NUMERICAL SIMULATION OF THE INFLUENCE OF O_3, CO_2 AND SPECTRUM VARIATION ON THE PHOTOSYNTHESIS OF CROP CANOPY*

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ABSTRACT

Coupled the photosynthesis with transpiration and adjustment of stoma, a dynamic ecological model for simulating the canopy photosynthesis of winter wheat was established by scaling up from the biochemical scale to canopy scale, in which the effects of O_3, CO_2 and solar spectrum on crop photosynthesis were fully considered. Validation of the model against the data measured with CI-301PS portable photosynthesis analyzer showed that the leaf photosynthesis model passed the correlation significance test and had a fairly high accuracy. Numerical analysis showed that the canopy photosynthesis rate would be reduced by 29% if the O_3 concentration increases from 0 ppbv to 200 ppbv, whereas the canopy photosynthesis rate would increase by about 37% while the CO_2 concentration increases from 330 ppmv to 660 ppmv, and the canopy photosynthesis rate would be reduced by 27% or so under the condition that the spectrum coefficient changed from 0.5 to 0.4. If the O_3 concentration reached 200 ppbv at noon on the typical sunny day with higher radiation, the canopy photosynthesis will be reduced slightly in the suburb area where the pollution is serious and the photochemical fog is easy to be formed, contrast with that in the clear region and regardless of the climate change, due to the fact that the positive effect of CO_2 on crop photosynthesis can not compensate the negative effect of O_3 on crop photosynthesis. The canopy photosynthesis will be reduced by 35% or so than the BASE value at present, when the spectrum of photosynthetic active radiation (PAR) reduces to 0.4 or so.

Key words: O_3, CO_2, solar spectrum, photosynthesis, numerical simulation

I. INTRODUCTION

Human activities and the quickly developed industry have greatly influenced the global atmospheric environment. The CO_2 concentration in the atmosphere has already increased from (275 ± 10) ppmv before industrial revolution to 350 ppmv at present, and the trend of concentration variation is still increasing steadily (IPCC 1995). In addition, though the surface averaged O_3 concentration is only about 0—50 ppbv in the lower atmosphere, the instantaneous O_3 concentration could reach as high as 200 ppbv or so at noon on the typical

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clear day with higher radiation in the suburb region, where the pollution is serious and the photochemical fog is easy to be formed due to the increase of O_3 in the lower atmosphere which resulted from the atmospheric chemical reaction caused by industrial pollution (Chamecides 1994). The radiation spectrum is also changed with the variation of the atmospheric component simultaneously, with the increase of greenhouse gases resulting from industrial pollution (Bian and Lu 1996).

It has been widely recognized by the scientists that reduction of O_3 concentration in the stratosphere has great negative effects on both human beings and the terrestrial ecosystems (Zhou et al. 1995). The great negative effects of O_3 increase in the lower atmosphere due to industrial pollution on the terrestrial plants are also being identified gradually (Krupa 1994; Heck and Adams 1983; Heck 1984; Kobayashi 1990). The CO_2 is one of the important greenhouse gases, which contributes to the global warming with its concentration increasing and therefore affects the crop photosynthesis indirectly. At the same time, the change of CO_2 concentration can also influence the crop photosynthesis process directly, because the CO_2 itself is the source of photosynthesis. What is more, the variation of the spectrum can influence the crop photosynthesis process directly, since the amount of the photosynthetic active radiation (PAR) in the global radiation changes with the spectrum variation (Feng and Tao 1991). It has become an important task for the scientists to study the effects of the variation of CO_2, O_3 and solar spectrum on crop photosynthesis and yield, which is considered more and more seriously by lots of research institutes and governments all over the world.

Lots of progress on the possible effects of the enhancement of CO_2 and O_3 concentration and the variation of spectrum on crops has been achieved in the previous research. However, only the single factorial effect was considered in these studies (Wang and Wang 1993; Wang et al. 1997; Wang et al. 2002; Cure 1986). It is difficult to consider the direct influence of the greenhouse gases, such as CO_2, O_3, etc. on crop growth using statistical assessment (Wang and Wang 1993). Some results have been obtained in the single factorial experiments by the Top Open Chamber (TOP) (Wang et al. 1997; Wang et al. 2002; Cure 1986). However, no research results about the composite effects of variation of O_3, CO_2, and solar spectrum variation on crop photosynthesis have been reported until now. Considering the fact that the crop photosynthesis process is surely influenced comprehensively by these three factors, a numerical model with higher mechanism and accuracy was established in this study, which was used to simulate the canopy photosynthesis of winter wheat on the clear day. Sensitivity analysis was also done using the model to identify the different influence of each factor on the crop canopy photosynthesis in this study.

II. ESTABLISHMENT OF THE MODEL

1. *Calculation of the Microclimate Factors in the Canopy*

(1) *Radiation transformation*

The direct solar radiation $S(\omega)$ and the scattered radiation $D(\omega)$ at a given time on a typical clear day can be expressed as (Yu, Wang et al. 1998; Liu et al. 1999; Liu et al.

2001)

$$S(\omega)=\pi(\sin\psi\sin\delta+\cos\psi\cos\delta\cos\omega)\cdot\tau[\omega_0\sin\psi\sin\delta+\cos\psi\cos\delta\sin\omega_0]^{-1}\cdot S, \quad (1)$$

$$D(\omega)=\pi(\sin\psi\sin\delta+\cos\psi\cos\delta\cos\omega)\cdot\tau[\omega_0\sin\psi\sin\delta+\cos\psi\cos\delta\sin\omega_0]^{-1}D, \quad (2)$$

where ψ is the latitude, ω is the hour angle, ω_0 is the hour angle at sunset time, which can be expressed as $\omega_0=\arccos(-\mathrm{tg}\psi\,\mathrm{tg}\delta)$, τ is the daylength, S is the total daily direct solar radiation, D is the total daily scattered radiation, and δ is the declination. At the given time ω, the direct photosynthetically active radiation $S^*(\omega)$ and the scattered $D^*(\omega)$ can be expressed as

$$S^*(\omega)=\eta S(\omega), \quad (3)$$

$$D^*(\omega)=\mu D(\omega). \quad (4)$$

The G function at solar direction n_s can be expressed as

$$G(n_s)=G(h,A)=\frac{1}{2\pi}\int_0^{2\pi}\mathrm{d}\phi_L\int_0^{\pi/2}g(\theta_L,\phi_L)\,|\cos n_s n_L|\sin\theta_L\mathrm{d}\theta_L, \quad (5)$$

where h is the solar altitude, A is the solar azimuth, θ_L is the leaf inclination, ϕ_L is the leaf azimuth, $g(\theta_L,\ \phi_L)$ is the distribution function of leaf inclination, n_L is the unit vector in the leaf normal direction, $\cos n_s n_L$ is the cosine value of the angle between the sun light direction and the leaf normal direction. The transmission coefficient of the direct radiation $\tau_s(L,\ n_s)$ and that of the scattered radiation $\tau_d(L)$ can be expressed as

$$\tau_s(L,n_s)=\mathrm{e}^{-L\frac{G(n_s)}{\sin h}}, \quad (6)$$

$$\tau_d(L)=\frac{1}{\pi}\int_0^{2\pi}\int_0^{\pi/2}\tau_s(L,n)\cos\theta\sin\theta\,\mathrm{d}\theta\mathrm{d}\phi, \quad (7)$$

where $\tau(L,\ n)$ is the transmission function in the vector direction defined by the inclination θ and azimuth ϕ. The direct PAR received by the leaf at the leaf layer from the accumulated leaf area index (LAI) $L-1$ to L, with the leaf inclination θ_L and leaf azimuth ϕ_L, can be expressed as

$$S^*(L-1,\theta_L,\phi_L)=\frac{S^*(L-1,n_s)}{\sin h}|\cos n_s n_L|. \quad (8)$$

At the time the solar altitude is h and the azimuth is A, the scattered PAR at horizon level in the accumulated LAI L, when only a single scattering process is considered, can be simulated according to the following equation

$$D^*(L)=D^*(\omega)\tau_d+\frac{Q^*(\omega)\sigma^*K(\mathrm{e}^{-KL}-\mathrm{e}^{-L})}{1-K}, \quad (9)$$

where $\sigma^*=(\rho^*+\tau^*)/2$, ρ^* is the reflection coefficient of PAR received by the leaves, and τ^* is the transmission coefficient of PAR received by the leaves. According to the theory of isotropic radiation, the scattered radiation received by the leaves is independent of the leaf azimuth angle, and therefore, the scattered radiation which is received by the leaves and located within the layer from accumulated LAI $L-1$ to L, with leaf inclination θ_L and leaf azimuth ϕ_L can be expressed as

$$D^*(L-1\sim L,\theta_L\phi_L)=D^*(L-1)\frac{(1+\cos\theta_L)}{2}. \quad (10)$$

(2) *Calculation of the wind velocity above the leaf*

The general model to estimate the average wind velocity within the crop canopy in the field can be expressed as (Fu et al. 1994)

$$U = U_H \frac{\ln z - \ln z_0}{\ln H - \ln z_0}[\alpha e^{-knf} + \beta(1 - f)], \quad (11)$$

where H is the height of the plant; z_0 is the roughness, which can be defined as $z_0=0.13$ H; U_H is the wind velocity at the plant height H; n is the ray number accounted from the field boundary; f is the function of relative LAI; α, β and k are coefficients, which are 0.74, 0.26 and 2.78 respectively.

2. *Leaf Photosynthesis Model*

Ball (Sellers 1996) stated that the stomatal conductivity g_s is the function of humidity (h_s), CO_2 concentration (C_s) at the leaf surface and the rate of photosynthesis (P_n) of the leaves, which can be expressed as

$$g_s = a \frac{P_h \times h_s}{C_s} + g_0, \quad (12)$$

where a and g_s are coefficients. Leuning put forward the modified Ball-Berry model by substituting the saturation vapor pressure e for humidity h_s (Yu, Ren et al. 1998; 2000; Sellers 1996)

$$g_s = a \frac{P_n}{(C_s - \Gamma)(1 + e/e_0)} + g_0, \quad (13)$$

where Γ is the compensation point of CO_2. The CO_2 concentration inside the stoma can be simulated as

$$C_i = C_s - P_n/g_s, \quad (14)$$

thus the g_0 must be a very small constant approaching to 0. Coupled Eq. (12), Eq. (13) with Eq. (14), the C_i can be calculated as follows:

$$C_i = C_s - 1/a\,(C_s - \Gamma)\,(1 + e/e_0). \quad (15)$$

The photosynthesis rate of leaf responds to the light according to the following equation

$$\theta P^2 - P(\alpha I + P_{\max}) + \alpha I P_{\max} = 0, \quad (16)$$

where P is the rate of gross photosynthesis, θ is the degree of convexity, α is the initial quantum efficiency, and $P_{\max}$ is the maximum rate of photosynthesis. The reasonable resolution of P is

$$P = \frac{1}{2\theta}[\alpha I + P_{\max} - \sqrt{(\alpha I + P_{\max})^2 - 4\theta(\alpha I P_{\max})}]. \quad (17)$$

The rate of net photosynthesis can be calculated as

$$P_n = P - R_d.$$

The initial quantum efficiency is affected by the CO_2 concentration:

$$\alpha = \alpha_0(C_i - \Gamma)/(C_i + 2\Gamma), \quad (19)$$

where α_0 is the maximum capacity of quantum efficiency. The maximum rate of photosynthesis is mainly determined by the Rubisco, and affected by CO_2 concentration and temperature

$$P_{\max} = V_m\,(Ci - \Gamma)\,(C_i + C), \quad (20)$$

where V_m is the maximum capacity of Rubisco catalysis, C is a parameter related to reaction curve of CO_2, which belongs to parts of the Rubsico reaction. C is defined as a constant in this study. V_m depends on the temperature

$$V_m = \frac{V_{m_0}}{1 + e^{\frac{-a+bT}{RT}}}, \tag{21}$$

where V_{m_0}, a and b are parameters, R is the constant of ideal gas. Dark respiration R_d in Eq. (18) has a positive proportional relationship with V_m, and can be expressed as

$$R_d = kV_m. \tag{22}$$

Considering that P_n is affected by the O_3 concentration, the rate of net photosynthesis P_j can be calculated as

$$P_j = P_n \times \zeta(O_3), \tag{23}$$

where P_j is the leaf photosynthesis rate corrected by O_3 concentration, $\zeta(O_3)$ is the normalized function characterizing the effect of O_3 on the photosynthesis, which can be expressed as the following equation based on the measured data:

$$\zeta(O_{3b}) = [\frac{A_1 - A_2}{1 + ([O_3]/[O_{3b}])^p} + A_2]/A_1, \tag{24}$$

where $[O_3]$ is O_3 concentration, A_1, A_2, $[O_{3b}]$ and p are parameters in the model.

3. *Canopy Photosynthesis Model*

When the wind velocity u above the leaf at the accumulated LAI L has been calculated according to the microclimate model, the boundary resistance of the leaf r_b can be expressed as

$$r_b = 100\frac{0.13\sqrt{w/u}}{L}, \tag{25}$$

where w is the average width of leaves. If the ambient CO_2 concentration is C_a, then the CO_2 concentration at the leaf surface C_s can be calculated as

$$P_j = \frac{C_a - C_s}{r_c}, \tag{26}$$

where r_c is the boundary resistance of CO_2 at the leaf surface. According to the ratio in molecular weight of water to CO_2, $r_c = 1.6\, r_b$.

Coupled the equations from Eq. (17) to Eq. (26), the equations with two variables, C_s and C_i above leaves, can be obtained. Since Eq. (15) is also an equation related to these two variables, the CO_2 concentration C_s at the leaf surface and the stomatal CO_2 concentration C_i can be calculated by these simultaneous equations, then the net photosynthesis P_j at the accumulated LAI L can be obtained. It is obviously that P_j is affected comprehensively by lots of factors such as CO_2 concentration, radiation, spectrum, temperature, humidity, wind velocity, etc. The canopy photosynthesis at a given layer is the integral of the total leaf photosynthesis at different accumulated LAI:

$$P_z(\omega) = \int_0^L\int_0^{2\pi}\int_0^{\pi/2} P_j(\omega, L, \theta_L, \phi_L)P(L, \theta_L, \phi_L)\mathrm{d}\theta_L\mathrm{d}\phi_L\mathrm{d}L. \tag{27}$$

The discrete expression of the integral of photosynthesis can be calculated as

$$P_z(\omega) = \sum_{L=1}^{I_{LA}}\sum_{i=1}^{6}\sum_{j=1}^{8} P_j(\omega, L, \theta_L, \phi_L)P(L, \theta_L, \phi_L)\Delta\theta_L\Delta\phi_L\Delta L, \tag{28}$$

where $I_{LA} = \mathrm{INT}(LAI) + 1$.

III. DETERMINATION OF THE PARAMETERS AND VALIDATION OF THE LEAF PHOTOSYNTHESIS MODEL

1. *Determination of the Parameters*

The architecture and photosynthesis of the winter wheat were measured in canopy during the jointing period of winter wheat in April 1999, at the Lysimeter Section in Yucheng Comprehensive Experimental Site, Chinese Academy of Sciences. The area density of leaf inclination and the accumulated LAI at different depth were measured (Table 1), then the leaf photosynthesis rate and corresponding ambient meteorological factors were measured with CI-301PS portable photosynthesis analyzer made in CID Corporation of America. The parameters for the leaf model were obtained by the trial method as follows: $V_{m_0}=140$ μmol/(m^2 s), $Q_{10}=2.4$, $k=0.034$, $a_1=22000$ kJ/mol, $b=703$ J/(mol K), $R=8.314$ J/(mol K), $e_0=1500$ Pa, $\Gamma=50$ mol/mol, $C=100$ μmol/mol, $a_0=0.08$, and $\theta=0.55$. The data measured in the open top chamber (OTP) were used to determine the effect of enhancement of O_3 concentration on the winter wheat. The parameters of the influence of O_3 concentration on the leaf photosynthesis of winter wheat were determined based on the averaged value of the data measured during a few days. The parameters are: $A_1=17.9$, $A_2=8.7$, $[O_{3b}]=141.6$, and $p=1.7$.

Table 1. The Area Density of the Leaf Inclination of Winter Wheat (Yucheng, 1999-04-12)

Height	Accumulated	Leaf inclination (deg.)								
(cm)	LAI	0—10	10—20	20—30	30—40	40—50	50—60	60—70	70—80	80—90
45—40	0—0.125	0.00	0.00	0.04	0.08	0.08	0.12	0.16	0.28	0.24
45—30	0—0.975	0.00	0.00	0.03	0.07	0.06	0.16	0.19	0.27	0.22
45—20	0—2.325	0.02	0.03	0.04	0.09	0.05	0.14	0.17	0.25	0.21
45—10	0—3.525	0.04	0.07	0.09	0.07	0.05	0.11	0.14	0.23	0.20
45—0	0—3.975	0.06	0.08	0.07	0.09	0.06	0.10	0.12	0.22	0.20

2. *Validation of the Leaf Model*

Figure 1 shows the comparison of simulated value with measured photosynthesis rate. It can be seen clearly that the general trend of the variation of the simulated value fits that of the measured data fairly well. The data are scattered at both sides of the diagonal line. The analysis of the correlation between the measured data and the simulated value showed that the slope is 0.999, close to 1, and the intercept is −0.036, close to 0. The correlation coefficient is 0.893 with 432 samples, which passed through a significance test of 0.001. This means that the leaf photosynthesis rate can be simulated accurately with the established leaf model.

IV. NUMERICAL ANALYSIS OF THE EFFECTS OF O_3, CO_2 AND SPECTRUM VARIATION ON CANOPY PHOTOSYNTHESIS

The effects of the concentration of O_3 and CO_2, spectrum, temperature, humidity and wind velocity on crop photosynthesis are so complex that no instrument can identify the

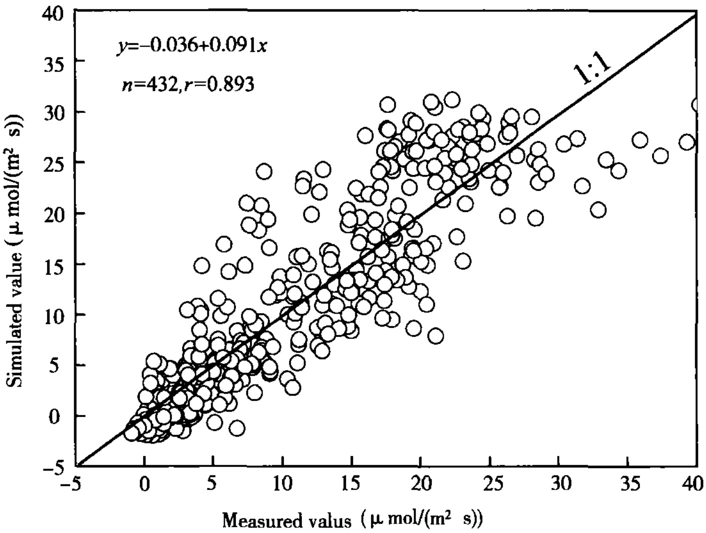


Fig. 1. Validation of the leaf photosynthesis model.

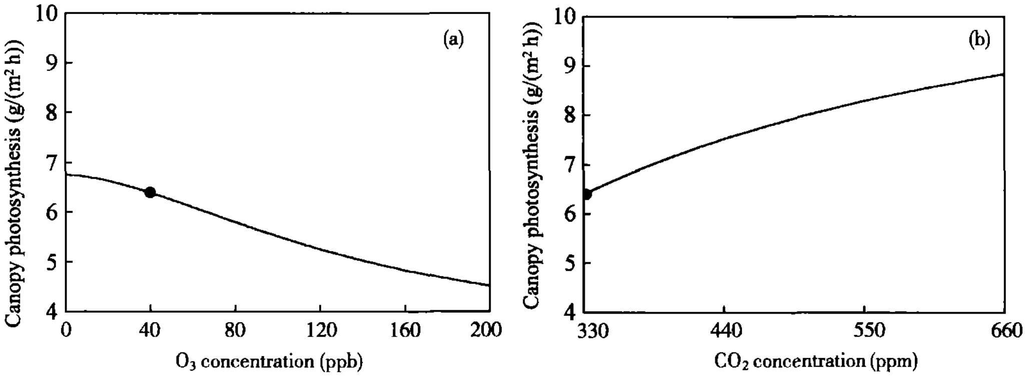
factor which causes the variation of photosynthesis measured in the field. In other words, it is difficult to conduct the comprehensive multiple factorial experiment in the field. However, the leaf model established in this study was fully validated against the measured data with CID instrument, and the scaling up processes from canopy scale to spatial scale were calculated with a clear academic process. Therefore the effects of single factor or multiple factors, such as O_3 and CO_2 et al., on the canopy photosynthesis can be revealed by numerical experiments with the canopy photosynthesis model established in this study.

Considering there are lots of factors influencing crop photosynthesis, the simulation scenario was defined first. The simulated location was the Yucheng Comprehensive Experimental Site (36°50′N, 116°40′E), Chinese Academy of Sciences. The simulated experiment was conducted on April 12, which corresponded to the jointing period of winter wheat. Given the assumption that it was a typical clear day with 12 MJ/m^2 of total daily direct radiation and 4 MJ/m^2 of total daily-scattered radiation, the canopy photosynthesis at noon was numerically analyzed with the model, under the following assumed conditions, such as (a) the concentration of O_3 was 40 ppbv, (b) the concentration of CO_2 was 330 ppmv, (c) the ratio of PAR to the whole spectrum of direct radiation equaled 0.42, (d) the ratio of PAR to the whole spectrum of scattered radiation was 0.56, (e) the temperature was 25℃, (f) the vapor pressure was 800 hPa, and (g) the wind velocity above the winter wheat canopy was 3 m/s.

1. *Single Factorial Influence*

First, the concentrations of O_3 and CO_2 and percentage of PAR in the spectrum were adjusted while the other factors under the BASE condition remained unchanged. The relationship between η and λ is very complex, and they do not change equally when the spectrum changes. However, the research result (Zuo et al. 1991) showed that η and λ always have the synchronous change under most conditions, thus the proportional coefficient of the spectrum B was defined as: $\eta = \eta_0 \times B/0.5$; $\lambda = \lambda_0 \times B/0.5$. It can be made the conclusion from the above definition that the proportion of PAR in the spectrum equals that of the BASE value when B is 0.5. The value of B was adjusted from 0.4 to 0.6 in the numerical analysis, in order to fit the possible variation range for both η and λ.

The single factorial numerical analysis showed that the canopy photosynthesis reduced with O_3 concentration increasing (Fig. 2). It reduced slowly when the O_3 concentration increased from 0 ppb to 40 ppb, but rapidly reduced linearly with O_3 concentration increasing from 40 ppb to 140 ppb. However, the canopy photosynthesis reduced more slowly when the O_3 concentration increased further. The canopy photosynthesis would reduce from 6.8 g/(m^2 h) to 4.8 g/(m^2 h) while the O_3 concentration increased from 0 ppb to 200 ppb. Canopy photosynthesis increased with CO_2 concentration increasing, but the rate of enhancement reduced obviously with CO_2 concentration increasing. The canopy photosynthesis would increase from 6.5 g/(m^2 h) to 8.9 g/(m^2 h) when the CO_2 concentration changed from 330 ppm to 660 ppm. The canopy photosynthesis reduced rapidly with decline of spectrum proportional coefficient B (Fig. 2c). The dotted line in Fig. 2c is a line that passes through two points, whose proportional coefficients are 0.4 and 0.6. It can be seen from Fig. 2c that the canopy photosynthesis reduced with



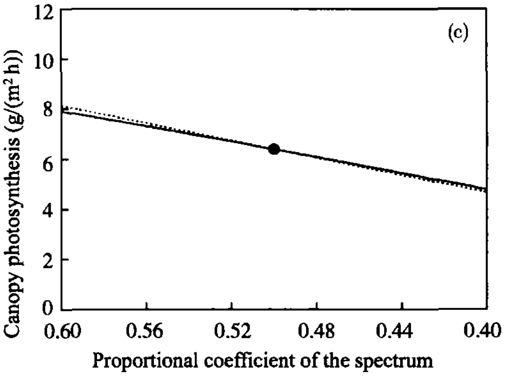


Fig. 2. The single factorial influence of O_3, CO_2 and spectrum variation on canopy photosynthesis P_j (the dots correspond to the BASE value): (a) the effect of O_3 concentration [O_3] on the canopy photosynthesis, (b) the effect of CO_2 concentration [CO_2] on the canopy photosynthesis, and (c) the effect of spectrum proportional coefficient B on the canopy photosynthesis.

spectrum proportional coefficient reducing with a linear form. The canopy photosynthesis increased with spectrum proportional coefficient increasing, but the rate of enhancement became smaller than that according to the linear form.

2. *Multiple Factorial Influence*

The comprehensive effects of spectrum proportional coefficient, concentrations of O_3 and CO_2 on crop photosynthesis were shown in Fig. 3. The effects of concentration variation of CO_2 and O_3 were shown in Fig. 3b, when the spectrum proportional efficient equaled 0.5. The spectrum proportional efficient corresponds to the BASE value of the spectrum at present, which equals 0.5. It can be seen from Fig. 3b that the canopy photosynthesis rate reduces with O_3 concentration increasing, while it increases with CO_2 concentration increasing. The variation range of the canopy photosynthesis is from 5.0 to 9.0 g/(m^2 h), and the maximum value is nearly twice the minimum value. When O_3 concentration equals 40 ppb and CO_2 concentration equals 330 ppm, the canopy photosynthesis rate corresponds to the BASE value 6.5 g/(m^2 h). The canopy photosynthesis is about 6.2 g/(m^2 h) as the O_3 concentration increases to 200 ppb and the CO_2 concentration increases to 660 ppm. At this time, the negative effect of the enhancement of O_3 on photosynthesis exceeds the positive effect of the enhancement of CO_2 on photosynthesis. This result has no conflict with the foregoing results of single factorial analysis. Because of the coupled effects, the effect of O_3 on canopy photosynthesis may be greater than that of the CO_2 among these two comprehensive effects. It is not reasonable for scientists to consider the comprehensive effects as the simple sum of the single factorial effects. If the spectrum variation is considered further, the canopy photosynthesis rate will be about 4.2 g/(m^2 h), which will reduce by 35% or so than that at present, corresponding to the O_3 concentration of 200 ppb, CO_2 concentration of 660 ppm and the spectrum proportional coefficient of 0.4.

It can be also seen from the analysis results (Fig. 3b) that the effect of CO_2 concentration on crop canopy is very significant when the O_3 concentration changes from 400 ppb to 160 ppb, according to the well-proportioned increasing form. The effect of CO_2 concentration on canopy photosynthesis is different when the O_3 is either at the lower concentration, changing from 0 ppb to 40 ppb, or at a higher concentration, changing from 160 ppb to 200 ppb. The canopy photosynthesis increases rapidly with CO_2 concentration increasing when the CO_2 concentration changes from 330 ppm to 450 ppm, while the O_3 is at a lower concentration, changing from 0 ppb to 40 ppb. However, the increase rate of the canopy photosynthesis reduced obviously with CO_2 concentration increasing when the CO_2 concentration reaches 450 ppm. The increase rate of CO_2 concentration reduces to nearly half with CO_2 concentration increasing, when the CO_2 concentration changes from 450 ppm to 580 ppm. When CO_2 concentration increases further and is greater than the level of 580 ppm, the increase rate of canopy photosynthesis equals the increase rate at the CO_2 concentration changing from 330 ppm to 450 ppm. The canopy photosynthesis increases quickly with CO_2 concentration increasing from 330 ppm to about 400 ppm, when the O_3 concentration is at a higher level from 160 ppb to 200 ppb. However, the increase rate reduces obviously with CO_2 concentration increasing when the

CO_2 concentration exceeds the level of 400 ppm. In other words, the positive effect will reduce obviously as long as the CO_2 concentration exceeds 400 ppm, when the O_3 concentration reaches 200 ppb or so. Comparison among Fig. 3a, Fig. 3b and Fig. 3c showed that the adjustment of spectrum proportional coefficient only changes the extent at which O_3 and CO_2 affect canopy photosynthesis, but it has no influence on the general trend of the effects of O_3 and CO_2 on canopy photosynthesis. The canopy photosynthesis becomes more sensitive to the variations of O_3 and CO_2 concentrations if the spectrum proportional coefficient is at a higher value.

The effect of CO_2 concentration increase on crops has been revealed by experiments made under the open top chamber conditions. The results showed that the increase of the CO_2 concentration had obvious distinguished effect on crop photosynthesis and the crop yields would be improved rapidly due to the direct effect of CO_2, regardless of the climate change. Based on the foregoing study results, it can be concluded that the positive effect of CO_2 on crop photosynthesis will be cut down seriously in the future, on the condition that the spectrum proportional coefficient reduces to 0.4 or so and the O_3 concentration increases due to industrial pollution, even under the suitable temperature and moisture conditions and regardless of the indirect impact of climate change on the crops.

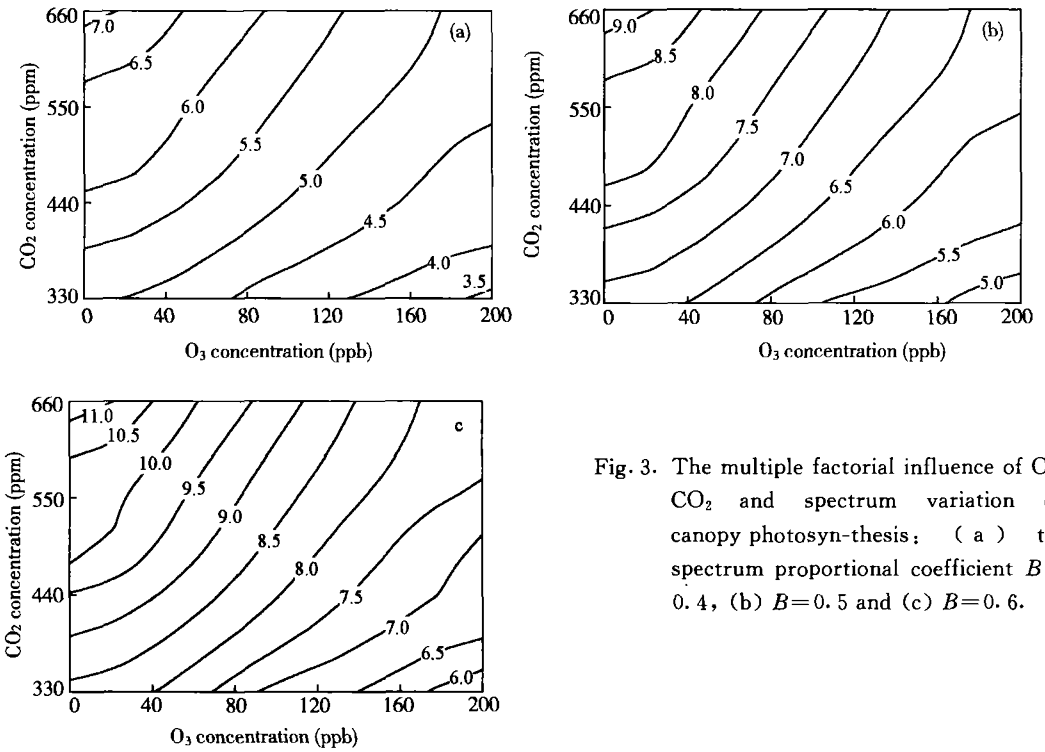


Fig. 3. The multiple factorial influence of O_3, CO_2 and spectrum variation on canopy photosyn-thesis; (a) the spectrum proportional coefficient $B=0.4$, (b) $B=0.5$ and (c) $B=0.6$.

V. SUMMARY AND DISCUSSION

(1) Based on the biochemical knowledge, an agrometeorological model was developed for simulating the canopy photosynthesis of winter wheat in this study, in which the effect of the stomatal adjustment on crop photosynthesis was fully considered. The model has coupled the variation of O_3, CO_2 and spectrum with crop photosynthesis reasonably, in which the effect of plant architecture on photosynthesis was considered in the scaling up process from leaf scale to canopy scale at the first time. This made the model possess the subtle spatial resolution and higher accuracy. All of the parameters used in the model were the data measured in Huang-Huai-Hai Region, which will provide plenty of model parameters for the further research on the possible effects of O_3 and CO_2 on crop photosynthesis. Based on this study, a comprehensive crop model with clearer mechanism will be established if the development submodel and dry matter partitioning submodel are added to this model, in order to assess the effects of O_3, CO_2 and spectrum variation on terrestrial ecosystem objectively in the future.

(2) The results of the single factorial numerical analysis showed that the canopy photosynthesis decreases with O_3 concentration increasing. The canopy photosynthesis will reduce by 29% or so if the O_3 concentration rises from 40 ppb to 200 ppb. The canopy photosynthesis increases with CO_2 concentration increasing, and it will increase by about 37% as the CO_2 concentration rises from 330 ppm to 660 ppm. The canopy photosynthesis reduces with spectrum proportional coefficient variation according to a linear form, and it will reduce by 27% or so if the spectrum proportional coefficient decreases from the present value of 0.5 to 0.4 in the future.

(3) It can be made the conclusion from the multiple factorial analysis in the paper that the canopy photosynthesis increased quickly with CO_2 concentration increasing and the positive effect of CO_2 on crop photosynthesis is very distinct when O_3 concentration reached 50 ppb at noon on the typical clear day, as for the clean area in the village far from the city with little pollution. But as for the suburban area where the pollution is very serious and the photochemical fog is easy to be formed, when the O_3 concentration reaches 220 ppb, the canopy photosynthesis will reduce slightly than that at present CO_2 concentration in the clear region with the O_3 concentration level of 40 ppb, even the CO_2 concentration is doubled. The reason is that the positive effect of the CO_2 increase can not compensate the negative effect of the O_3 increase on crop photosynthesis. If the spectrum reduces to 0.4 or so, the canopy photosynthesis will reduce by about 35% than the BASE value at present, under the scenario of O_3 concentration 200 ppb and the CO_2 doubling, even regardless of the climate change.

(4) Because of the uncertainty of the climate change, the numerical analysis was made under the fixed climatic scenario, i.e., only the direct effects of variation of O_3 and CO_2 on crop photosynthesis are fully considered. Based on this study, the comprehensive impact of variation of the greenhouse gases on the crop photosynthesis will be better revealed if the climate change scenario is considered in the future.

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