.: Increased exposure to UV-B radiation during early development leads to enhanced photoprotection and improved long-term performance in *Lactuca sativa*. – Plant Cell Environ. **34**: 1401-1413, 2011.

Xu, K., Qiu, B.S.: Response of superhigh-yield hybrid rice Liangyoupeijiu to enhancement of ultraviolet-B radiation. – Plant Sci. **172**: 139-149, 2007.

Yao, Y., Xuan, Z., Li, Y., He, Y., Korpelainen, H., Li, C.: Effects of ultraviolet-B radiation on crops growth, development, yield and leaf pigment concentration of tartary buckwheat (*Fagopyrum tataricum*) under field conditions. – Eur. J. Agron. **25**: 215-222, 2006.

Zhang, W.H., Sun, C.Q., Sato, T., Hidama, J., Kumagai, T., Wang, X.K.: [Effects of supplemental ultraviolet-B radiation on yield and the concentration of protein in rice (*Oryza sativa* L.).] – Acta Agron. Sin. **29**: 908-912, 2003. [In Chin.]

Zu, Y.Q., Li. Y., Chen, J.J., Cheng, H.Y.: Intraspecific responses in grain quality of 10 wheat cultivars to enhanced UV-B radiation under field conditions. – J. Photochem. Photobiol. B: Biol. **74**: 95-100, 2004.