Growth Responses of Wheat (Triticum aestivum L. var. HD 2329) Exposed to Ambient Air Pollution under Varying Fertility Regimes

Anoop Singh, S.B. Agrawal*, and Dheeraj Rathore

*Assistant Professor and Principal Investigator, Lab of Air Pollution and Global Climatic Change, Department of Botany, Allahabad Agricultural Institute- Deemed University, Allahabad- 211 007, India

E-mail: madhoo@bhu.ac.in / sbagrawal@sify.com

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The problem of urban air pollution has attracted special attention in India due to a tremendous increase in the urban population; motor vehicles vis a vis the extent of energy utilization. Field studies were conducted on wheat crops (Triticum aestivum L. var. HD 2329) by keeping the pot-grown plants in similar edaphic conditions at nine different sites in Allahabad City to quantify the effects of ambient air pollution levels on selected growth and yield parameters. Air quality monitoring was done at all the sites for gaseous pollutants viz. SO₂, NO₂, and O₃. Various growth parameters (plant height, biomass, leaf area, NPP, etc.) showed adverse effects at sites receiving higher pollution load. Reduction in test weight and harvest index was found to be directly correlated with the levels of pollutant concentrations. The study clearly showed the negative impact of air pollution on periurban agriculture.

KEYWORDS: air pollution, fertility level, plant growth, total biomass, yield, Triticum aestivum

DOMAINS: ecosystem and communities, risk and impact assessment, plant ecology, terrestrial environmental toxicology

INTRODUCTION

Rapid industrialization, especially in urban areas of India, is affecting the air quality[1]. Cities in developing countries tend to have high vehicle densities and therefore are likely to experience a high contribution from motor vehicles to the total urban pollution load. In developing countries, vehicle fleets tend to be older and poorly maintained, a factor that increases the significance of motor vehicles as a pollutant source[2]. Another cause of air pollution is emissions from various heavy and medium industries in and around cities, which produce deleterious effects on human health, economic plants, and general vegetation. The data from urban cities in India, using a range
of different analytical methods, have demonstrated a 7-h mean O₃ concentration in summer months, which exceeds 40 ppb and in some cases approaches 60 ppb[3].

Crop production is highly dependent on environmental conditions, among which air quality plays a major role. Urban air pollution has a direct impact on periurban agriculture due to dispersion of emissions in all directions along the wind. During transportation, primary pollutants often form secondary pollutants causing greater adverse effects in periurban areas. Air pollutants (O₃, SO₂, etc.) in ambient air have long been known to be phytotoxic[4,5] and cause the greatest amount of any gaseous pollutants by reducing growth and productivity of many plant species through reduction in photosynthesis, accelerated leaf senescence, and decreased root growth[6,7].

The nature and extent of impact of a mixture of pollutants on vegetation may not be the same as that of a single pollutant. The response depends on the type of species, nature and intensity of the pollutant, duration of exposure, and interaction with other environmental factors[8,9]. Ayer and Bedi[10] recorded highest degradation in growth performance, biochemical parameters, and yield of wheat in the most polluted zone of Baroda City. Wahid et al.[11] have demonstrated a grain yield reduction of 46 and 38% for two cultivars of wheat in an open top chamber study in the vicinity of Lahore (Pakistan) using ambient and charcoal filtered air, respectively.

Mineral nutrient supply may increase pollutant injury to crops[12], but some studies have indicated that plants grown at low nutrient supply are more sensitive to air pollutant injury[13,14,15]. Ormrod and Adedipe[16] have suggested that mineral nutrients may modify the responses of plants to air pollutants and responses vary with the specific element and species under consideration.

While the impact of air pollutants on agriculture in developed countries has received considerable attention, there has been little recognition of its potential impacts in developing countries, including India. Emissions of major air pollutants are growing rapidly in different parts of the country, with industrialization, urbanization, and the growth of transport, while the high temperature and high solar radiation are proving favorable for production of high concentrations of O₃.

In view of the above, the present study was undertaken to assess the impact of air pollution on growth and yield of wheat (Triticum aestivum L. var. HD 2329) in periurban areas of Allahabad City.

MATERIALS AND METHODS

The study was performed in the periurban and rural environment of Allahabad City, Eastern Gangetic plains of India at 24° 47' N latitude, 81° 19' and 82° 21' E longitudes, and 315’ above mean sea level. The climate of Allahabad City is tropical monsoonic with three distinct seasons, i.e., summer, rainy, and winter. Annual average temperature is 24°C, RH 65%, and 959 mm annual precipitation. The traffic on highways is dominated by heavy commercial vehicles, while in other areas there is multiplicity of vehicles along with nonmotorized vehicles. In many places, there is a disruption in the free flow of traffic due to narrow and poorly maintained roads, so increasing the emission of pollutants. The plant species Triticum aestivum L. chosen for this study is a staple food for India.

Wheat (Triticum aestivum L. var. HD 2329) plants were grown from germination to maturity in pots having similar edaphic conditions at nine different sites viz. Allahabad Agricultural Institute (AAI), Arail (Ar), Sadowkala (Sd), Bahrana (Bh), Jhunsi (Jh), Prayag (Pr), Mehdeori (Mh), Civil lines (CL), and Rajrooppur (RRP) around and within the city, under seven treatments of fertilizers (i.e., without fertilizer [F₀]; recommended dose of N, P, and K [F₁]; one and half times of recommended dose of N, P, and K [F₂]; two times of recommended dose of N, P, and K [F₃]; recommended dose of N and P [F₄]; recommended dose of P and K [F₅]; and recommended dose of N and K [F₆]). Nitrogen, phosphorous, and potassium were given in the form of urea,
single super phosphate, and murate of potash, respectively. A half dose of nitrogen and full dose of phosphorous and potassium was given as basal dressing and another half as top dressing. Pots were placed in an unshaded area and received uniform light as measured by a light intensity meter. Plants were watered twice a week and received 500 ml pot\(^{-1}\) deionized water in each watering. For analysis, triplicate random samples of plants from each treatment of each site were taken. For total biomass determination, plants were oven dried at 80°C until the constant weight was obtained and values were expressed as g plant\(^{-1}\).

Portable gas samplers performed air quality monitoring weekly, for 6 h daily (10 AM to 4 PM) for SO\(_2\), NO\(_2\), and O\(_3\) using wet chemical methods. SO\(_2\), NO\(_2\), and O\(_3\) were scrubbed separately in tetra chloromurcurate, NaOH (0.1N) and buffered KI (0.1N), respectively. These absorbing solutions were later analyzed colorimetrically for SO\(_2\)[17], NO\(_2\)[18], and O\(_3\)[19] pollutants. No continuous advanced gas monitors are available in Allahabad and this wet chemical sampling regime was the maximum possible with the resources available. Monitoring of pollutants for more than 6 h is also not possible due to the safety of samplers during the night \textit{via} vs. failure/availability of electricity at various sites as samplers have battery backup of only 6 h.

**RESULTS**

Results of air monitoring are shown in Table 1, which clearly indicated that RRP was the most polluted site among all the selected experimental sites and Sd was least polluted. The concentrations of SO\(_2\), NO\(_2\), and O\(_3\) were recorded in the range between 30.83 to 42.50, 38.13 to 65.04, and 17.0 to 30.83 \(\mu\)g m\(^{-3}\), respectively at RRP, and at Sd (reference site) these gases were found in the range between 2.5 to 10.0, 10.23 to 14.55, and 5.5 to 12.92 \(\mu\)g m\(^{-3}\), respectively.

**TABLE 1**

Concentrations of SO\(_2\), NO\(_2\) and O\(_3\) (\(\mu\)g m\(^{-3}\) air) at Different Sites During Experiment

| Experimental Sites | SO\(_2\) | NO\(_2\) | O\(_3\) |
|--------------------|---------|---------|--------|
|                    | Min.    | Max.    | Min.   | Max.   | Min.   | Max.   |
| RRP                | 30.83   | 42.5    | 38.13  | 65.04  | 17.0   | 30.83  |
| Ar                 | 2.5     | 12.5    | 10.16  | 18.29  | 3.33   | 13.33  |
| AAl                | 15.83   | 30.0    | 14.23  | 36.26  | 10.66  | 28.33  |
| Sd                 | 2.5     | 10.0    | 10.23  | 14.55  | 5.5    | 12.92  |
| CL                 | 10.0    | 17.5    | 14.23  | 24.22  | 10.0   | 25.0   |
| Jh                 | 2.5     | 22.5    | 10.13  | 22.36  | 8.33   | 17.66  |
| Mh                 | 2.5     | 17.5    | 14.23  | 18.13  | 7.08   | 24.17  |
| Pr                 | 12.5    | 17.5    | 15.48  | 22.36  | 10.42  | 28.75  |
| Bh                 | 25.0    | 37.5    | 14.39  | 46.09  | 12.91  | 29.59  |

Reduction in plant height and biomass accumulation was recorded due to increase in levels of air pollution depending on the site (Figs. 1, 2). F\(_2\) treatment showed positive impact by increasing these parameters at all the sites. Plant height and total biomass were recorded maximum 66.13 cm and 3.74 g, respectively, at Sd in F\(_2\) treatment. At all sites, F\(_5\) treatment (without N) was found less effective to overcome the losses through air pollution, in comparison to F\(_4\) and F\(_6\) (without K and P, respectively). In F\(_4\), F\(_5\), and F\(_6\), plant height and biomass were recorded 50.87, 40.97,
and 55.30 cm and 2.613, 2.022, and 2.82 g, respectively. Results of two-way ANOVA showed significant variation ($p < 0.001$) in total biomass due to sites and treatment (Table 2). Leaf area and net primary productivity (NPP) were also recorded maximum in F$_2$ treatment at all experimental sites (Figs. 3, 4). Leaf area increased from 30.41 cm$^2$ (F$_0$ treatment) to 62.25 cm$^2$ (F$_2$ treatment) at RRP. Maximum NPP was observed in F$_2$ treatment at each experimental site and recorded to be maximal (0.0357 g plant$^{-1}$ day$^{-1}$) at Sd. Among F$_4$, F$_5$, and F$_6$, minimum increase in leaf area (18.91%) was observed in F$_5$ treatment (without N) while F$_4$ and F$_6$ showed 59.19 and 75.63% increase with respect to F$_0$ (control) at Sd. Two-way ANOVA test showed significant effect ($p < 0.001$) of treatments and level of pollutant concentration on NPP (Table 2).
TABLE 2
Variance Ratio for Growth and Yield Parameters of Wheat Plants Grown at Different Fertility Levels

| Parameters       | Site | Treatment | Site x Treatment |
|------------------|------|-----------|------------------|
| Plant height     | ***  | ***       | NS               |
| Total biomass    | ***  | ***       | ***              |
| Leaf area        | ***  | ***       | NS               |
| NPP              | ***  | ***       | ***              |
| Test weight      | ***  | ***       | NS               |
| Harvest index    | **   | ***       | ***              |

FIGURE 3. Effect of different fertility levels on net primary productivity of wheat plants grown at various sites.

Test weight (1000 seed weight) of wheat plants grown at various sites significantly decreased with increasing pollution load (Table 3). Minimum test weight (20.45 g) was recorded at RRP in F0 treatment, which increased up to 28.52 g in F2. Maximum test weight (34.30 g) was found at Sd in F2 treatment. Increase in test weight was less in F5 treatment (0.39%) than F4 and F6 (29.29 and 13.79%, respectively) at RRP. Harvest index (HI) has also shown similar results, and it decreased with increasing levels of air pollutants (Fig. 5). F2 treatment minimized the pollutant-induced adverse effect by increasing the test weight and harvest index of wheat plants. HI increased up to 18.74% (F2) from 11.73% (F0), at RRP. Losses in yield were recorded maximum at highly polluted sites (Fig. 6). Yield losses were recorded to be 10.24 to 23.0% at Sd used as a reference site (showing minimum pollution load) in F0 treatment, which reduced up to 2.08 to 14.81% in F2 treatment, while F1 showed maximum yield loss, i.e., 21.29% at RRP and minimum (5.05%) at Ar. Among F4, F5, and F6, maximum yield loss (22.91%) was found in F5 treatment, while 16.41 and 18.15% yield losses were recorded in F4 and F6, respectively, at RRP.
**DISCUSSION**

Air pollution can influence plant species in diverse ways and thus affect ecosystems at various levels of organization[20]. A positive correlation was observed among the pollutants (viz. SO₂,
NO$_2$, and O$_3$). In another experiment, the O$_3$ concentration was negatively correlated to nitric oxide (NO), but was positively correlated to (NO$_2$), moreover, an O$_3$ level and NO$_2$/NO[21]. Agrawal[22] reported that the annual NOx concentrations varied from 10 to 90 µg m$^{-3}$ in various parts of the country. Varshney and Agrawal[23] have shown ground level O$_3$ concentration between 20 to 273µg m$^{-3}$ in Delhi. Back ground concentrations of O$_3$ have been reported to increase during the last decades and it is expected that they follow rising next years [24, 25].

![Figure 5](image1.png)

**FIGURE 5.** Effect of different fertility levels on harvest index of wheat plants grown at various sites.

![Figure 6](image2.png)

**FIGURE 6.** Effect of different fertility levels on yield loss against Sd (reference site) of wheat plants grown at various sites.
The deterioration in air quality has been shown to adversely affect the crop growth. Reduction in plant height and total biomass accumulation was observed, in the present study, with an increase in pollution load. Pandey and Agrawal[26] have reported reductions in height of three woody perennials under varying air pollution stress in the urban environment of Varanasi, the adjoining city of Allahabad. Ashmore et al.[27] have also reported a decline in biomass accumulation in different plant parts along a gradient of air pollution around London. Any detrimental acidification due to the products of SO2 and NOx pollution may consequently have an inhibitory effect on processes such as CO2 fixation[28]. Soil nutrition has a dramatic effect on the sensitivity of vegetation to air pollutants. Increase in biomass accumulation in the radish plant was observed by Kostka-Rick[29] with increasing nitrogen supply and was reduced due to a long-term chronic exposure of air pollutants. Agrawal and Verma[30] reported that total plant height was reduced significantly in SO2 treated plants, except those grown using recommended and twice the recommended N, P, and K applications.

Ziska and Caulfield[31] also noticed greater O3 damage in ragweed plants due to continuous exposure until maturity. The joint action of O3 and SO2 caused significant suppression in dry matter of tomato shoot and root at all concentrations[32]. Rao and DeKok[33] and Verma et al.[15] reported reduction in biomass accumulation in wheat plants due to higher levels of SO2. Shahare and Varshney[34] observed that plant height, number of branches, nodes, and leaf per plant were reduced due to SO2 exposure. McKee et al.[35] reported that elevated O3 caused a 15% decline in total biomass accumulation in wheat plants.

F2 treatment showed positive impact on plant height and biomass by decreasing the negative impact of air pollutants. Verma et al.[15] suggested that nutrient status modifies the response of wheat cultivars to SO2. Accumulation of dry matter was higher in fertilizer-amended plants as compared to the unamended ones. Nutrient application has stimulated plant growth and a large proportion of absorbed sulfur due to SO2 exposure is being utilized in metabolic processes rather than accumulated as SO4$^{2-}$[15]. Nitrogen supply also increases leaf photosynthesis via the amount of N-containing component such as ribulose-1, 5 bisphosphate carboxylase/oxygenase activity[36].

Leaf area and NPP were negatively affected with increasing pollution load. Topa et al.[37] also found significant reduction in biomass and leaf area of sugar maple seedling due to O3. Since biomass accumulation is a function of net carbon gain, it is not surprising that reported declines in growth resulting from O3 are often correlated with reduction in photosynthesis[38]. Krupa et al.[39] also suggested that atmospheric pollution by O3 could result in depression in plant biomass and crop yield. Such a depression reflects a decline in carbon gain, caused by an inhibition of photosynthesis that could be mainly attributed to reduced carboxylation activity of Rubisco and/or to a decrease in Rubisco quantity[40]. O3, SO2, and NO2 individually and in combination are known to reduce the yield of many crop plants[41,42]. Plants supplemented with NPK fertilizers were less damaged by SO2 pollution[14,43,44]. NPP is highly correlated with biomass accumulation. In the present investigation, reduction in biomass was observed at heavier polluted sites, resulting that NPP also decreased. Significant reductions in leaf area and biomass of potato plants were also reported by Petitte and Ormrod[45] due to SO2 and NO2 treatment. Ambient O3 concentrations in Europe can cause a range of effects including visible leaf injury, growth and yield reductions, and altered sensitivity to biotic and abiotic stresses[46,47]. Ayer and Bedi[10] reported maximum damage in various growth parameters viz. root length, shoot length, leaf area, biomass, NPP, RGR, and grain yield in Triticum aestivum plants due to urban industrial air pollution in Baroda City (India). However, Ziska[48] suggested that O3 levels associated with urban environment in the U.S. might not limit the growth or reproductive development of ragweed. According to Ollerenshaw and Lyons[49] the reduction in grain yield in field grown winter wheat induced by O3 was due to decrease in number of grains per spikelet or due to the increases in number of infertile florets. It is well documented that N and P deficiency reduces chlorophyll concentration[50,51]. Nutrient deficiency has modified the carbon allocation pattern...
in plants exposed to SO$_2$ while nutrient amendment has lowered the magnitude of reduction in chlorophyll and also photosynthesis[30]. Stephens[52] found enhanced growth of young *Nothofagus fusca* tree by increasing N supply.

The supply of N, P, and K has increased the yield of wheat by increasing photosynthetic activity in foliar tissue, which have further reduced the magnitude of reduction in biomass and yield due to air pollutants. Coleman et al.[53] have suggested that plants growing in nutrient-poor conditions may be more sensitive to air pollution with respect to changes in carbon gain. N limitation has been shown to decrease chlorophyll and protein content, RuBP carboxylase activity, and increase of mesophyll resistance, which all limit CO$_2$ fixation[54]. High P availability is found to increase the rate of photosynthesis[50]. K fertilization is also beneficial due to its role in stomatal opening, photosynthesis, protein synthesis, osmotic regulation, and pH regulations[55]. The increase in yield may be attributed to the favorable effect of nutrients on photosynthesis, biomass accumulation and consequently on translocation of assimilates to reproductive parts.

**CONCLUSION**

In the present study, the wheat plants were maintained under similar climatic and edaphic conditions but with varying air pollution load and observed the differences in plant growth performance. As pollutant concentrations increased, the plant height, total biomass, leaf area, NPP, and RGR decreased *vis a vis* decline in test weight and HI indicating that air pollutants suppressed the growth and yield of wheat plants. It might be due to reduction in physiological and biochemical processes and restrain of defense mechanism. Enhanced fertilizer than the recommended dose (F$_2$) resulted in the positive response by increasing the total biomass, test weight, and total yield. Response of individual nutrients showed that N was most important than P and K. Potassium was least important, to overcome the negative impact of air pollutants.

The present investigation suggests that urban air quality of Allahabad is affecting the agriculture production unfavorably in periurban areas. Further research is required in this direction on some important crop plants to increase the food production to meet the requirement of growing population of developing countries like India.

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**REFERENCES**

1. Sunita, M. and Rao, K.V.M. (1997) Air pollution tolerance capacities of selected plant species. *J. Indian Bot. Soc.* 76, 95–98.
2. WHO/UNEP (1992) Urban Air Pollution in the Mega Cities of the World. World Health Organization and United Nations Environment Programme. Blackwell, Oxford.
3. Thimmaiah, S. (1996) Air Pollution in India with Respect to Deleterious Impacts on Agriculture [M.Sc. Thesis]. Imperial College, Center for Environmental Technology, London.
4. Agrawal, M. (1998) Effect of Air Pollution on Urban Agriculture In and Around Varanasi City. Final Technical Report of ODA Sponsored Research Project. Department of Botany, B. H. U., India.
5. Tripathi, B.D. and Tripathi, A. (1992) Foliar injury and leaf diffusive resistance of rice and white bean in response to SO$_2$ and O$_3$, singly and in combination. *Environ. Pollut.* 75, 265–268.
6. Bortier, K., Ceulemans, R., and Temmerman, L. (2000) Effect of tropospheric ozone on woody plants. In Environmental Pollution and Plant Responses. Agrawal, S.B. and Agrawal, M., Eds. Lewis Publishers, Boca Raton, FL. pp. 153–174.

7. Rudorff, B.F.T., Mulchi, C.L., and Lee, E.H. (2000) Plant responses to elevated CO2 and interactions with O3. In Trace Gas Emissions and Plants. Singh, S.N., Ed. Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 155–179.

8. Winner, W.E., Gillespie, C., Wen-Shame, S., and Mooney, H.A. (1988) Stomatal responses to SO2 and O3. In Air Pollution and Plant Metabolism. Schulke-Hostede, S., Darrall, N.M., Blank, L.W., and Wellburn, A.R., Eds. Elsevier Science, London. pp. 255–271.

9. Tripathi, B.D., Tripathi, A., and Mishra, K. (1991) Atmospheric dust fall deposits in Varanasi city. Atmos. Environ. 25B(1), 109–112.

10. Ayer, S.K. and Bedi, S.J. (1991) Effect of industrial air pollution on Triticum aestivum. Proc. Natl. Acad. Sci. Ind. 61, 223–229.

11. Wahid, A., Maggs, R., Shamsi, S.R.A., Bell, J.N.B., and Ashmore, M.R. (1995) Air pollution and its impacts on wheat yield in the Pakistan Punjab. Environ. Pollut. 88, 147–154.

12. Pell, E.J., Winner, W.E., Vinten-Johansen, C., and Mooney, H.A. (1990) Response of radish to multiple stresses. I. Physiological and growth responses to changes in ozone and nitrogen. New Phytol. 115, 439–446.

13. Ayazloo, M., Bell, J.N.B., and Garsed, S.G. (1980) Modification of chronic sulphur dioxide injury to Lolium perenne L. by different sulphur and nitrogen nutrient treatments. Environ. Pollut. 22, 295–307.

14. Rajput, M. and Agrawal, M. (1994) Responses of soybean plants to sulphur dioxide at varying soil fertility regimes. Biotronics 23, 81–92.

15. Verma, M., Agrawal, M., and Deepak, S.S. (2000) Interactive effects of sulphur dioxide and mineral nutrient supply on photosynthetic characteristics and yield in four wheat cultivars. Photosynthetica 38(1), 91–96.

16. Ormrod, D.P. and Adedipe, N.O. (1974) Protecting horticultural plants from atmospheric pollutants. A review. Hortic. Sci. 9, 108–111.

17. West, P.W. and Gaeke, G.C. (1956) Fixation of SO2 as sulfitomurcurate (II) and subsequent colorimetric estimation. Anal. Chem. 28, 1816–1819.

18. Merryman, E.L., Spicer, C.W., and Lery, A. (1973) Evaluation of arsenite modified Jacobs Hochheiser procedure. Environ. Sci. Technol. 7, 1056–1059.

19. Byers, D.H. and Saltzman, B.E. (1958) Determination of ozone in air by neutral and alkaline iodide procedures. J. Am. Indus. Hyg. Assoc. 19, 251–257.

20. Agrawal, M. and Agrawal, S.B. (2000) Effects of air pollution on plant diversity. In Environmental Pollution and Plant Responses. Agrawal, S.B. and Agrawal, M., Eds. Lewis Publishers, Boca Raton, FL. pp. 137–152.

21. Lu, W., Wang, X., Wang, W., Leung, A.Y.T., and Yuen, K. (2002) A preliminary study of ozone trend and its impact on environment in Hong Kong. Environ. Int. 28, 503–512.

22. Agrawal, M. (2000) Effect of Air Pollution on Urban Agriculture In and Around Varanasi City. Final Technical Report DIFD Project. Imperial College of Science, Technology, and Medicine, London.

23. Varshney, C.K. and Agrawal, M. (1992) Ozone pollution in the urban atmosphere of Delhi. Atmos. Environ. 26, 291–294.

24. Chameides, W.L., Kasibhata, P.S., Yienger, J., and Levy, H., II (1994) Growth of continental-scale metropolises, regional pollution and world food production. Science 264, 74–77.

25. Jonson, J.E., Sundet, J.K., and Tarasson, L. (2001) Model calculation of present and future levels of ozone and ozone precursors with a global and regional model. Atmos. Environ. 35, 525–537.

26. Pandey, J. and Agrawal, M. (1994) Evaluation of air pollution phytotoxicity in a seasonally dry tropical urban environment using three woody perennials. New Phytol. 126, 53–61.

27. Ashmore, M.R., Brown, V., Kristiansen, L., and Shah, D. (1987) Effects of ambient air pollution, water stress and aphid pests on Vicia faba. In The European Communities Research Project on Open-Top Chambers. Results on Agricultural Crops. Bonte, J. and Mathy, P., Eds. Commission of the European Communities, Brussels.

28. Wellburn, A.R. (1987) Biochemical mechanism of combined action of atmospheric pollutants upon plants. In Methods for Assessing the Effects of Mixtures of Chemicals. Vouk, V.B., Butler, G.C., Upton, A.C., Parke, D.V., and Ashor, S.C., Eds. SCOPE. pp. 813–829.

29. Kostka-Rick, R. and Manning, W.J. (1993) Radish (Raphanus sativus L.): a model for studying plant responses to air pollutants and other environmental stresses. Environ. Pollut. 82, 107–138.

30. Agrawal, M. and Verma, M. (1997) Amelioration of sulphur dioxide phytotoxicity in wheat cultivars by modifying NPK nutrients. J. Environ. Manage. 49, 231–244.

31. Ziska, L.H. and Caulfield, F.A. (2000) Rising CO2 and pollen production of common ragweed (Ambrosia artemisiifolia), a known allergy inducing species: implications for public health. Aust. J. Plant Physiol. 27, 893–898.

32. Khan, M.R. and Khan, M.W. (1994) Single and interactive effect of O3 and SO2 on tomato. Environ. Exp. Bot. 34(4), 461–469.

33. Rao, M.V. and DeKok, L.J. (1994) Interactive effects of high CO2 and SO2 on growth and antioxidant levels.
in wheat. *Phyton* **34**, 279–290.

34. Shahare, C.B. and Varshney, C.K. (1994) Impact of sulphur dioxide pollution on some trees with reference to their growth. *J. Environ. Pollut.* **1(3&4)**, 149–155.

35. McKee, I.F., Bullimore, J.F., and Long, S.P. (1997) Will elevated CO2 concentrations protect the yield of wheat from O3 damage. *Plant Cell Environ.* **20**, 77–84.

36. Sivasankar, A., Bansal, K.C., and Abrol, Y.P. (1993) Nitrogen in relation to leaf area development and photosynthesis. *Proc. Indian Natl. Sci. Acad. Part B* **59**, 235–244.

37. Topa, M.A., Vanderklein, D.W., and Corbin, A. (2001) Effects of elevated ozone and low light on diurnal and seasonal carbon gain in sugar maple. *Plant Cell Environ.* **24**, 663–677.

38. Coleman, M.D., Isebrands, J.G., Dickson, R.E., and Karnosky, D.F. (1995) Photosynthetic productivity of aspen clones varying in sensitivity to tropospheric ozone. *Tree Physiol.* **15**, 585–592.

39. Krupa, S.V., McGrath, M.T., Andersen, C.P., Booker, F.L., Burkey, K.O., Chappelka, A.H., Chevone, B.L., Pell, E.J., and Zilinskas, B.A. (2001) Ambient ozone and plant health. *Plant Dis.* **85**, 4–12.

40. Pell, E.J., Schlagnhaufer, C.D., and Arteca, R.N. (1997) Ozone induced oxidative stress: mechanism of action and reaction. *Physiol. Plant.* **100**, 264–273.

41. Renaud, J.P., Allard, G., and Mauffette, Y. (1997) Effects of ozone on yield, growth and root starch concentrations of two alfalfa (*Medicago sativa* L.) cultivars. *Environ. Pollut.* **95**, 273–281.

42. Heggested, H.E. and Lesser, V.M. (1990) Effects of ozone, sulphur dioxide, soil water deficit and cultivar on yields of soybean. *J. Environ. Qual.* **19**, 488–495.

43. Cotrufo, C. and Berry, C.R. (1970) Some effects of a soluble NPK fertilizer on sensitivity of Eastern white pine to injury from SO2 pollution. *For. Sci.* **16**, 72–73.

44. Van Haut, H. and Stratmann, H. (1970) Farbtafelateas uber Schwefeldioxid wirkungen an pflanzen. Verlag W. Girardet, Essen, Germany.

45. Petite, J.M. and Ormrod, D.P. (1988) Effects of sulphur dioxide and nitrogen dioxide on shoot and root growth of Kennebec and russet Burbank potato plants. *Am. Potato J.* **65**, 517–527.

46. Jager, H.J., Unsworth, M., De Temmerman, L., and Mathy, P. (1993) Effect of Air Pollution on Agricultural Crops in Europe. Air Pollution Research Report 46. Commission of European Communities, Brussels.

47. Fuhrer, J. and Aichmann, B. (1994) Critical Levels for Ozone. A UNECE Workshop Report. Les cahiers de la FAC no. 16. Liebefeld-Bern, Switzerland.

48. Ziska, L.H. (2002) Sensitivity of ragweed (*Ambrosia artemisiiifolia*) growth to urban ozone concentrations. *Funct. Plant Biol.* **29**, 1365–1369.

49. Ollerenshaw, J.H. and Lyons, T. (1999) Impacts of ozone on the growth and yield of field grown winter wheat. *Environ. Pollut.* **106**, 67–72.

50. Rousseau, J.V.D. and Reid, C.P.P. (1990) Effects of phosphorus and ectomycorrhizas on the carbon balance of loblolly pine seedlings. *For. Sci.* **36**, 101–112.

51. Lawlor, D.W., Kontussi, M., and Young, A.T. (1989) Photosynthesis by flag leaves of wheat in relation to protein, ribulose bis-phosphate carboxylase activity and nitrogen supply. *J. Exp. Bot.* **40**, 43–52.

52. Stephens, D.W., Millard, P., Turnbull, M.H., and Whitehead, D. (2001) The influence of nitrogen supply on growth and internal recycling of nitrogen in young *Nothofagus fusca* trees. *Aust. J. Plant Physiol.* **28**, 249–255.

53. Coleman, J.S., Mooney, H.A., and Gorham, J.N. (1989) Effects of multiple stresses on radish growth and resource allocation I. Responses of wild radish plants to a combination of SO2 exposure and decreasing nitrate availability. *Oecologia* **81**, 124–131.

54. Osman, A.M. and Milthorpe, F.L. (1971) Photosynthesis of wheat leaves in relation to age, illuminance, and nutrient supply. II. Results. *Photosynthetica* **5**, 61–70.

55. Wyn Jones, R.G. and Pollard, A. (1983) Proteins, enzymes and inorganic ions. In *Inorganic Plant Nutrition*. Encyclopedia of Plant Physiology, New Series, 15B. Lauchli, A. and Bieleski, R.L., Eds. Springer-Verlag, Berlin.
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