Ground-level ozone in China: Distribution and effects on crop yields

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More research is needed to reliably estimate ozone caused crop losses in China.

Abstract

Rapid economic development and an increasing demand for food in China have drawn attention to the role of ozone at pollution levels on crop yields. Some assessments of ozone effects on crop yields have been carried out in China. Determination of ozone distribution by geographical location and resulting crop loss estimations have been made by Chinese investigators and others from abroad. It is evident that surface level ozone levels in China exceed critical levels for occurrence of crop losses. Current levels of information from ozone dose/response studies are limited. Given the size of China, existing ozone monitoring sites are too few to provide enough data to scale ozone distribution to a national level. There are large uncertainties in the database for ozone effects on crop loss and for ozone distribution. Considerable research needs to be done to allow accurate estimation of crop losses caused by ozone in China.

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1. Introduction

As the most populous country in the world, China must provide food for one fifth of the world's population with only 7% of the world's land area. After nearly three decades of effort, China produced 0.43 billion tons of grain in 2003, which met the country's minimum food requirement (Xinhua News Agency, 2004). Grain production, however, is threatened by agricultural land loss due to economic development and urbanization and air pollution effects on yields. The Chinese government has addressed the land loss issue by passing laws to protect agricultural land. Yield losses due to air pollution, especially ozone, have received little governmental attention, even though there are published reports that ground-level ozone may be adversely affecting grain production (Chameides et al., 1999; Feng et al., 2003; Wang and Mauzerall, 2004; Wang et al., 2005).

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Economic expansion in China is driven by increasingly higher consumption of fossil fuels. Primary energy consumption increased by 53% from 1990 to 2002. In 2002, primary energy consumption was 1.514 billion coal equivalent tons, of which 66.3% was coal, 23.5% was oil, and 2.6% natural gas. Energy consumption is estimated to reach 4 billion coal equivalent tons in 2020 (China Energy Middle–Long-Term Development Plan). In the future, more than 75% of energy will be derived from fossil fuels. Measures to limit electricity consumption now were established in China in 2003.

Increasing consumption of fossil fuels in China results in increased emissions of sulfur oxides (SO_x) and nitrogen oxides (NO_x) as well as soot and fine particulates and carbon dioxide. In Europe and North America, emissions from fossil fuel consumption are decreasing, while in China, they are rapidly increasing, especially in cities and industrial areas (He et al., 2002; Coyle et al., 2003; Ashmore, 2005). NO_x includes both nitrogen dioxide (NO₂) and nitric oxide (NO). NO₂ is the starting point for the photochemical oxidant cycle that results in formation of ozone. Increasing levels of NO_x also means increasing levels of ozone in China.

The Yangtze Delta is one of the world's continental scale Metro-Agro-Plexes (MAPs). As Chameides et al. (1994) point out, the growth of MAPs results in increased ground-level ozone to pollution levels. Yet few papers have estimated present and future crop losses from ozone in the Yangtze Delta and elsewhere in China. There is an urgent need to address this problem. Here we present what is known about current distribution of surface levels of ozone and their effects on crop yields and consideration of how to improve crop loss estimates for current and future levels of ozone in China.

2. Surface level ozone distribution and implications for crop losses

In the 1980s, air pollution began to receive attention in China. Air quality monitoring stations were established by the government in cities, such as Beijing and Shanghai, and capitals of the provinces. In many cities, SO_x, NO_x, and particulates are monitored routinely (He et al., 2002). There are only a few ozone analyzers in some of the large developed cities in eastern coastal areas. Little of the ozone monitoring data is available.

Individual Chinese scientists have established ozone-monitoring programs. As early as 1983, Su et al. (1987) began monitoring ozone in the Beijing-Tianjing Region, in collaboration with W.E. Wilson, Atmospheric Science Research Laboratory, US EPA. Since then, ozone monitoring has been carried out at urban, suburban and rural sites (Fig. 1). Due to equipment shortages and problems with funding and logistics, records from these sites are often short-term and or incomplete.

Two projects supported by the National Nature Science Foundation of China focused on ozone monitoring on a countrywide scale. Project PRO1 focused on five sites, with monitoring data available from August 1994 to July 1995. The five sites included: a WMO baseline station (Waliguan site); two WMO regional baseline stations (Longfeng Shan and Linan sites); a CEPA monitoring site (Qindao site); and a background

station in Hong Kong (Luo et al., 2000). Project PRO2 focused on six sites in the Yangtze Delta: one of the most highly polluted areas in China. Ozone was monitored at Changsu, Linan, Sheshan, Jiaying, Jianhu and Jurong from June 1999 to June 2000 (Zhou, 2004).

Looking at the data for all locations, the maximum hourly mean ozone concentrations were larger than 56 ppb, suggesting that they could cause crop losses. Ozone concentrations were not highest in urban areas. In Guangzhou, for example, ozone concentrations were of the order urban < suburban < rural areas. In remote areas, such as the Emei and Taishan sites, ozone concentrations are high (Table 1).

This implies that crops in these regions might be damaged by high ozone concentrations. Su et al. (1987) found that ozone exceeded 80 ppb on 50% of the days they monitored in the Beijing-Tianjin region, with a maximum reading of 170 ppb reported during 1983–1986. Results from recent ozone monitoring in the Yangtze Delta shows that 6.1–10.4% of the hourly mean concentrations exceeded 60 ppb. A maximum high concentration of ozone at 196 ppb was reported from Sheshan, near Shanghai (Zhou, 2004).

In most locations, ozone concentrations were lower in the winter. Peak concentrations vary with location (Table 1). At the central station of Guangzhou city, Guangdong Province in 1999, the seasonal mean and maximal ozone concentrations were 23 ppb and 55 ppb in spring, 24 ppb and 53 ppb in summer, 34 ppb and 76 ppb in fall, and 39 ppb and 82 ppb in winter (Wang et al., 2003). In PRO1 peaks occurred in fall/early winter (Luo et al., 2000). In PRO2, peaks occurred in summer, followed by fall. Summer and fall are times when crops are growing fast. Peaks of ozone during these times could result in crop losses.

Multiple-day episodes of high ozone concentrations have been noted at some sites in Eastern China, due to the presence of a strong and stationary high-pressure ridge (Luo et al., 2000). The impacts of these episodes on crop production, however, are unknown.

Fig. 1. The distribution of O₃ monitoring stations in China.

Table 1
Mean O₃ concentrations at monitoring sites by season

Site	Location	Measurement period	Concentration (ppb)						Reference
			Annual	Spring	Summer	Fall	Winter	Hourly maximum	
Beijing-Tianjin region	Urban	1983–1986	45	32	45	67	37	170	Su et al., 1987
Mount Omei	Rural	8–20 Oct. 1985					25	56*	Hong, 1988
Xiaozhangzhuang, Hefei	Suburban	Oct. 1993					24	57.9	Yao et al., 1995
DongquXiaoyuan, Hefei	Urban	Oct. 1993					19.8	65.6	Yao et al., 1995
Waliguan	Rural	Aug. 1994–Jul. 1995						130	Li et al., 1999
Longfengshan	Rural	Aug. 1994–Jul. 1995						80	Li et al., 1999
Linan	Rural	Aug. 1994–Jul. 1995						120	Li et al., 1999
Qingdao	Rural	Aug. 1994–Jul. 1995						90	Li et al., 1999
Jinhushan	Rural	Jul. 1998–Jun. 1999	20	21	16	15	27	55*	Bai et al., 2003
Central Station, Guangzhou	Urban	Jan.–Dec. 1999	59	45	47	66	77	161	Wang et al., 2003
Luhu Park, Guangzhou	Suburban	Jan.–Dec. 1999	74	74	71	75	74	180	Wang et al., 2003
Longgui, Guangzhou	Rural	Jan.–Dec. 1999	74	59	77	75	84	174	Wang et al., 2003
Changshu	Rural	Jun. 1999–Oct. 2000	31	25	45	28	26	120*	Zhou, 2004
Linan	Rural	Jun. 1999–Oct. 2000	35	29	43	29	37	136*	Zhou, 2004
Sheshan	Rural	May 1999–Jun. 2000	33	31	43	28	31	196*	Zhou, 2004
Jiaxing	Rural	May 1999–Jun. 2000	29	35	40	27	12	188*	Zhou, 2004
Jianhu	Rural	May 1999–Dec. 1999			41	27	32	114*	Zhou, 2004
Jurong	Rural	Dec. 1999–Jun. 2000		17	37			141*	Zhou, 2004
Waliguan, Qinghai	Rural	Aug. 1994–Dec. 2001	48	44.9	54.2	50.6	41.5	65	Nie et al., 2004
Hongkou, Shanghai	Urban	Jan.–Dec. 2002	19	20.5	21	23.5	12	128	Zhang et al., 2003
Yanji, Jilin	Urban	Mar.–May 2003		29	19			48.8	Li et al., 2003
Jinan, Shandong	Urban	May–Oct. 2003			54.5	46.5	30	316	Yin et al., 2004
Taishan, Shandong	Rural	Jul.–Nov. 2003			62	49		120	Gao et al., 2005
Jiangbei, Chongqing	Rural	1993–1996		7	8	21		93	Zheng et al., 1998

*Maximum O₃ concentration monitored.

Long-term ozone monitoring data from established sites in China is either non-existent or not readily available. There is a WMO baseline monitoring site at Wanliguan that has been active for more than 10 years. Data from 1994 to 2001 indicate a linear increment trend for ozone in a 9% slope (Nie et al., 2004).

Many descriptors can be used to express cumulative ozone data in relation to crop loss. Indices such as mean and cumulative can be based on timescales such as hourly, daily, monthly, seasonally and yearly. Initially a 7-hour (09:00–16:00) seasonal mean index (M7) was proposed. This was later extended to a 12-hour (08:00–20:00) seasonal mean index (M12) to include late day high ozone concentrations (Hogsett et al., 1988). Since then, cumulative indices have become more widely used (SUM 0, SUM60, W126).

SUM0 is the sum of all ozone exposure in ppb or ppm hours. SUM60 is the accumulated hourly mean ozone concentrations in three consecutive months at 60 ppb and above, expressed as ppb or ppm hours. W126 weights the accumulated hourly means to give preference to higher values. SUM60 and W126 have been used to analyze crop loss due to ozone (US EPA, 1996; Wang and Mauzerall, 2004). The European Union has developed the AOT40 cumulative index. This includes hourly ozone averages at 40 ppb and above during daylight hours during the growing season, expressed as ppm hours.

In project PRO2, SUM06, AOT40 and M7 indices were calculated for the period of April to June in Changsu, Sheshan, Linan, Jurong, and Jiaxing. The relationship between SUM06 and AOT40 was strong and significant ($r^2 = 0.97$),

while both were weakly related to M7 ($r^2 \leq 0.1$) (Zhou, 2004). Averages for SUM60, AOT40, and 7M for the five stations in the wheat-growing period from April to June were 33 ppm h, 19ppm h, and 59 ppb (Wang et al., 2005).

China is a very large country with many climatic regions. This makes application of exposure indices difficult as the crops and cropping practices are different in each region and are subject to varying climatic influences. The periods of consecutive months for calculating indices will vary with each location.

In China, the main crops are winter wheat, oilseed rape, rice, corn and soybeans. Except for Northeastern China, where crops are limited by precipitation and temperature, and parts of Southwestern China, where crops are limited by temperature, more than one crop is planted during one year. Spring and fall seasons are the most important seasons for growing crops. Elevated ozone concentrations during these times could adversely affect crop growth and yields.

Calculations of seasonal changes in SUM60 were made for Longfeng San, Qingdao, Linan, and Hong Kong (Fig. 3 in Chameides et al., 1999). Taking local cropping practices into account, assessment of ozone impact on crop yields can be determined. Corn and soybean are sown in Longfeng San in May and harvested in September. SUM06 was highest there from September to January of the next year. This indicates that ozone effects on corn and soybeans there would likely be small. In Linan, winter wheat and rape are sown in late winter and harvested in May. Corn and rice are sown in June and harvested in October. While SUM60 values are higher here, they occur during early season slow crop growth periods. In Hong

Kong, SUM60 values peak from October to December, when much cropland is fallow. In Qindao, SUM60 values peak from July to September and could seriously affect yields of later seasonal crops of corn and rice.

3. Plant responses to ozone in China

3.1. Screening plants for ozone sensitivity by exposure to ozone in chambers

A wide variety of plants have been screened for sensitivity to ozone, based on foliar injury expression following exposure under controlled conditions (Table 2). Wheat seemed to be one of the most sensitive crop plant under these conditions (Jin et al., 2001). Variation in sensitivity within genotypes was also noted, especially for tobacco (Yang et al., 2004).

3.2. Short-term investigations in open-top chambers (OTCs)

Short-term experiments (most less than one month) were done with ozone and a variety of plants in OTCs. Aspects of visible symptom expression, microanatomical effects, reproduction, nutrient status, stomatal physiology, antioxidant responses, pollen development and ethylene emission were investigated. (Wang and Guo, 1990; Huang and Wang, 1991; Huang et al., 2004; Wang and Men, 1991; An and Wang, 1994; Qiu et al., 1994; and Yu et al., 1994; Jiang and Totsuka, 1995; Sun et al., 1998; Jin and Feng, 2000; Jin et al., 2000; Bai et al., 2002; Yang et al., 2004; Huang et al., 2004). Results of these investigations, while useful, cannot be extrapolated to crop loss studies and are mentioned here to provide a complete record of research done on ozone effects on plants in China.

3.3. Long-term crop loss studies with OTCs in the field

The National Nature Science Foundation of China supported an OTC dose/response study with wheat and rice in

Hebei Province. The Chinese Academy of Meteorological Sciences established 5 OTCs in Dingxing. Wheat and rice were exposed to either non-filtered air (NF), charcoal-filtered air (FA), FA + 50 ppb ozone, FA + 100 ppb ozone, or FA + 200 ppb ozone for 3–4 months. Only one OTC was used for each ozone exposure regime. When crop yields for wheat were compared to those from FA + ozone at 50, 100, and 200 ppb, reductions of 10.5, 58.6, and 80.4% occurred. Similar comparisons for rice resulted in reductions of 8.2, 26.1 and 49.1% for rice (Feng et al., 2003).

Using these results, Jin et al. (2001) proposed the following dose/response relationships for wheat and rice:

$$Y_{\text{wheat}} = -1.296x$$

$$Y_{\text{rice}} = -0.256x$$

where Y_{wheat} and Y_{rice} are % yield losses and x is an AOT40 in ppm h during the exposure period. From this, it was concluded that yield loss for wheat was 5 times that for rice at the same ozone exposure regimes.

3.4. Other yield effects investigations

Huang et al. (2004) exposed soybean plants to 100 ppb ozone and obtained a yield reduction of 60%. They concluded that soybean was more sensitive to ozone than wheat. Pakchoi biomass was reduced by 38–84% and 69–86% after exposure to ozone at 100 or 200 ppb for 20 days (Bai et al., 2002).

4. Chemical treatments to prevent ozone injury

Wang and his colleagues have evaluated a variety of chemical compounds to prevent ozone injury on plants in China (Table 3). The experiments, however, were all of short duration and very high ozone concentrations were used. Additional work involving using these chemical compounds under ambient conditions might lead to useful results.

Table 2
Results and screening studies for ozone sensitivity in crop plants

Authors	Indicator for assessment	Results
Zheng et al., 1998	Growth response to exposure of elevated O ₃ of 15 ppb overnight rising to a midday maximum of 75 ppb for 28 days	<i>Nicotiana tabacum</i> 'Bel-W3' > <i>Planago major</i> 'Valsain' > <i>Triticum Aestivum</i> 'Hanno' > <i>Raphanus sativa</i> 'Cherry Bell' > <i>Capsicum annum</i> 'Yu2' > <i>Capsicum annum</i> 'Yu3' > <i>Oryza sativa</i> 'Xiaoyou 2' > <i>Capsicum annum</i> 'Yu4' > <i>Capsicum annum</i> 'Yu5' > <i>Solanum melongena</i> 'Sanyue' > <i>Brassica oleracea</i> 'Mogu' > <i>Brassica pekinensis</i> 'Lubei 1' > <i>Lycopersicon esculentum</i> '85004' > <i>Lactuca sativa</i> 'Erqingpi' > <i>Triticum aestivum</i> 'Yumai 4' > <i>Zea mays</i> '3203' > <i>Raphanus sativa</i> '88059' > <i>Cucurbita pepo</i> 'Zhaoqin'
Jin et al., 2001	Production reduction in exposure to O ₃ concentration of 100 and 200 ppb for 3 months	<i>Spinacia oleracea</i> 'Zhongbo 1' > <i>Brassica chinensis</i> 'Wuyueman' > <i>Triticum aestivum</i> 'Jingdong 6' > <i>Oryza sativa</i> 'Zhongzuo 9321'
Zhou and Feng, 2001	Symptoms with fumigation under 150 ppb for 0.5 h	Most sensitive vegetables: <i>Spinacia oleracea</i> , <i>Cucumis sativus</i> , <i>Ipomoea aquatica</i> , <i>Lycopersicon esculentum</i> , <i>Raphanus sativus</i> , <i>Capsicum annum</i> Sensitive vegetables: <i>Solanum melongena</i> , <i>Vigna unguiculata</i> , <i>Phaseolus Vulgaris</i> , <i>Brassica pekinensis</i> , <i>Luffa cylindrica</i> Insensitive vegetables: <i>Brassica alboglabra</i> , <i>Brassica juncea</i> , <i>Momordica charantia</i>
Yang et al., 2004	Flecks on leaf in exposure to O ₃ concentration of 332 ppb for 12 h	<i>Nicotiana tabacum</i> 'K326' > 'NC628' > 'K346' > 'Yunyan 85' > 'Yunyan 87'

Table 3
Comparison and effectiveness of a variety of chemical compounds in prevention of ozone effects on plant

Chemicals	Method	Plant	Results	Reference
Plant growth regulator, Meffluidide	10 ppm spray	Broadbean (<i>Vicia faba</i>)	Photosynthesis recovery from 0.2 ppm O ₃ fumigation for 4 h	Wang et al., 1991
Fertilizer containing rare earth	3 g/L in a solvent spray	Wheat (<i>Triticum aestivum</i>)	Preventing of reduction in chlorophyll, and increase in membrane permeability due to O ₃ exposure	An and Wang, 1994
Magnetized water	Watering	Pepper (<i>Capsicum annuum</i>)	Prevention of reduction in growth due to O ₃ exposure	Wang and Huang, 1999
CaCl ₂	Seeds soaked with 3% CaCl ₂ before planting	Wheat (<i>Triticum aestivum</i>)	Preventing of reduction in chlorophyll, and increase in membrane permeability due to O ₃ exposure	Wang et al., 1993

Ethylenediurea (*N*-[2-(2-oxo-1-imidazolidinyl)ethyl]-*N'*-phenylurea), abbreviated as EDU, used as a foliar spray, soil/potting medium drench, or stem injection, is systemic and persistent in plants. It has been widely used to prevent foliar ozone injury and determine ozone effects on growth and yield of many plants (Gatta et al., 1997; Manning, 2000, 2005). Tiwari et al. (2005) used EDU with two cultivars of wheat in India and were able to demonstrate ozone effects on yields. Elagoz and Manning (2005) used EDU to assess ozone impact on snapbeans in Massachusetts. EDU is especially useful in areas where electricity and other infrastructure are limited.

5. Ozone interactions with other gases

5.1. Sulfur dioxide

In the USA, Canada and most of Europe, emissions of sulfur dioxide have been reduced by as much as 70% (Grennfelt and Munthe, 2005). In China, however, coal is used extensively and its use will increase in the future, unless emission controls are improved. The effects of combined exposure to sulfur dioxide and ozone on plants have not been investigated extensively in China. In one experiment, tobacco plants were exposed to ozone and sulfur dioxide alone and in combination for 8 h in OTCs. Synergism was found for effects on foliar injury when plants were exposed to both sulfur dioxide and ozone (Chen et al., 1996). EDU protects plants from ozone injury, but not from injury caused by sulfur dioxide. Its use in the field would allow identification of injury caused by ozone or sulfur dioxide.

6. Projecting ozone concentration and resulting crop loss

6.1. Determining ozone distribution in China

In recent years, models have been developed to estimate ozone distribution at various geographic scales (He and Huang, 1993; Chameides et al., 1999; Aunan et al., 2000; Luo et al., 2000; Wang and Mauzerall, 2004; Wu et al., 2004; Yang and Lu, 2004; Zhang et al., 2004; Zhao et al., 2004; Zheng et al., 2003). Ozone distribution for China was modeled, using MOZART-2, CTM, and updated RADM, by Wang and Mauzerall (2004) and Luo et al. (2000). Validating the models is difficult due to a lack of actual data. Wang and Mauzerall (2004)

concluded that MOZART-2 over-estimated ozone concentrations for all but one month by several to 20 ppb at the Lian site. Luo et al. (2000) concluded that their model could estimate key features of ozone distribution, but that there was a poor relationship in day-to-day variations in ozone at a given site between the model predictions and actual observations.

The highest ozone concentrations have occurred in the Yangtze Delta region where industry and population are concentrated. The SUM06 for the Yangtze Delta for the 1990 s were more than the 50 ppm h and 25 ppm h predicted by the models of Aunan et al. (2000) and Chameides et al. (1999).

6.2. Projecting ozone concentrations

Wang and Mauzerall (2004) predicted that in July 2020, surface ozone concentrations in central China will exceed 65 ppb, an increase of 15 ppb over 1990 levels. Almost all exposure indices, except the 7-h mean, will increase dramatically for winter wheat. SUM06 for soybeans will increase by 6–70 ppb. Aunan et al. (2000) predict an increase for SUM06 (June–August) from less than 10 ppm h to 30–66 ppm h by 2020.

6.3. Crop losses

Rapid economic development has resulted in high ozone concentrations in the Yangtze River Delta and other sites, such as Lian. Using a variety of methods, several crop loss scenarios have been established or projected (Table 4). Feng et al. (2003) concluded a 10% loss for wheat and 5% for rice in the Yangtze River Delta in the 1990s. Aunan et al. (2000) and Wang et al. (2004) have estimated crop loss from ozone in China at 0–23%. Increased ozone levels in the future may range from 2.3–64% (Table 4). Even though there are large uncertainties in these estimations, they indicate that ozone may significantly reduce crop yields in the future in China.

7. Conclusions

Surface level ozone concentrations that would affect crop productivity are fairly recent in China. While there is not enough monitoring or crop loss data available, several conclusions can be drawn.

Table 4
Crop loss estimated in China in 1990 and 2020

Estimator	Region	Crop loss caused by tropospheric ozone (%)							
		1990 s				2020			
		Winter wheat	Rice	Corn	Soybean	Winter wheat	Rice	Corn	Soybean
Wang and Mauzerall, 2004	China	6–13	3–5	1–9	15–23	7–63	7–10	16–64	24–64
Aunan et al., 2000	China	0–1.7	1.1–1.5	0–2.8	1.9–11.7	2.3–13.4	3.7–4.5	7.2	17.8–20.9
Feng et al., 2003	Yangtze River Delta	>10	<5						
Wang et al., 2005	Yangtze River Delta	20–30							

1. There appears to be widespread occurrence of levels of surface ozone that exceed background levels that could cause crop losses.
2. While some experiments have been conducted on ozone effects on crop loss and some modeling of ozone effects on crop losses has been done, much remains to be learned about ozone effects on crop losses. Long-term experiments with different crops and local conditions need to be done, with both open-top chambers and the protectant EDU, to develop a database for crop losses. Models that relate well to crops and conditions in China need to be developed.
3. A national program of air quality monitoring for ozone, integrated with assessment of ozone effects on crop losses, needs to be developed and implemented.

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