Front. Agr. Sci. Eng. 2015, **2**(2): 152–158
DOI: 10.15302/J-FASE-2015067

REVIEW

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

Zhaozhong FENG[1], Xuejun LIU (✉)[2], Fusuo ZHANG[2]

1 State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
2 College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China

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 (O_3) 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 O_3 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 O_3 concentration in 2020, if no pollution control measures are implemented. Strict mitigation of NO_x and VOC_s (two major precursors of O_3) emissions is crucial for reducing the negative impacts of ground-level O_3 on food security. Breeding new crop cultivars with tolerance to high ground-level O_3 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 O_3 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, SO_2 and VOC_s), ground-level ozone (O_3) 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, O_3 concentration has risen at a much higher rate in China than in other countries and the mean daily (24 h average) O_3 concentration reaches more than 50 ppb during the crop growing season in some regions of China[4,5]. Ground-level O_3 concentration in China coincided with the emission of NO_x because the latter is one of the most important precursors of O_3[6–8]. Published results show that ambient O_3 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 O_3-free air[9]. A field survey around Beijing found a total of 28 species or cultivars exhibiting typical symptoms of O_3 damage[10]. Therefore, it can be inferred that food security in China is being or has already been affected by current O_3 concentrations and this damage will continue in the future. In this manuscript, we review the current and future O_3 pollution, and its impacts on the production of food crop throughout China.

2 Current situation of ground-level O_3 pollution in China

O_3 exists in both stratosphere and troposphere. Stratospheric O_3 is commonly known as good O_3, because it absorbs ultraviolet light harmful to living things and prevents it from reaching ground. The loss of this O_3, caused by chlorofluorocarbons and other substances, induces increasing UV-B radiation — a serious global environmental problem.

Received July 9, 2015; accepted August 12, 2015

Correspondence: liu310@cau.edu.cn

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 predicted 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 $\mu g \cdot m^{-3}$ 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

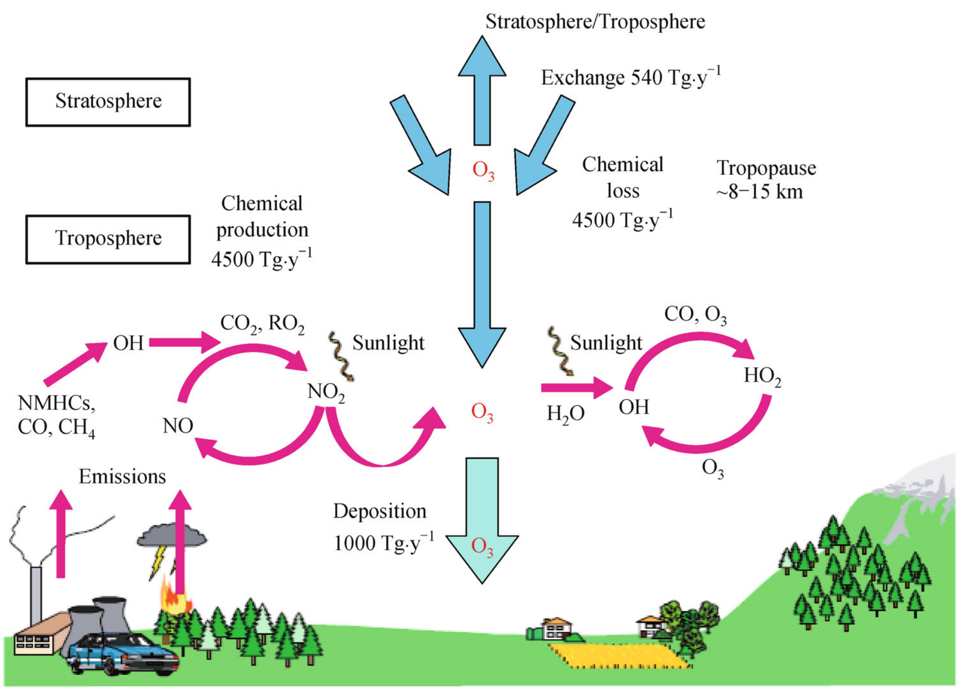

Fig. 1 A schematic view of the sources and sinks of ozone (O_3) in the troposphere[3]. Besides O_3 deposition directly from stratosphere to troposphere, secondarily O_3 in the troposphere formed from reactions of NO_x (sum of NO and NO_2) and VOC_s (e.g., $NMHC_s$, CH_4, CO) under sunlight is the major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

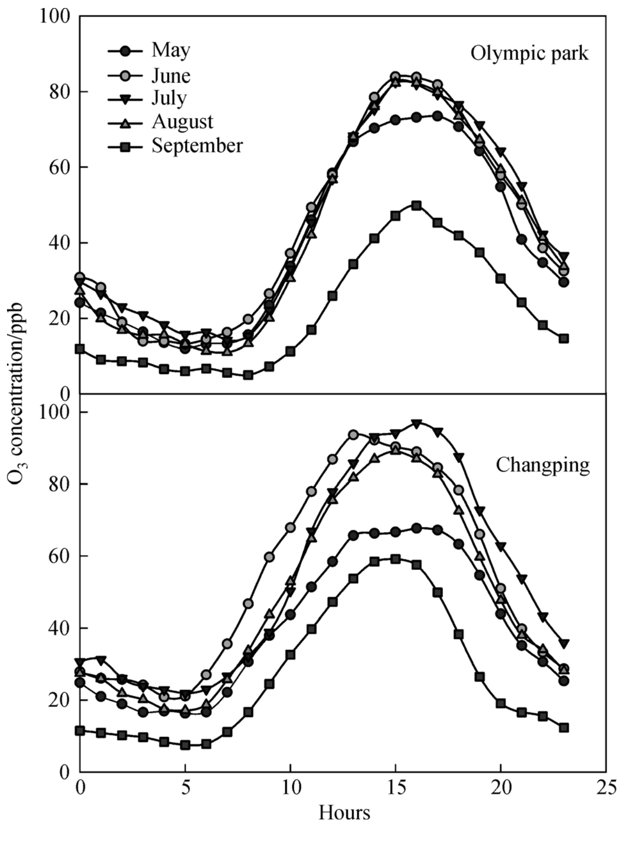

Fig. 2 The diurnal change of ground-level O_3 concentration in the ambient air monitored in the city (Olympic park, city center of Beijing) and over cropland (Changping, rural region of Beijing). Highest O_3 concentration was recorded from 1 to 5 p.m., while lowest O_3 concentration occurred in the early 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 bisphosphate 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 O_3 pollution were similar to a recent report by Rai and Agrawal[33], who summarized the impact of tropospheric O_3 on crop plants worldwide. However, the quantitative assessment of ambient O_3 effects on food crop yield is rare in China. It is necessary to launch large joint programs to assess the current O_3 effects on food crop production and develop a critical O_3 standard to protect crops against O_3.

Due to the limited number of O_3 impact studies in China and large regional differences in climate, cultivars and management, there are many uncertainties to assess when studying the O_3 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 O_3 concentrations on a national scale, and there were large differences in O_3 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 O_3 concentration in 2000 caused an estimated yield loss in wheat of 6.4%–15.0% throughout China. Projected to 2020, the O_3 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 O_3-free air concentration enrichment, a recent meta-analysis on grain quality of wheat in response to O_3 showed that O_3 significantly decreased starch concentration. O_3 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 O_3[36].

It is projected that NO_x, VOC_s and O_3 concentrations will continue to rise in China in the future. It can be inferred that crops will be exposed to higher levels of O_3 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 O_3.

4 Policy recommendations to tackle negative effects of ground-level O_3 pollution on food security

4.1 Reducing ground-level O_3 concentration by mitigating anthropogenic NO_x and VOC_s emissions

In Europe and North America, air quality and ground-level O_3 concentration has decreased substantially with strict air pollution control measures implemented since the 1990s[37]. Most of the ground-level O_3 was produced from the photochemical reaction of NO_x and VOC_s under sunlight. Therefore, the most effective measure to reduce O_3 concentration is to mitigate the emissions of O_3 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 O_3 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 O_3 pollution

Due to the fact that plant species and cultivars vary greatly in tolerance[20,27,38,39], breeding O_3-tolerant genotypes is a further good method to reduce yield loss. Some genes conferring O_3 tolerance have been found in rice and soybean[40–42] and O_3 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 O_3 tolerant breeding as ground-level O_3 concentrations are rapidly increasing in developing nations like China and India.

4.3 Integrated soil-crop system management for reducing ground-level O_3 pollution impacts

Besides air pollution control measures and adoption of O_3 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 O_3. 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 O_3 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 O_3 pollution. Future studies of the effects of ground-level O_3

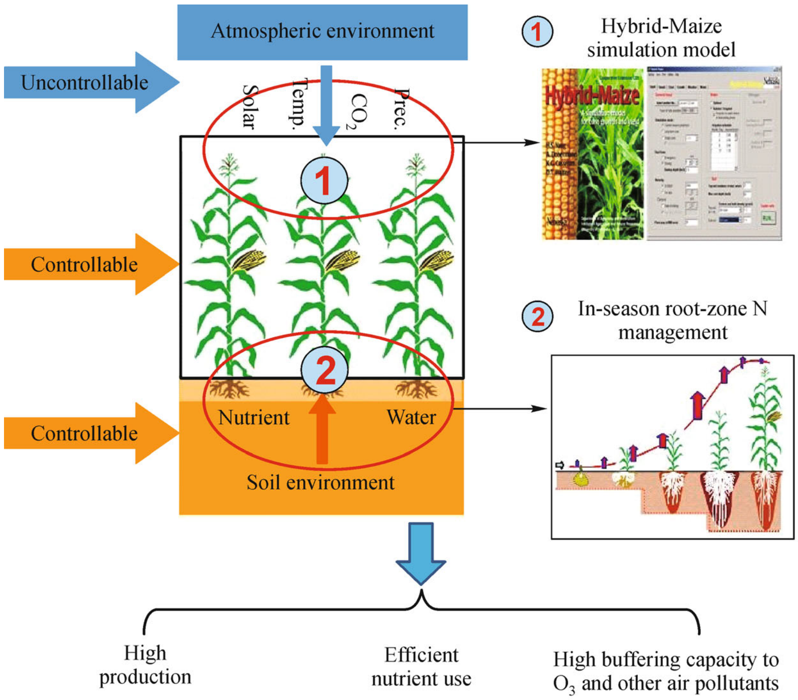

Fig. 3 Diagram of integrated soil-crop system management for high yield, high efficiency and high buffering capacity to air pollution by O_3 (taking maize as an example, modified from Chen et al.[43]). Part 1 refers to optimized crop canopy and part 2 refers to soil nutrient (e.g., N) management in time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

Acknowledgements This work was financially supported by the China National Funds for Distinguished Young Scientists (40425007), the Hundred Talents Program of Chinese Academy of Sciences (CAS), and State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, CAS.

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.

References

1. Chan C K, Yao X H. Air pollution in mega cities in China. *Atmospheric Environment*, 2008, **42**(1): 1–42
2. Zhao D W, Sun B Z. Air pollution and acid rain in China. *Ambio*, 1986, **15**: 2–5
3. The Royal Society. Ground-level ozone in the 21st century: future trends, impacts and policy implications. *The Royal Society*, 2008, Science Policy Report **15/08**: 1–132
4. Tang H, Takigawa M, Liu G, Zhu J, Kobayashi K. A projection of ozone-induced wheat production loss in China and India for the years 2000 and 2020 with exposure-based and flux-based

approaches. *Global Change Biology*, 2013, **19**(9): 2739–2752
5. Zhao C, Wang Y, Zeng T. East China plains: a “basin” of ozone pollution. *Environmental Science & Technology*, 2009, **43**(6): 1911–1915
6. Feng Z, Hu E, Wang X, Jiang L, Liu X. Ground-level O_3 pollution and its impacts on food crops in China: a review. *Environmental Pollution*, 2015, **199**: 42–48
7. Feng Z, Paoletti E, Bytnerowicz A, Harmons H. Ozone and Plants. *Environmental Pollution*, 2015, **202**: 215–216
8. Liu X, Duan L, Mo J, Du E, Shen J, Lu X, Zhang Y, Zhou X, He C, Zhang F. Nitrogen deposition and its ecological impact in China: an overview. *Environmental Pollution*, 2011, **159**(10): 2251–2264
9. Feng Z, Kobayashi K. Assessing the impacts of current and future concentrations of surface ozone on crop yield with meta-analysis. *Atmospheric Environment*, 2009, **43**(8): 1510–1519
10. Feng Z, Sun J, Wan W, Hu E, Calatayud V. Evidence of widespread ozone-induced visible injury on plants in Beijing, China. *China Environmental Pollution.*, 2014, **193**: 296–301
11. Intergovernmental Panel on Climate Change. Summary for Policymakers. In: Stocker T F, Qin D, Plattner G K, Tignor M, Allen S K, Boschung J, Nauels A, Xia Y, Bex V Midgley P M, eds. Climate change 2013: the physical science basis. Cambridge: *Cambridge University Press*, 2013
12. Fowler D, Cape J N, Coyle M, Smith R I, Hjellbrekke A G, Simpson D, Derwent R G, Johnson C E. Modelling photochemical oxidant formation, transport, deposition and exposure of terrestrial ecosystems. *Environmental Pollution*, 1999, **100**(1–3): 43–55
13. Meehl G A, Stocker T F, Collins W D, Friedlingstein P, Gaye A T, Gregory J M, Kitoh A, Knutti R, Murphy J M, Noda A, Raper S C B, Watterson I G, Weaver A J, Zhao Z C. Global climate projections, In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K B, Tignor M, Miller H L, eds. Climate change 2007: the physical science basis. Cambridge: *Cambridge University Press*, 2007
14. Yin Y Q, Li C M, Ma G X, Cui Z J. Ozone concentration distribution of urban. *Environmental Sciences*, 2004, **25**(6): 16–20
15. Wang Y, Zhang Y, Hao J, Luo M. Seasonal and spatial variability of surface ozone over China: contributions from background and domestic pollution. *Atmospheric Chemistry and Physics*, 2011, **11**(7): 3511–3525
16. Convention L R T A P. Mapping critical levels for vegetation, manual on methodologies and criteria for modeling and mapping critical loads & levels and air pollution effects, risk and trends. Available at ICP Vegetation Website on September 28, 2014
17. Schraudner M, Langebartels C, Sandermann H. Changes in the biochemical status of plant cells induced by the environmental pollutant ozone. *Physiologia Plantarum*, 1997, **100**(2): 274–280
18. Heath R L, Lefohn A S, Musselman R C. Temporal processes that contribute to nonlinearity in vegetation responses to ozone exposure and dose. *Atmospheric Environment*, 2009, **43**(18): 2919–2928
19. Pleijel H, Eriksen A B, Danielsson H, Bondesson N, Sellden G. Differential ozone sensitivity in an old and a modern Swedish wheat cultivar—grain yield and quality, leaf chlorophyll and stomatal conductance. *Environmental and Experimental Botany*, 2006, **56**(1): 63–71
20. Biswas D K, Xu H, Li Y G, Sun J Z, Wang X Z, Han X G, Jiang G M. Genotypic differences in leaf biochemical, physiological and growth responses to ozone in 20 winter wheat cultivars released over the past 60 years. *Global Change Biology*, 2008, **14**: 46–59
21. Feng Z, Tang H, Uddling J, Pleijel H, Kobayashi K, Zhu J, Oue H, Guo W. A stomatal ozone flux-response relationship to assess ozone-induced yield loss of winter wheat in subtropical China. *Environmental Pollution*, 2012, **164**: 16–23
22. Fiscus E L, Booker F L, Burkey K O. Crop responses to ozone: uptake, modes of action, carbon assimilation and partitioning. *Plant, Cell & Environment*, 2005, **28**(8): 997–1011
23. Laisk A, Kull O, Moldau H. Ozone concentration in leaf intercellular air spaces is close to zero. *Plant Physiology*, 1989, **90**(3): 1163–1167
24. Langebartels C, Wohlgemuth H, Kschieschan S, Grun S, Sandermann H. Oxidative burst and cell death in ozone-exposed plants. *Plant Physiology and Biochemistry*, 2002, **40**(6–8): 567–575
25. Turcsányi E, Lyons T, Plöchl M, Barnes J. Does ascorbate in the mesophyll cell walls form the first line of defence against ozone? Testing the concept using broad bean (*Vicia faba* L.). *Journal of Experimental Botany*, 2000, **51**(346): 901–910
26. Wang J, Zeng Q, Zhu J, Chen C, Liu G, Tang H. Apoplastic antioxidant enzyme responses to chronic free-air ozone exposure in two different ozone-sensitive wheat cultivars. *Plant Physiology and Biochemistry*, 2014, **82**: 183–193
27. Feng Z, Pang J, Kobayashi K, Zhu J, Ort D R. Differential responses in two varieties of winter wheat to elevated ozone concentration under fully open-air field conditions. *Global Change Biology*, 2011, **17**(1): 580–591
28. Zhang W, Wang G, Liu X, Feng Z. Effects of elevated O_3 exposure on seed yield, N concentration and photosynthesis of nine soybean cultivars (*Glycine max* (L.) Merr.) in Northeast China. *Plant Science*, 2014, **226**: 172–181
29. Feng Z, Kobayashi K, Ainsworth E A. Impact of elevated ozone concentration on growth, physiology and yield of wheat (*Triticum aestivum* L.): a meta-analysis. *Global Change Biology*, 2008, **14**: 2696–2708
30. Zhu X, Feng Z, Sun T, Liu X, Tang H, Zhu J, Guo W, Kobayashi K. Effects of elevated ozone concentration on yield of four Chinese cultivars of winter wheat under fully open-air field conditions. *Global Change Biology*, 2011, **17**(8): 2697–2706
31. Wang X, Zhang Q, Zheng F, Zheng Q, Yao F, Chen Z, Zhang W, Hou P, Feng Z, Song W, Feng Z, Lu F. Effects of elevated O_3 concentration on winter wheat and rice yields in the Yangtze River Delta, China. *Environmental Pollution*, 2012, **171**: 118–125
32. Shi G, Yang L, Wang Y, Kobayashi K, Zhu J, Tang H, Pan S, Chen T, Liu G, Wang Y. Impact of elevated ozone concentration on yield of four Chinese rice cultivars under fully open-air field conditions. *Agriculture, Ecosystems & Environment*, 2009, **131**(3–4): 178–184
33. Rai R, Agrawal M. Impact of tropospheric ozone on crop plants. *Proceedings of the National Academy of Sciences of the United States of America*, 2012, **82**: 241–257
34. Aunan K, Berntsen T K, Seip H M. Surface ozone in China and its possible impact on agricultural crop yields. *Ambio*, 2000, **29**(6): 294–301
35. Wang X, Mauzerall D L. Characterizing distributions of surface

ozone and its impact on grain production in China, Japan and South Korea: 1990 and 2020. *Atmospheric Environment*, 2004, **38**(26): 4383–4402

36. Broberg M C, Feng Z, Xin Y, Pleijel H. Ozone effects on wheat grain quality—a summary. *Environmental Pollution*, 2015, **197**: 203–213
37. Sutton M A, Bleeker A., Howard C M, Bekunda M, Grizzetti B, de Vries W, van Grinsven H J M, Abrol Y P, Adhya T K, Billen G, Davidson E A, Datta A, Diaz R, Erisman J W, Liu X J, Oenema O, Palm C, Raghuram N, Reis S, Scholz R W, Sims T, Westhoek H, Zhang F S. Our nutrient world: the challenge to produce more food and energy with less pollution. Edinburgh: *NERC/Centre for Ecology & Hydrology*, 2013
38. Flowers M D, Fiscus E L, Burkey K O, Booker F L, Dubois J J B. Photosynthesis, chlorophyll fluorescence, and yield of snap bean (*Phaseolus vulgaris* L.) genotypes differing in sensitivity to ozone. *Environmental and Experimental Botany*, 2007, **61**(2): 190–198
39. Zhang W, Feng Z, Wang X, Niu J. Responses of native broadleaved woody species to elevated ozone in subtropical China. *Environmental Pollution*, 2012, **163**: 149–157
40. Frei M, Tanaka J P, Chen C P, Wissuwa M. Mechanisms of ozone tolerance in rice: characterization of two QTLs affecting leaf bronzing by gene expression profiling and biochemical analyses. *Journal of Experimental Botany*, 2010, **61**(5): 1405–1417
41. Frei M. Breeding of ozone resistant rice: relevance, approaches and challenges. *Environmental Pollution*, 2015, **197**: 144–155
42. Gillespie K M, Rogers A, Ainsworth E A. Growth at elevated ozone or elevated carbon dioxide concentration alters antioxidant capacity and response to acute oxidative stress in soybean (*Glycine max*). *Journal of Experimental Botany*, 2011, **62**(8): 2667–2678
43. Chen X P, Cui Z L, Vitousek P M, Cassman K G, Matson P A, Bai J S, Meng Q F, Hou P, Yue S C, Römheld V, Zhang F S. Integrated soil-crop system management for food security. *Proceedings of the National Academy of Sciences of the United States of America*, 2011, **108**(16): 6399–6404
44. Chen X, Cui Z, Fan M, Vitousek P, Zhao M, Ma W, Wang Z, Zhang W, Yan X, Yang J, Deng X, Gao Q, Zhang Q, Guo S, Ren J, Li S, Ye Y, Wang Z, Huang J, Tang Q, Sun Y, Peng X, Zhang J, He M, Zhu Y, Xue J, Wang G, Wu L, An N, Wu L, Ma L, Zhang W, Zhang F. Producing more grain with lower environmental costs. *Nature*, 2014, **514**(7523): 486–489
45. Hewitt C N, MacKenzie A R, Di Carlo P, Di Marco C F, Dorsey J R, Evans M, Fowler D, Gallagher M W, Hopkins J R, Jones C E, Langford B, Lee J D, Lewis A C, Lim S F, McQuaid J, Misztal P, Moller S J, Monks P S, Nemitz E, Oram D E, Owen S M, Phillips G J, Pugh T A M, Pyle J A, Reeves C E, Ryder J, Siong J, Skiba U, Stewart D J. Nitrogen management is essential to prevent tropical oil palm plantations from causing ground-level ozone pollution. *Proceedings of the National Academy of Sciences of the United States of America*, 2009, **106**(44): 18447–18451