Impact of climate change with enhanced UV-B radiation on China's agricultural NPP

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Abstract: Global climate change may have adverse effects on the net primary productivity (NPP) of crops. Several studies have investigated the potential influence of future changes in temperature and precipitation on agricultural NPP, but the potential effects of UV-B radiation on agricultural NPP has received little attention. This paper describes an NPP model that can calculate the effects of climate change on agricultural NPP, and couples the impact of UV-B increase into this model. Results indicate that 1) in the case of a reduction in precipitation and ozone concentration, temperature increases will have a negative effect on agricultural NPP, 2) in the case of no changes to precipitation, any temperature increase will partially counteract the negative influence of UV-B increase, and 3) in the case of a precipitation increase, the negative influence of a UV-B increase will completely counteract any temperature increase, which will benefit agriculture NPP in China. In all three cases, the degree of effect that global change will have in each climate condition is in the order of semi-arid, humid, and arid regions from low to high.

Introduction

One component of global climate change is the loss of stratospheric ozone, which recently has received increased attention in assessing the potential damage to vegetation due to enhanced levels of Ultraviolet-B (UV-B, 280-320 nm) radiation (Grant 1990; Bornman 1991; Nunez et al. 1994). Satellite measurements have proven the expansion of stratospheric ozone losses, and ground-level measurements have detected significant UV-B increases (Kerr and McElroy 1993). Increased UV-B radiation caused by reduced stratospheric ozone is expected to continue into the 21st century (Madronich et al. 1998). A substantial number of studies have been conducted that have evaluated the potential consequences of an increase in UV-B radiation on many plants (Krupa and Kickert 1989; Zheng 2003), and approximately 400 species of plants have been screened for sensitivity to UV-B radiation and of these, about two-thirds were found to be sensitive in some parameter (Sullivan and Rozema 1999).

The concern for producers and agricultural scientists is whether enhanced UV-B radiation reduces economic yields or the quality of field crops (Kakani 2003). Numerous studies evaluating the impact of enhanced UV-B on crop yields have been carried out in both field and greenhouse environments. Nearly half of these studies showed that enhanced UV-B radiation decreases crop yield (Kakani 2003). NPP of agriculture vegetation is important in estimating farmland carrying capacity, and the quantity of energy remaining after crops have satisfied their respiratory needs. Therefore, enhanced UV-B radiation must be accounted for in estimating the potential impacts of global climate changes on agriculture NPP (Caldwell et al. 1998; Madronich et al. 1998). In previous studies, however, the potential impact of enhanced UV-B radiation on NPP of agriculture vegetation has largely been ignored. In this paper, a method of adding the impact of UV-B radiation to a NNP model is developed, and the dependency of China's agricultural NPP on global changes, including the enhanced UV-B radiation, is examined under different scenarios.

Methods

Because this research adopts parameters derived by Zheng's (1997) study, the geographic focus is on the same areas of China; with the exception of Hainan province, Taiwan, and Hong Kong. Based on different humidity conditions, Zheng's study divided China area into three regions: humid region, semi-arid region and arid region (Figure 1).

NPP model:

At present, there are four models which can calculate NPP: the Miami model (Lieth 1975), the Thornthwaite model (Lieth 1972), the Chikugo model (Uchijima and Seino 1985), and the Synthetic model (Zhou 1996). The Miami model empirically derives correlation of net primary productivity with mean annual temperature and precipitation. The Thornthwaite model is similarly an empirical model for estimating potential evapotranspiration (Zhang 1989; Chang 2003). The Chikugo model is a regression model based on correlation between NPP and climate variables. Generally, the potential of application of empirical or regression models for future projection is limited as regressions may not necessarily be appropriate for climatic conditions that are novel to terrestrial ecosystems (Melillo *et al.*

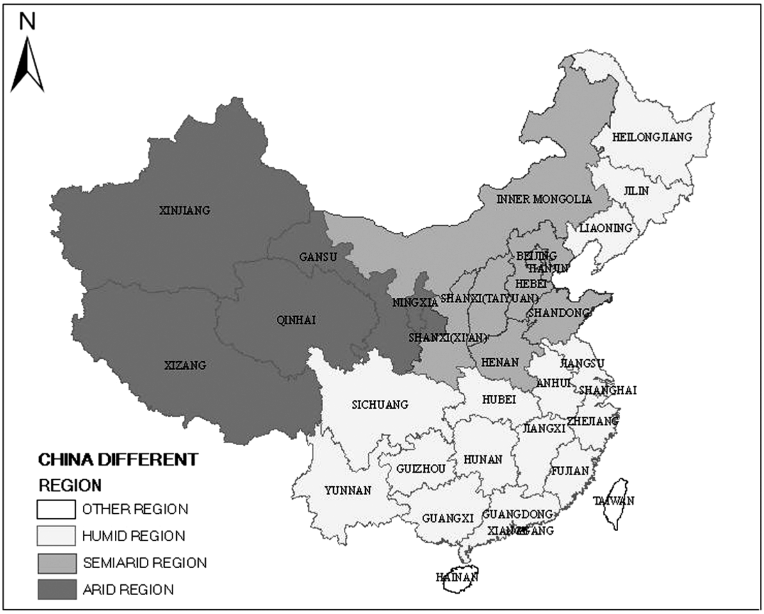

Figure 1: *Study area (humid region, semi-arid region and arid region)*

1993). Although the Synthetic model is based on the eco-physiological features of plants as well as climatic factors, it is known to better simulate NPP of natural vegetation in semi-arid and arid areas in China than other models (Zhou 1996). This paper adopts the Synthetic model to calculate the effect of climate change and UV-B increase on agriculture NPP in China. The calculating formula of the Synthetic model is expressed as follows.

[1]

$$NPP = RDI \frac{rR_n(r^2 + R_n^2 + rR_n)}{(R_n + r)(R_n^2 + r^2)} \cdot \exp(-\sqrt{9.87 + 6.25RDI})$$

Where R_n is net radiation, *r* is annual precipitation, unit of NPP is t DW·hm^{-2}·a^{-1}, and RDI is aridity.

Based on the result of Zhang (1994), RDI in formula [1] can be expressed as:

[2] $$RDI = (0.629 + 0.237PER - 0.00313PER^2)^2$$

Where PER is potential evapotranspiration rate which can be expressed as:

[3] $$PER = PET / r = BT \cdot 58.93 / r$$

Where PET is annual potential evapotranspiration (mm) and BT is Mean annual biology temperature (ºC). BT can be expressed as:

[4] $$BT = \sum t/365 = \sum T/12$$

Where *t* is daily mean temperature, which ranges from 0°C to 30°C. and T is monthly mean temperature, which also ranges from 0°C to 30°C. Rn in formula [1] can thus be represented as:

[5] $$R_n = RDI \cdot r$$

Based on the above derivation, NPP of agriculture vegetation can be calculated from biology temperature and precipitation.

Modified model:

Equation [1] does not allow for the role of UV-B. In order to add the effect of UV-B to the model, equation [1] was modified by multiplying it by a coefficient 'Cuv.' In this way, the influence of the enhanced UV-B (i.e., the reduced Ozone) on the NNP is estimated in the model. Based on experimental data of Zheng et al. (2000), the coefficient Cuv can be expressed as:

[6] $$\mathrm{Cuv} = 1.9716 \times \mathrm{x} + 0.9763$$

Where Cuv is the percentage of NPP decreasing, and x is percentage of UV-B increasing.

If the percentage increase in UV-B is available, NPP can be calculated under the enhanced UV-B modified model. Some researchers have predicted ozone depletions of 0 - 4% in the tropics and 4 - 12% at high latitudes by about 2050 (TOLBA 1992). For consistency, this study adopts the assumption of ozone reducing 5% in China by about 2050 (Xiong 1993). The increment of UV-B radiation can be derived from the ozone reduction by using the technique developed by Xiong (1993). A decreasing percentage of NPP is thus calculated using equation [6]. Table 1 indicates that decreased Ozone produces enhanced UV-B radiation and reduced NPP. The increment of UV-B and the reduction of agricultural NPP in China vary by region. The reduction of NPP ranks first in the humid region, second in the arid region, and last in the semi-arid region.

Table 1: *Increment of UV-B and decrease of NPP when ozone reduces 5% in different area of China.*

Region	Province	summer	winter	average	Decreasing to percent of NPP
Semi-arid Region	Inner Mongolia	3.40%	5.80%	4.60%	88.56%
	Beijing	3.35%	5.25%	4.30%	89.15%
	Tianjing	3.35%	5.25%	4.30%	89.15%
	Hebei	3.35%	5.25%	4.30%	89.15%
	Shanxi(Taiyuan)	3.25%	5.25%	4.25%	89.25%
	Shandong	3.25%	4.90%	4.08%	89.60%
	Henan	3.15%	4.80%	3.98%	89.79%
	Shanxi(Xi'an)	3.15%	4.65%	3.90%	89.94%
Humid Region	Liaoning	3.35%	5.30%	4.33%	89.10%
	Jilin	3.50%	6.00%	4.75%	88.26%
	Heilongjiang	3.35%	6.00%	4.68%	88.41%
	Shanghai	3.05%	4.40%	3.73%	90.29%
	Zhejiang	3.10%	4.10%	3.60%	90.53%
	Anhui	3.15%	4.80%	3.98%	89.79%
	Fujian	3.10%	3.70%	3.40%	90.93%
	Jiangxi	3.10%	4.50%	3.80%	90.14%
	Hubei	3.10%	4.30%	3.70%	90.34%
	Hunan	3.10%	3.90%	3.50%	90.73%
	Guangdong	3.10%	4.10%	3.60%	90.53%
	Guangxi	3.05%	4.10%	3.58%	90.58%
	Sichuan	3.05%	4.05%	3.55%	90.63%
	Guizhou	3.00%	3.90%	3.45%	90.83%
	Yunnan	3.00%	3.75%	3.38%	90.98%
Arid Region	Gansu	3.20%	5.00%	4.10%	89.55%
	Qinhai	3.20%	5.00%	4.10%	89.55%
	Ninxia	3.15%	5.00%	4.08%	89.60%
	Xinjiang	3.50%	5.50%	4.50%	88.76%

Source: Xiong 1993

Results

This study calculates agricultural NPP under different scenarios of global climate change. Three common assumptions are adopted: 1) precipitation increases by 20 percent, temperature increases by two degrees Celsius, ozone reduces by 5%; 2) similar to (1), but precipitation does not change; and 3) similar to (1) but precipitation is reduced by 20 percent (Zheng 1997). Table 2 gives the input parameters of the model. NPP variations for different regions in China under each of the three cases are shown in Figure 2 and Table 3. From Figure 2, it can be seen that different global changes produce different variations and trends of NPP. In the first case NPP decreases sharply, which indicates that when both precipitation and ozone are reduced, temperature increases will have a negative effect on agriculture production. In case 2 the average NPP also decreases but the reduction is obviously smaller compared to case 1, which indicates that when precipitation does not change, a temperature increase will

Table 2: *Input parameters of model.*

Region	Province	Precipitation mm	Biology temperature °C	aridity	NPP of agriculture vegetation t DW·hm^{-2}·a^{-1}
Semi-arid Region	Inner Mongolia	351.6	3.3	1.11	2.4
	Beijing	644.2	11.5	1.22	7.9
	Tianjing	566.9	17.5	1.66	8.7
	Hebei	573.9	10.8	1.5	4.9
	Shanxi(Taiyuan)	497	9	1.73	3.9
	Shandong	769.8	12.7	1.28	12.6
	Henan	763.8	14.3	1.49	6.2
	Shanxi(Xi'an)	630.6	11.6	1.448	7.3
Humid Region	Liaoning	723.9	8.3	1.02	5.5
	Jilin	645.3	4.9	0.88	4.3
	Heilongjiang	485.5	3	0.84	4
	Shanghai	1123.7	15.7	1.05	20.4
	Zhejiang	1441.1	17	0.86	10.6
	Anhui	1056.9	15.3	1.06	19
	Fujian	1490.6	21.6	0.94	7.7
	Jiangxi	1550	17.8	0.79	11.8
	Hubei	1097.8	16.1	1.01	5.8
	Hunan	1395.7	17	0.83	11
	Guangdong	1673.7	22.5	0.9	14.4
	Guangxi	1597.8	21	0.83	13.2
	Sichuan	975.1	13.3	1.11	9.6
	Guizhou	1199	15.5	1	10.1
	Yunnan	1037.7	14.9	1.26	8
Arid Region	Gansu	325.7	8.3	2.47	4.5
	Qinhai	420.2	7.1	2.06	3.4
	Ninxia	287.4	7.7	2.86	4.2
	Xinjiang	106.1	9.4	5.84	3

Source: Zheng 1997

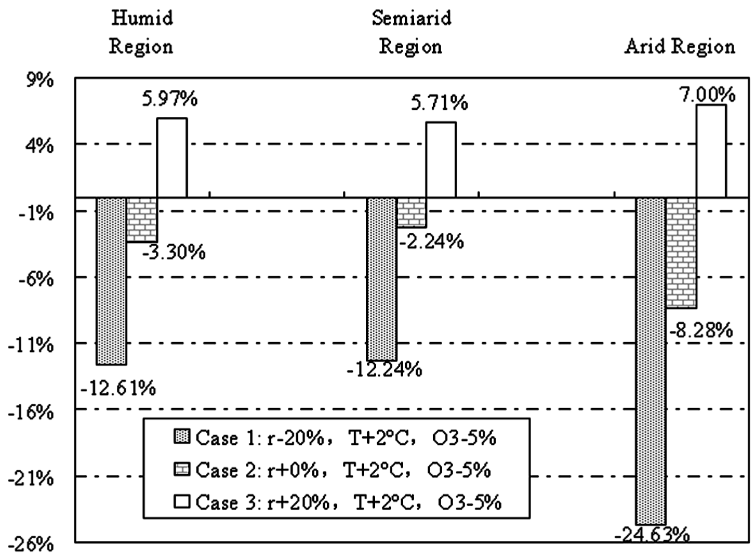

Figure 2: *NPP average variations in different regions under three cases.*

partially counteract the negative influence of UV-B increase. Case 3 benefits agriculture, and NPP increases. This implies when both precipitation and temperature increase, the negative influence of a UV-B increase is completely counteracted. That being said, the degree of influence in each climatic region is different. In case 1 the average NPP in the arid region reduces by about 25 percent. The reduction is almost twice as much as that in other regions. Humid and semi-arid regions have similar results, but the reduction in the humid region is slightly larger than the semi-arid region. In case 2 the dependence of reduction on the humidity conditions is similar to case 1. In case 3 the differences of NPP increments are not significant across different humidity regions, but we still can draw a conclusion that the increment is largest in the arid areas and the least significant in semi-arid areas. Table 3 gives the maximum and minimum NPP variations in China for the different regions and under the three cases. From this table, it can be seen that the magnitude of NPP variation ranks first in the arid area, second in the humid area, and last in the semi-arid area.

Table 3: *The maximum and minimum NPP variations in different regions under three cases.*

Regions	Case 1: r-20%, T+2ºC, O3-5%		Case 2: r +0%, T+2ºC, O3-5%		Case 3: r+20%, T+2ºC, O3-5%	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Humid	-14.19%	-9.91%	-4.89%	0.85%	3.31%	11.62%
Semi-arid	-9.63%	-19.59%	-6.66%	0.37%	2.90%	10.37%
Arid	-57.01%	-12.37%	-24.34%	-2.18%	4.45%	6.51%

Discussion and Conclusion

This paper described an NPP model capable of calculating the effect of climate change on agricultural NPP, and coupled the impact of UV-B increase into the NPP model. The impact of UV-B increase on agricultural NPP is remarkable in different climatic zones in China. The reduction of NPP ranks first in the humid region, second in the arid region, and last in the semi-arid region. The results indicate that it is necessary to include a UV-B parameter in NPP models in order to improve the accuracy of prediction under different scenarios of global change. The results of the modified NPP demonstrate that: 1) in the case of reducing precipitation and ozone, a temperature increase will have a negative effect on agricultural production; 2) in the case of no change in precipitation, a temperature increase will partially counteract the negative influence of a UV-B increase; 3) in the case of precipitation increase, the negative influence of a UV-B increase will be completely counteracted with a temperature increase, which will benefit agriculture in China; 4) in all three cases, the nature and magnitude of the effect that global change will have in each climatic region is different: with only minor effects in semi-arid regions, but large effects in arid regions.

These results demonstrate that the effects on plants will be different for each region depending on the pre-existing climatic conditions and the adaptation potential of local cultivated species (Chartzoulakis 2004); and that arid regions are the most sensitive to global change. Previous research has reported that plants can change form under increased UV-B radiation and thus capture more sunlight for photosynthesis (Barnes 1988; Barnes 1995). Therefore, plants are presumably adapted to more UV-B radiation and better buffered against increasing UV-B. Because there is less cloud cover in the arid regions of China, crops in this region might adapt to increased UV-B and the decrement of agricultural NPP in this region might be less than in other climatic regions. The NPP model results, however, are not in agreement with this notion; agricultural NPP in humid and semi-arid areas are potentially less affected by increased UV-B, possibly due to greater cloud cover.

In conclusion, there are a number of limitations to this research that need to be noted in future studies. First, global change will most likely result in different behaviors across different areas; but the model assumes a rather homogeneous pattern within each climatic region. Second, changes in temperature, precipitation, and UV-B were included in evaluating the effect of global change on the agricultural NPP, but the responses of these changes to ecology and environment were ignored and the interaction between temperature, precipitation, UVB, and agriculture in climatic zones not considered. Third, this paper only identified UV-B input at a fixed value, and it would be very instructive to vary the UV-B model input to measure sensitivity to this parameter. Finally, the expression used to calculate NPP decrement with increasing UV-B was derived based on the experimental data of previous research in this region, but the data only spanned three years and results thus need to be tested by future experimental research.

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