

Air pollution affects food security in China: taking ozone as an example

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Abstract Air pollution is becoming an increasingly important environmental concern due to its visible negative impact on human health. However, air pollution also affects agricultural crops or food security directly or indirectly, which has not so far received sufficient attention. In this overview, we take ozone (O₃) as an example to analyze the principles and extent of the impact of air pollution on food security in China based on a review of the literature. Current O₃ pollution shows a clear negative impact on food security, causing around a 10% yield decrease for major cereal crops according to a large number of field studies around the world. The mean yield decrease of winter wheat is predicted to be up to 20% in China, based on the projection of future ground-level O₃ concentration in 2020, if no pollution control measures are implemented. Strict mitigation of NO_x and VOC_s (two major precursors of O₃) emissions is crucial for reducing the negative impacts of ground-level O₃ on food security. Breeding new crop cultivars with tolerance to high ground-level O₃ should receive serious consideration in future research programs. In addition, integrated soil-crop system management will be an important option to mitigate the negative effects of elevated ground-level O₃ on cereal crop production and food quality.

Keywords air pollution, ozone damage, anthropogenic activity, crop production, mitigation of reactive N emission

1 Introduction

Air pollution has been a serious environmental concern in China since the 1980s^[1,2]. Among various atmospheric

pollutants (e.g., fine particulate matter, NO_x, SO₂ and VOC_s), ground-level ozone (O₃) has been assumed to be the most phytotoxic air pollutant due to significant damage to plants and the rising trend in the concentration at a regional scale^[3]. With the rapid industrialization and urbanization over the last two decades, O₃ concentration has risen at a much higher rate in China than in other countries and the mean daily (24 h average) O₃ concentration reaches more than 50 ppb during the crop growing season in some regions of China^[4,5]. Ground-level O₃ concentration in China coincided with the emission of NO_x because the latter is one of the most important precursors of O₃^[6–8]. Published results show that ambient O₃ concentrations with an average of 40 ppb have significantly decreased the yield of major food crops (including potato, rice, soybean and wheat) by about 10% compared with O₃-free air^[9]. A field survey around Beijing found a total of 28 species or cultivars exhibiting typical symptoms of O₃ damage^[10]. Therefore, it can be inferred that food security in China is being or has already been affected by current O₃ concentrations and this damage will continue in the future. In this manuscript, we review the current and future O₃ pollution, and its impacts on the production of food crop throughout China.

2 Current situation of ground-level O₃ pollution in China

O₃ exists in both stratosphere and troposphere. Stratospheric O₃ is commonly known as good O₃, because it absorbs ultraviolet light harmful to living things and prevents it from reaching ground. The loss of this O₃, caused by chlorofluorocarbons and other substances, induces increasing UV-B radiation—a serious global environmental problem.

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In contrast, tropospheric O_3 is known as bad O_3 due to its greenhouse effect and toxicity. In the troposphere, O_3 absorbs infrared rays emanating from the Earth and its radiative power ranks third in the atmosphere after carbon dioxide and methane^[11]. The greenhouse effect of this O_3 is more significant in the upper troposphere than in other layers. However, O_3 at ground level mainly acts as a major air pollutant and is one of the main oxidants. It is also known to cause photochemical smog, which disturbs human respiratory functions and plant photosynthesis. Ground-level O_3 is produced from the photochemical reaction of nitrogen oxides (NO_x) and volatile organic compounds (VOC_s) under sunlight (Fig. 1). The amount of O_3 generated by photochemical reaction of air pollutants is much larger than the inflow from the stratosphere. Therefore, O_3 concentrations are strongly affected by human activities.

Tropospheric O_3 has been a global air pollution problem. Currently, the O_3 concentration on a global scale has reached about 40 ppb due to a high use of fossil fuels and it has risen at a rate of 0.5%–2.0% per year since the preindustrial era^[11]. O_3 pollution is highest in Central Europe, Eastern China, and the Eastern USA in the world. In Europe, the highest O_3 levels occur in Central and Southern Europe^[3]. Nearly one quarter of the earth's surface is currently at risk from elevated O_3 concentrations in excess of 60 ppb during midsummer, with even greater concentrations occurring locally^[12]. Models have pre-

dicted that tropospheric O_3 concentration could rise by 20%–25% between 2015 and 2050, and further increase by 40%–60% by 2100, if current emission trends continue^[13].

In most parts of China, ground-level O_3 has been the main air pollutant in summer due to the high emission of NO_x from a rapid increase in the number and use of automobiles. The highest hourly O_3 concentration was observed to be 316 ppb in the North China Plain^[14]. In recent years, the summertime O_3 concentration frequently exceeded the second national standard level (i.e., hourly O_3 concentration: $200 \mu\text{g}\cdot\text{m}^{-3}$ or approximately 100 ppb) for human health issued by the Chinese Environmental Protection Agency. Due to unbalanced development in the economy and in urbanization between regions, O_3 concentrations differ among geographical locations. In the central and northern part of China, the O_3 reaches a maximum in summer. However, in southern China, the O_3 concentration is generally characterized by a peak in fall and a trough in summer^[6,7]. On the monthly-mean basis, ground-level O_3 peaks in May in the Yangtze River Delta, June in the North China Plain, and October in the Pearl River Delta^[15]. The annual mean background O_3 concentration over China shows a spatial gradient from 33.7 ppb in the South China to 23.5 ppb in the North and North-east China^[6,7].

Due to significant NO_x titration effect in cities, O_3 concentration is lower in cities than rural regions. Fig. 2 shows the diurnal O_3 concentration monitored in the city

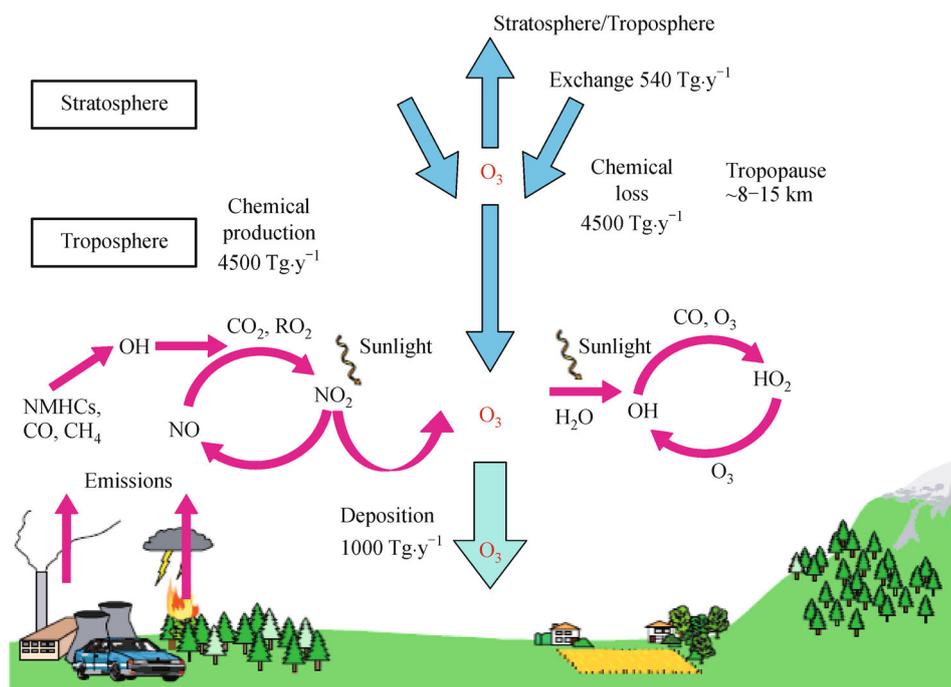


Fig. 1 A schematic view of the sources and sinks of ozone (O_3) in the troposphere^[3]. Besides O_3 deposition directly from stratosphere to troposphere, secondarily O_3 in the troposphere formed from reactions of NO_x (sum of NO and NO_2) and VOC_s (e.g., $NMHC_s$, CH_4 , CO) under sunlight is the major contributor to surface O_3 on earth.

and cropland in rural regions. The peak of O_3 concentration in rural regions appears earlier and it lasts longer from 3 to 4 p.m. to 8 p.m. in urban regions compared with rural regions. This O_3 concentration difference is quite common. Furthermore, the emission of NO_x in China will continue increasing for some decades due to the rapid rise in the use of automobiles and industrial activity^[6,7], so the concentrations of ground-level O_3 are predicted to increase in the future. Therefore, it can be inferred that the high ground-level O_3 concentration in China, particularly in rural regions, negatively affect food security given that the measured concentrations exceed the critical level of O_3 for crop production^[16].

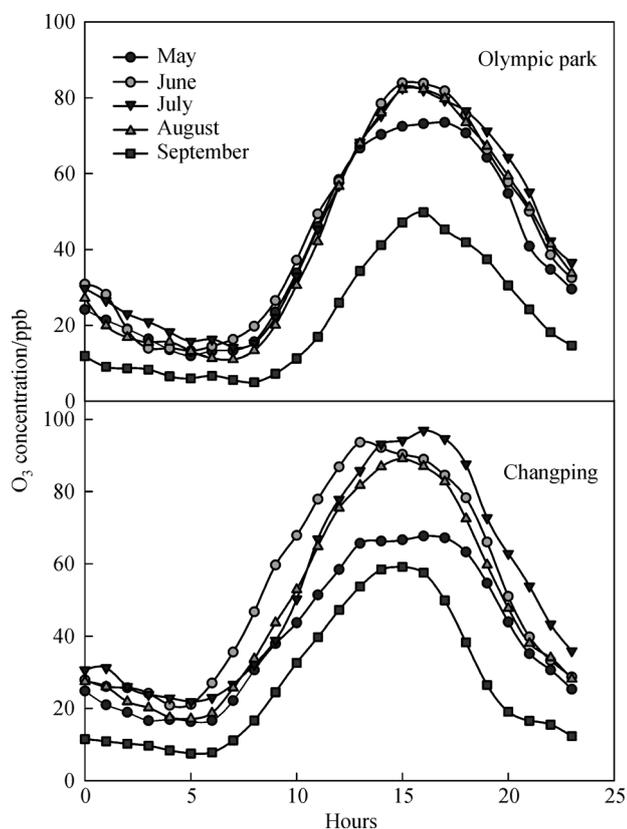


Fig. 2 The diurnal change of ground-level O_3 concentration in the ambient air monitored in the city (Olympic park, city center of Beijing) and over cropland (Changping, rural region of Beijing). Highest O_3 concentration was recorded from 1 to 5 p.m., while lowest O_3 concentration occurred in the early morning (5 to 6 a.m.) at both locations.

3 Effect of air pollution by O_3 on food security in China

3.1 Mechanisms of ground-level O_3 pollution affecting crop production and food security

The phytotoxicity of O_3 to plants derives primarily from its oxidative damage to the plasma membranes^[17]. Heath

et al.^[18] reviewed the interaction of O_3 and plant tissues, and proposed three distinct processes: external O_3 concentration, uptake, and detoxification. It is well known that O_3 penetrates plant leaves through open stomata and dissolves into the apoplastic fluid, suggesting that plants with large stomatal conductance would allow a higher O_3 uptake, and thus experience more damage^[19–21]. Following its entry into leaves through open stomata, O_3 is dissolved in the liquid phase of the apoplastic space surrounding the substomatal cavity^[22,23], and produces a series of reactive oxygen species including hydroxyl radical, singlet oxygen and hydrogen peroxide, which could cause severe damage to cellular components such as membranes and chloroplasts^[24–26]. High O_3 concentration also reduces the central biochemical processes controlling photosynthesis, such as the maximum carboxylation efficiency, and the maximum rate of ribulose biphosphate regeneration^[27,28], thus decreasing the light and dark reactions of photosynthesis, causing a range of adverse effects on plants including reduced photosynthetic activity, altered carbon allocation, diminished biomass accumulation, reduced yield and accelerated senescence, with or without visible injury^[28–30]. Ground-level O_3 pollution negatively affects grain yield and quality of food crops mainly due to its oxidative damage during the growth period in particular the grain filling stage.

3.2 Effect of O_3 pollution on cereal crop production and food quality

Experiments in Europe, Japan and the United States indicate that yield losses of agricultural crops may occur even under current O_3 concentrations. Surrounding Beijing, 28 plant species/cultivars including amenity trees, natural forest species and crops (e.g., peanut and snap bean) were found with typical O_3 symptoms during a recent O_3 injury survey^[10]. On the basis of open-top chamber results, a meta-analysis showed that the yield of cereal crops including rice, soybean and wheat was reduced by about 8% when ambient O_3 concentration reach 40 ppb^[9]. This suggests that food production in China will be partly reduced by the current O_3 concentrations. There have been some field studies to investigate the impact of elevated O_3 on the food crops (winter wheat, rice and oilseed rape) and details can be found in a review by Feng et al.^[6].

In an open top chamber experiment lasting 5 years, wheat yields decreased by 8.5%–58.0% and 40%–73% and rice yields by 10%–34% and 16%–43% as compared with charcoal filtered air for O_3 -1 (75 or 100 ppb) and O_3 -2 (150 or 200 ppb) treatments^[31], respectively. While at the Jiangdu site, a mean of 25% enhancement above the ambient O_3 concentration (A- O_3 , 45.7 ppb) reduced grain yield in winter wheat by 20% with significant variation in the range from 10% to 35% among the various combinations of cultivar and season^[30]. In rice, elevated O_3 also

reduced the grain yield by 12% on average across four cultivars. However, there were large differences in the extent of these yield losses^[32]. These reduced yields caused by O₃ pollution were similar to a recent report by Rai and Agrawal^[33], who summarized the impact of tropospheric O₃ on crop plants worldwide. However, the quantitative assessment of ambient O₃ effects on food crop yield is rare in China. It is necessary to launch large joint programs to assess the current O₃ effects on food crop production and develop a critical O₃ standard to protect crops against O₃.

Due to the limited number of O₃ impact studies in China and large regional differences in climate, cultivars and management, there are many uncertainties to assess when studying the O₃ effects on food crops in China. So far, there have been only three studies estimating the yield loss of food crops at current and projected O₃ concentrations on a national scale, and there were large differences in O₃ dose responses, even within each study^[6,7]. Of these, only the study by Tang et al.^[4] is based on the one dose–response relationship from the field experiment of four local cultivars in subtropical regions of China. Their results indicated that the ground-level O₃ concentration in 2000 caused an estimated yield loss in wheat of 6.4%–15.0% throughout China. Projected to 2020, the O₃ is estimated to induce yield loss of winter wheat in China of 15%–23%^[4], which is much higher than the results from Aunan et al.^[34] and Wang and Mauzerall^[35].

On the basis of research conducted in open-top chambers and O₃-free air concentration enrichment, a recent meta-analysis on grain quality of wheat in response to O₃ showed that O₃ significantly decreased starch concentration. O₃ increased grain protein content and the concentration of several nutritionally important minerals (P, K, Ca, Mg, Cu, Zn, and Mn), but reduced yield^[29,36]. Some baking properties (Zeleny value and Hagberg falling number) were positively influenced by ground-level O₃^[36].

It is projected that NO_x, VOC_s and O₃ concentrations will continue to rise in China in the future. It can be inferred that crops will be exposed to higher levels of O₃ stress, and economic losses will affect not only China but also the neighboring countries (e.g., Japan, Korea, Europe, USA) through long-range transport of both NO_x and O₃.

4 Policy recommendations to tackle negative effects of ground-level O₃ pollution on food security

4.1 Reducing ground-level O₃ concentration by mitigating anthropogenic NO_x and VOC_s emissions

In Europe and North America, air quality and ground-level O₃ concentration has decreased substantially with strict air pollution control measures implemented since the 1990s^[37]. Most of the ground-level O₃ was produced

from the photochemical reaction of NO_x and VOC_s under sunlight. Therefore, the most effective measure to reduce O₃ concentration is to mitigate the emissions of O₃ precursors such as NO_x and VOC_s, which are mainly from automotive exhaust. Three national actions by policy makers will be implemented in order to achieve the goal of lower ground-level O₃ pollution. The first action is to use the Euro standard V for automotive exhaust, which will be enforced throughout China by 2020. The second is to use electric vehicles widely, which has been encouraged by the central and local governments through different preferential policies, such as refunds and tax exemptions. The third is to reduce the total number of automobiles (especially private cars) on road by further developing public transportation in major and populous cities, increasing parking charges and taxation of cars entering city centers.

4.2 Breeding crop cultivars tolerant to ground-level O₃ pollution

Due to the fact that plant species and cultivars vary greatly in tolerance^[20,27,38,39], breeding O₃-tolerant genotypes is a further good method to reduce yield loss. Some genes conferring O₃ tolerance have been found in rice and soybean^[40–42] and O₃ tolerance genes could be added to other crops using modern molecular biology techniques. There is a strong need for new crop breeding programs to include breeding crop cultivars tolerant to air pollution. This is especially urgent for O₃ tolerant breeding as ground-level O₃ concentrations are rapidly increasing in developing nations like China and India.

4.3 Integrated soil-crop system management for reducing ground-level O₃ pollution impacts

Besides air pollution control measures and adoption of O₃ tolerant crop cultivars, integrated soil-crop system management^[43,44] is another important option to improve food security and nutrient resource use efficiency even with air pollution such as elevated O₃. The integrated soil-crop system management will promote a healthy crop canopy formation and match crop nutrient requirement by supplying nutrients in both space and time (Fig. 3). Therefore the soil-crop system management measures (including optimized plant density, crop residue retention, and real-time N management) will help to build a good buffering system for crops even under O₃ pollution. Although no field studies have systematically evaluated the impact of integrated soil-crop system management on crop yield, we believe at least half of the yield loss can be avoided by such integrated measures. For example, Hewitta et al.^[45] observed that N management, as part of soil-crop system management, is essential to prevent tropical oil palm plantations from ground-level O₃ pollution. Future studies of the effects of ground-level O₃

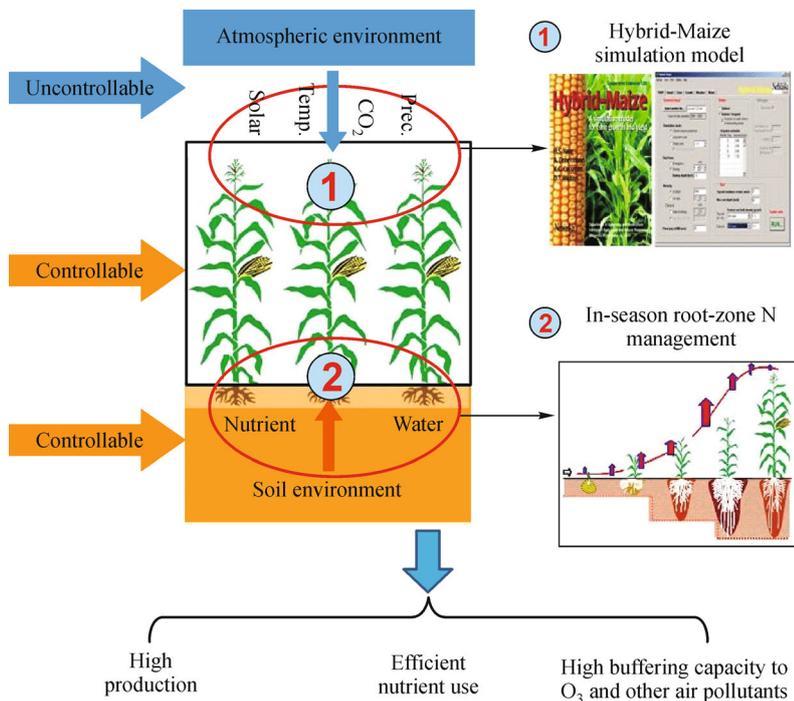


Fig. 3 Diagram of integrated soil-crop system management for high yield, high efficiency and high buffering capacity to air pollution by O_3 (taking maize as an example, modified from Chen et al.^[43]). Part 1 refers to optimized crop canopy and part 2 refers to soil nutrient (e.g., N) management in time and space.

pollution should evaluate the effectiveness of integrated soil-crop system management on the production and grain quality of food crops.

5 Conclusions

With continuing increases in emissions of O_3 precursors such as NO_x and VOCs in China with its rapid economic growth, air pollution, especially ground-level O_3 will increase drastically over the coming decades. There is a lack of systematic studies on air pollution effects on crop production and food security in China. Based on a limited literature search, we have selected O_3 pollution as an example to demonstrate the principles and extents of air pollution impact on food security in China. Current O_3 pollution can cause 6.4%–15.0% yield loss for major cereal crops according to a number of O_3 -free air concentration enrichment studies. The mean yield loss of cereal crops could reach more than 20% according to the ground-level O_3 concentrations projected for 2020. To avoid yield damage by O_3 pollution, three strategies need to be seriously considered for the future. The first strategy is strict mitigation of NO_x and VOCs emissions to reduce the ground-level O_3 concentration and its negative impact on food security. The second strategy is to breed and adopt new crop cultivars tolerant to high ground-level O_3

concentrations. The third strategy is to adopt integrated soil-crop system management, which will improve food security via increasing the buffering capacity of the soil-crop ecosystems to various air pollutants including O_3 .

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Compliance with ethics guidelines Zhaozhong Feng, Xuejun Liu, and Fusuo Zhang declare that they have no conflict of interest or financial conflicts to disclose.

This article does not contain any studies with human or animal subjects performed by any of the authors.

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