Ozone and ozone injury on plants in and around Beijing, China

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ABSTRACT

Ozone (O₃) levels were assessed for the first time with passive samplers at 10 sites in and around Beijing in summer 2012. Average O₃ concentrations were higher at locations around Beijing than in the city center. Levels varied with site locations and ranged from 22.5 to 48.1 ppb and were highest at three locations. Hourly O₃ concentrations exceeded 40 ppb for 128 h and 80 ppb for 17 h from 2 to 9 in August at one site, where it had a real-time O₃ analyzer. Extensive foliar O₃ injury was found on 19 species of native and cultivated trees, shrubs, and herbs at 6 of the 10 study sites and the other 2 sites without passive sampler. This is the first report of O₃ foliar injury in and around Beijing. Our results warrant an extensive program of O₃ monitoring and foliar O₃ injury assessment in and around Beijing.

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1. Introduction

Episodes of high concentrations of particulate and gaseous pollutants, referred to as smog, occur frequently in Beijing, raising concerns about effects on human health. Ozone (O₃) is a major part of this complex urban pollution mixture. Ozone levels increased at a rate of 1.1 ± 0.5 ppb/year from 2001 to 2006 (Tang et al., 2009). Ozone levels have been increasing significantly from 2002 to 2010 in China (Wang et al., 2011; Wang et al., 2012a,b,c; Xu and Zhang, 2006). The new air quality standards for O₃ for China established in 2012 says that an 8 h average of 80 ppb and an hourly average of 50 ppb are allowed for the First Grade Standard for nature reserves and scenic areas, and 100 ppb and 80 ppb for the Second Grade Standard for most areas, separately (GB 3095-2012). The higher value is permitted in the new standard than in the old one (GB 3095-1996). It reflected the incidence of high levels of ambient O₃ in China.

The effects of O₃ on crop plants and some tree seedlings have been reported from controlled field experiments with Open-Top Chambers and Free-Air Exposure Systems in China (Wang et al., 2007; Tang et al., 2011). Little is known about the effects of

ambient levels of O₃ on plants in and around Beijing or anywhere else in China.

Older leaves of ozone-sensitive plants exhibit characteristic injury symptoms when O₃ levels are high enough and exposure is long enough and environmental conditions are appropriate for gas exchange. Symptoms of ambient O₃ injury on a wide variety of native plants have been observed in the field and then verified as being caused by O₃ (Skelly et al., 1999; Innes et al., 2001; Porter, 2003; Manning and Godzik, 2004; Kohut, 2005; Davis, 2007; ICP Forests, 2010; Paoletti et al., 2009; Sanz and Catalayud, 2011). Using these references and pictorial data bases as a guide, symptom expression is a widely accepted and reliable method of assessing plant response to O₃ in the field and providing biological significance for O₃ monitoring data (Manning, 2003).

Coulson et al. (2003) rated tree species in mid-Atlantic States using O₃ injury symptoms. The Carpathian Mountain Range was surveyed for O₃ injury on plants over a 10-year period (Manning and Godzik, 2004). Davis (2007) and Davis and Orendovici (2006) used foliar O₃ injury symptoms on plants as evidence of O₃ injury to plants in Maine and Pennsylvania. Native bioindicator plants for O₃ were extensively used in forest health monitoring programs over a 16-year period in the Eastern USA (Smith et al., 2003, 2008; Smith, 2012). Ozone injury on ornamental plants has also been investigated in the field. Ozone symptom expression on *Hibiscus*

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Fig. 1. The distribution of 12 sites where the survey taken place from 11 to 15 August, 2012, Beijing. Sites: (1) The Olympic Aquatic Center, Shunyi District; (2) Mangshang Tianchi, Changping District; (3) Mountaintop in Dazhuangke village, Yanqing County; (4) Jietai Temple, Mentougou District; (5) Liangshui River in Yizhuang, Daxing District; (6) Haidian Bridge near the South Gate of Peking University; (7) RCEES (Research Center for Eco-Environmental Science); (8) Sijiqing Bridge, the West 4th Ring Road; (9) Beijing Teaching Botanical Garden, (10) Dongjiagou, Yanqing County; (11) The Olympic Forest Park, Chaoyang District; (12) Mutianyu Section of the Great Wall, Huairou District. O₃ passive samplers were set at sites 1–10.

syriacus was detected in the field and verified by treatment of plants to EDU (ethylenediurea) and exposure of plants to O₃ in open-top chambers (Paoletti et al., 2009).

Surveys for O₃ injury on native plants have been combined with and located near passive O₃ samplers or active real-time O₃ analyzers (Manning et al., 1996; Yuska et al., 2003; Bytnerowicz et al.,

2004; Manning & Godzik, 2004; Sager et al., 2005). This makes it possible to relate O₃ injury symptoms on native plants to O₃ exposure.

Here we report the results from our survey of native and cultivated plants at 10 study sites with O₃ passive samplers and two additional sites without passive samplers in and around Beijing.

Table 1
Environmental conditions and number of O₃ injured species of the sites investigated.

Sites	Locations	Elevation (m)	Land use	Dominant species	Number of injured species
1	Aquatic center	40	Plantation	<i>Populus tomentosa</i>	1
2	Tianchi	587	Natural secondary forest	<i>Morus alba</i> <i>Ailanthus altissima</i> <i>Pinus tabuliformis</i>	7
3	Dazhuangke	647	Natural secondary forest	<i>Rhamnus parvifolia</i> <i>Ailanthus altissima</i> <i>Juglans regia</i>	2
4	Jietai temple	369	Natural secondary forest	<i>Pinus tabuliformis</i> <i>Pinus bungeana</i> <i>Sophora japonica</i>	3
5	Liangshui river	36	City riverside park	<i>Morus alba</i> <i>Sophora japonica</i> <i>Rhus typhina</i>	6
6	Haidian bridge	51	City roadside park	<i>Populus tomentosa</i> <i>Pinus tabuliformis</i> <i>Ginkgo biloba</i>	1
7	RCEES	52	City roadside trees	<i>Platanus acerifolia</i> <i>Koeleruteria paniculata</i> <i>Sophora japonica</i>	—
8	Sijiqing bridge	57	City roadside park	<i>Ginkgo biloba</i>	—
9	Beijing teaching botanical garden	43	City popular science park	Various cultivated plant species	—
10	Dongjiagou	620	Shrubs and farmland	<i>Quercus aliena</i> <i>Ulmus</i> <i>Macrocarpa</i> <i>Zea mays</i> <i>Glycine max</i>	—
11	Olympic forest park	39	City park	<i>Populus tomentosa</i> <i>Ginkgo biloba</i> <i>Sophora aureus</i>	9
12	Mutianyu	486	Natural secondary forest	<i>Ulmus pumila</i> <i>Sophora japonica</i> <i>Koeleruteria paniculata</i>	3

2. Methods

2.1. Site selections

The study was conducted in the urban region and peri-urban region of Beijing. The annual mean temperature is approximately 11–12 °C (State Statistical Bureau, 2011). Mean annual precipitation is about 585 mm, with more than 70% occurring from June to August (Beijing Water Authority, 2010). The annual mean concentrations of NO₂, SO₂, PM_{2.5} and O₃ were 21.5 ppb, 9.76 ppb, 71.8 µg/m³ and 22.1 ppb from Nov. 1, 2008 to Oct. 30, 2009 (Wang et al., 2011). The NO₂, SO₂, and PM_{2.5} concentrations were higher in winter than in summer because coal burning for heating was the major pollution sources, while O₃ concentration was higher in summer because of the good meteorological conditions for photochemical reactions to generate O₃, with higher temperature, higher ultraviolet radiation and lower wind speed (Wang et al., 2011; Xu et al., 2011). The peak value usually occurred at 15:00 to 17:00 o'clock in the afternoon (Wang et al., 2011). Higher O₃ concentrations during the growing period and the afternoon would cause greater uptake of O₃ by plants, resulting in more injury and growth effects. From the O₃ monitoring data in Beijing, Wang et al. (2012a,b,c) had estimated that the AOT40 (accumulated exposure over a threshold of 40 ppb) during growing season was 20.12 ppm h, which far exceeded the AOT40 5 ppm h, the current critical level for ozone impacts on trees (UNECE, 2004), and the flux-based critical level AF_{st}1.6 by five tree species reached 5.11–17.7 mmol m⁻², exceeding the flux-based critical level for ozone impact trees (UNECE, 2004).

In this study, 12 sites were selected according to vegetation types and prevailing wind patterns (Fig. 1). The Sites 1, 2, 3, 4, 10 and 12 are natural generated forests dominated mainly by 3 tree species: *Ulmus pumila*, *Morus alba* and *Ailanthus altissima*. Around these sites, there were 3–5 shrub species, such as *Grewia biloba* var. *parviflora*, *Prunus davidiana*, and *Cotinus coggygria* var. *pubescens* and 15–20 herbaceous species. Other sites were park or roadside with cultivated plants and intensive managements with irrigation and fertilization, and were dominated by landscape plants, including trees (e.g., *Populus tomentosa*, *Sophora japonica*, *Rhus typhina* and *Ginkgo biloba*), shrubs (*Amygdalus triloba*, *Kerria japonica* var. *plenifolia* and *Hibiscus syriacus*) and many ornamental herbs. The location, elevation, land use and dominant species of these sites are showed in Table 1.

2.2. O₃ monitoring

One Ogawa passive sampler (Ogawa & Co. USA, Inc.) was installed at each of the study sites 1–10. Filters were replaced at

1-week intervals from 11 July to 9 August, resulting in 3 data samples by the time the vegetation survey was begun on 11 August. Mean ambient O₃ concentrations for each sampling location were statistically analyzed and used as an indicator of total O₃ exposure (SPSS 16.0). At one of the sites (Beijing Teaching Botanical Garden) O₃ was also continually monitored by a UV analyzer (Thermo Fisher 49i, Thermo Fisher Scientific Inc., USA). At site 2 (Tianchi), O₃ was also measured with a UV analyzer of the same model before the start of the survey.

2.3. Foliar O₃ injury assessment

Native and cultivated plants near the ten study sites with passive O₃ samplers and the two additional sites without passive samplers (site 11, Olympic Forest Park and site 12, Mutianyu) were surveyed for foliar O₃ injury from 11 to 15 August, 2012. Vegetation within 100 m from the passive samplers was surveyed for sites 1–10. Vegetation along roads was observed for sites 11 and 12.

The following criteria from the ICP Forests Manual part VIII, Assessment of Ozone Injury, were used to identify and characterize O₃ injury on the plants that we surveyed:

“Ozone visible injury can be identified and distinguished from symptoms caused by other biotic/abiotic factors by the following criteria:

1. Visible symptoms are typically expressed as tiny purple-red, yellow or black spots (described as stipple) or sometimes as a general even discoloration, reddening or bronzing.
2. Look for ozone visible injury on fully developed, light-exposed leaves.

Fig. 2. Mean O₃ concentration of 3 passive sampler data with 1-week intervals from 11 July to 9 August at study sites 1–10 in 2012. The error bars are standard deviations. The location orders are the same as that in Fig. 1.

Fig. 3. The O₃ injury symptoms on sensitive trees: (A) *Ailanthus altissima*, (B) *Populus tomentosa*, (C) *Rhus typhina*, (D) *Ulmus pumila*.

3. Symptoms are more severe on older middle-aged leaves than on younger leaves. Older leaves are the first ones to develop symptoms followed by accelerated senescence (age effect)
4. Shaded portions of two overlapping leaves do not show any visible injury (shade effect).
5. Ozone injury normally does not go through the leaf tissue. Both stippling and even discoloration occur only between veins (interveinal) and do not affect veins.
6. Towards the end of the growing season, foliar symptoms may progress to leaf yellowing or premature senescence, followed by leaf loss."

Based on the above information, the following questions should be answered when diagnosing possible ozone visible injury:
"Is there any stippling?

Is there any reddening and/or even discoloration?

Do the symptoms, as described above, occur on the upper leaf surface only (except during late season when visible injury becomes more severe and necrotic)?

Are the symptoms expressed between the veins only and are absent on the veins and veinlets (use hand lens and hold leaf against light)?

Are the symptoms evenly distributed?

Are the symptoms more developed on the older leaves (including leaflets, 'age effect')?"

If the above questions are answered affirmatively, the symptom can be considered as ozone visible injury.

Other handbooks, manuals and guides for identification of O₃ injury symptoms on plants were also consulted (Innes et al., 2001; Porter, 2003; Kohut, 2005; Sanz and Calatayud, 2011; Smith, 2012).

Fig. 4. The O₃ injury symptoms on sensitive shrubs: (A) *Amygdalus triloba*, (B) *Salix leucopithecia*, (C) *Hibiscus syriacus*, (D) *Kerria japonica* var. *pleniflora*.

3. Results

3.1. Ambient O₃ concentrations

Mean O₃ concentrations derived from passive samplers varied significantly from 22.5 to 48.1 ppb by sites during the month before the survey (Fig. 2). The highest concentrations occurred at sites 2, 3 and 4. From 11 July to 9 August, O₃ concentrations at site 9 (Beijing Teaching Botanical Garden) from the passive sampler and real-time analyzer were correlated (The coefficient of determination $R^2 = 0.56$). Results from site 2 (Tianchi) from the real-time analyzer (2–9 August) indicated a mean O₃ concentration of 54 ppb, with a maximum value of 135 ppb. During the period of 2–9 August, hourly O₃ concentrations exceeded 40 ppb for 128 h and 80 ppb for 17 h. The real-time analyzer at site 2 showed that higher O₃ concentrations occurred in May than August. The mean concentration was 74.4 ppb from 21 to 31 May and the peak value of 195.8 ppb occurred on 28 May.

3.2. Ozone injury on plants

Using the ICP Forests Criteria and questions during diagnoses, we found 19 species of native and cultivated trees, shrubs and herbs in and around Beijing that exhibited symptoms of foliar O₃ injury

(Figs. 3–5). Upper surface stipple, ranging from white to yellow to brown to red to black was observed on 12 species (Table 2). “Classic stipple” was observed on leaves of *Canavalia gladiata*. Dark brown blotching was found on two species. Deep purple-brown older leaves were found on one species, interveinal chlorosis was observed on 3 species and general chlorosis on one species.

O₃ injury was observed on plants at 6 of the 10 study sites and 2 of the additional sites that lacked passive samplers (Table 1). Frequency for foliar injury symptoms on the life forms were 56.3% (18/32) for trees, 15.6% (5/32) for shrubs, 21.9% (7/32) for herbs, 6.3% (2/32) for crop plants. *Ailanthus altissima* and *Populus tomentosa* occurred at 4 of the 12 sites. And *Sophora japonica* occurred at 3 of the 12 sites.

3.3. Site differences for O₃ injury

There were significant differences in the number of species with O₃ injury symptoms by site locations (Table 1). Site 2 (Tianchi) and site 3 (Dazhuangke) had high O₃ levels and relatively higher occurrence of species with O₃ injury symptoms. At sites 1, 2, 3, 4 and 6, where were natural regenerated forest, the number of species with O₃ injury symptoms increased with measured O₃ concentrations. Site 5, a riverside city park rich in landscape plants had the second largest number of foliar injured species observed with a

Fig. 5. The O_3 injury symptoms on sensitive crop and herbs: (A) *Cassia tora*, (B) *Ipomoea nil*, (C) *Canavalia gladiata*, (D) *Helianthus annuus*, (E) *Pharbitis purpurea*, (F) *Hyptis suaveolens*.

middle level of mean O_3 concentration. Site 11, the Olympic Forest Park, has extensive areas of cultivated ornamental plants. While O_3 was not monitored there, the largest number of plant species with O_3 injury was found there. *Populus tomentosa*, a widely planted native tree species, was the most sensitive plant. Extensive chlorosis and brown leaf blotching leading to defoliation was in progress. The Park is on the northern air flow gradient from central Beijing and should have high O_3 concentrations given the large number of species affected and the intensity of the injury that occurred there.

4. Discussion

We were able to use passive O_3 samplers to determine mean O_3 concentrations at 10 study sites in and around Beijing in summer 2012. Passive samplers have been widely used by others in similar monitoring programs (Manning et al., 1996; Yuska et al., 2003;

Bytnerowicz et al., 2004; Sager et al., 2005). Good agreement was also found between results from the real time O_3 analyzer and the passive sampler at Beijing Teaching Botanical Garden, validating the method (Yuska et al., 2003).

We also found that the highest average O_3 concentrations were at locations outside the center of the city (Figs. 1 and 2). These results are consistent of other reports that indicate that O_3 levels are often higher downwind of city centers. Mean concentrations were in the range 22.5–48.1 ppb, with highest values at sites 2, 3, and 4. These values are only means and do not reflect high values that may have been episodically experienced. Data from real-time O_3 analyzers showing the peak O_3 concentration value of 198.5 ppb and mean value of 74.4 ppb which occurred in May were both higher than that of August. The time exceeded 40 ppb and 80 ppb were 128 h and 17 h separately during 2–9 in August on site 2. It revealed that plants in and around Beijing was frequently exposed to high ambient O_3 concentration level.

Table 2Injury symptoms of O₃ sensitive species in and around Beijing.

Injury symptoms	Species	Life form	O ₃ injury occurrence		Figures
			Sites no.	Frequency	
Yellow/brown to black stipple	<i>Ailanthus altissima</i>	Tree	2, 3, 4, 12	4	Fig. 3A
	<i>Rhus typhina</i>	Tree	5	1	Fig. 3C
	<i>Juglans regina</i>	Tree	3	1	—
	<i>Hibiscus syriacus</i>	Shrub	11	1	Fig. 4C
	<i>Cassia tora</i>	Herb	11	1	Fig. 5A
	<i>Ipomoea nil</i>	Herb	4, 5	2	Fig. 5B
	<i>Phorbitis purpurea</i>	Herb	2, 5	2	Fig. 5E
	<i>Sophora japonica</i>	Tree	4, 5, 11	3	—
	<i>Sophora aureus</i>	Tree	11	1	—
	<i>Canavalia gladiata</i>	Crop	2	1	Fig. 5C
White stipple	<i>Amgdalus triloba</i>	Shrub	2, 11	2	Fig. 4A
	<i>Salix leucopithecia</i>	Shrub	11	1	Fig. 4B
Brown to dark mottle/blotch	<i>Populus tomentosa</i>	Tree	1, 6, 11, 5	4	Fig. 3B
	<i>Ulmus pumila</i>	Tree	2, 12	2	Fig. 3D
Dark brown leaves	<i>Morus alba</i>	Tree	2, 5	2	—
Interveinal chlorosis	<i>Kerria japonica</i> var. <i>plenifolia</i>	Shrub	11	1	Fig. 4D
	<i>Hyptis suaveolens</i>	Herb	11	1	Fig. 5F
General chlorosis	<i>Vigna unguiculata</i>	Crop	2	1	—
	<i>Helianthus annuus</i>	Herb	12	1	Fig. 5D

Much has been written and reported about air pollution and its effects on humans in Beijing (Wan et al., 2012), but this is the first report of O₃ injury on plants in and around Beijing. This is evidence that not only are people at risk from air pollution in Beijing, but also is vegetation. Plants play an important part in ecosystem services in cities and anything that affects them will affect people. Finding O₃ injury on plants in Beijing means that air quality is also not appropriate for humans. O₃ injury on plants is a good bioindicator of relative O₃ pollution levels.

Following established criteria for identifying foliar O₃ injury in the field (Innes et al., 2001; Porter, 2003; Kohut, 2005; IPC Forests, 2010; Sanz and Calatayud, 2011; Smith, 2012), we identified 19 species of native and cultivated trees, shrubs, and herbs with O₃ injury. *Ailanthus altissima* is a verified bioindicator plant for ambient O₃ (Porter, 2003; Seiler, 2012) as is *Hibiscus syriacus* (Paoletti et al., 2009; Sanz and Calatayud, 2011). O₃ injury has not previously been described for 9 species (*Cassia tora*, *Phorbitis purpurea*, *Canavalia gladiata*, *Amgdalus triloba*, *Kerria japonica* var. *plenifolia*, *Hyptis suaveolens*, *Vigna unguiculata*, and *Sophora aureus* and *Juglans regina*). Ozone injury on these plants should be verified with controlled exposure experiments.

Populus tomentosa is widely planted in Beijing and surrounding areas. This is the first report of O₃ injury on leaves of *P. tomentosa*. Other species in the genus *Populus* are known to be O₃ sensitive as well (Innes et al., 2001; Kohut, 2005; IPC Forests, 2010). There is a very large grove of *P. tomentosa* in the Olympic Forest Park. At the time of our survey, the older leaves on the trees were chlorotic with irregular brown blotches. Extensive premature defoliation was occurring with fallen leaves accumulating on the walkway.

The largest numbers of plants with O₃ injury was found at site 11 and site 5, the Olympic Forest Park and the Liangshui Riverside Park. Both of the parks had more open space and more cultivated plants than the other sites. And they were irrigated during the growing season and this might increase O₃ susceptibility in horticultural plants. None of the plants in 4 of the study sites (7, 8, 9, and 10) exhibited symptoms of O₃ injury. Either sensitive plant species were not present. Except for site 7, O₃ levels were lower (Figs. 1 and 2). Environmental conditions may also have not been conducive to O₃ uptake by plants.

Although foliar O₃ injury symptoms in field would be interfered by other stresses, such as nutrient deficiency, drought, insects and pests and other air pollutants, some specific identities of O₃ injury

on leaf make field observation possible. Basing on ICP Forests Manual part VIII, Assessment of Ozone Injury, and other handbooks, manuals and guides for identification of O₃ injury symptoms on plants (Innes et al., 2001; Porter, 2003; Kohut, 2005; Sanz and Calatayud, 2011; Smith, 2012), we can justify calling what we observed as being O₃ injury. SO₂ injury only occurs on newer leaves and not older ones. The injury does not resemble O₃ injury. NO₂ injury also occurs on newer leaves and does not resemble O₃ injury. SO₂ injury might be possible, but levels of NO₂ have to be quite high to cause injury. Particulates could not cause the kinds of injury that we observed. Nutrient deficiency caused chlorosis always appeared on the whole leaf. Fungi caused injury include veins. Insects' injuries were usually with traces of their biting or remnants, even the living insects. Basing on the criteria above, we could confirm at high confidential that the foliar injury symptoms we documented were caused by elevated O₃ exposure.

5. Conclusions

O₃ was assessed for the first time with passive samplers and with real-time analyzers in and around Beijing. Results indicate O₃ levels of concern for plants and people. O₃ injury on 19 plant species was found at 8 of the 12 sites surveyed. This is the first report of O₃ injury to plants in this area. One of the sites, the Olympic Forest Park, is used extensively by residents of Beijing. Results from this short initial assessment provide justification for a much more extensive and long-term investigation of O₃ and its effects on vegetation in and around Beijing and elsewhere in China.

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References

- Beijing Water Authority, 2010. Beijing Water Resources Bulletin 2009. China Water and Hydropower Publisher, Beijing.
- Bytnerowicz, A., Godzik, B., Grodzinska, K., Franzek, K., Musselman, R., Manning, W.J., Badea, O., Popescu, F., Fleisher, P., 2004. Ambient ozone in forests of the Central and Eastern European mountains. Environ. Pollut. 130, 5–16.

- Coulson, J.W., Smith, G.C., Smith, W.D., 2003. Regional assessment of ozone sensitive tree species using bioindicator plants. *Environ. Monit. Assess.* 83, 113–127.
- Davis, D.D., 2007. Ozone-induced symptoms on vegetation within the Moosehorn National Wildlife Refuge in Maine. *Northeast. Nat.* 8, 403–414.
- Davis, D.D., Orendovici, T., 2006. Incidence of ozone symptoms on vegetation within a National Wildlife Refuge in New Jersey, USA. *Environ. Pollut.* 143, 555–564.
- ICP Forests, 2010. Assessment of Ozone Injury, Part VIII. <http://icp-forests.net>.
- Innes, J.L., Skelly, J.M., Schaub, M., 2001. Ozone and Broadleaved Species. A Guide to the Identification of Ozone-induced Foliar Injury. Paul Haupt Publishing, Bern, Switzerland, ISBN 3-258-06384-2, 136 pp.
- Kohut, R., 2005. Handbook for Assessment of Foliar Ozone Injury on Vegetation in the National Parks. National Park Service U.S. Department of the Interior. http://www2.nature.nps.gov/air/permits/aris/networks/docs/Handbook_Ozone_Injury_Assessment.pdf.
- Manning, W.J., 2003. Detecting plant effects is necessary to give biological significance to ambient ozone monitoring data and predictive ozone standards. *Environ. Pollut.* 126, 375–379.
- Manning, W.J., Godzik, B., 2004. Bioindicator plants for ambient ozone in Central and Eastern Europe. *Environ. Pollut.* 130, 33–39.
- Manning, W.J., Krupa, S.V., Bergweiler, C.J., Nelson, K.L., 1996. Ambient ozone in three class I wilderness areas in the northeastern USA: measurement with passive Ogawa samplers. *Environ. Pollut.* 91, 399–403.
- Paoletti, E., Ferrara, A.M., Calatayud, V., Cervero, J., Gianetti, F., Sanz, M.J., Manning, W.J., 2009. Deciduous shrubs for ozone bioindication: *Hibiscus syriacus* as an example. *Environ. Pollut.* 157, 865–870.
- Porter, E., 2003. Ozone Sensitive Plant Species on National Park Service and U.S. Fish and Wildlife Service Lands: Results of the 2003 Workshop, Baltimore MD. <http://www2.nature.nps.gov/ard/pubs/index.htm>.
- Sager, E.P.S., Hutchinson, T.C., Croley, T.R., 2005. Foliar phenolics in sugar maple (*Acer Saccharum*) as a potential indicator of tropospheric ozone pollution. *Environ. Monit. Assess.* 105, 419–430.
- Sanz, M.J., Calatayud, V., 2011. Ozone Injury in European Forest Species. <http://ozoneinjury.org>.
- Seiler, L.S., 2012. Effectiveness of *Ailanthus altissima* as a Bioindicator of Ozone Pollution (M.S. thesis). The Pennsylvania State University.
- Skelly, J.M., Innes, J.L., Savage, J.E., Snyder, K.R., Vanderheyden, D., Zhang, J., Sanz, M.J., 1999. Observation and confirmation of foliar ozone symptoms of native plant species of Switzerland and Southern Spain. *Water Air Soil. Pollut.* 116, 227–234.
- Smith, G., 2012. Ambient ozone injury to forest plants in Northeast and North Central USA: 16 years of biomonitoring. *Environ. Monit. Assess.* 184, 4049–4065.
- Smith, G., Coulston, J., Jepsen, E., Prichard, T., 2003. A national ozone biomonitoring program – results from field surveys of ozone sensitive plants in northeastern forests (1994–2000). *Environ. Monit. Assess.* 87, 271–291.
- Smith, G.C., Coulston, J.W., O'Connell, B.M., 2008. Ozone Bioindicators and Forest Health: a Guide to the Evaluation, Analysis, and Interpretation of Ozone Injury Data in the Forest Inventory and Analysis Program. Gen. Tech. Rep. NRS-34. U. S. Dep. Agric. For. Serv. North. Res. Stn., Newt. Square, PA, p. 34.
- State Statistical Bureau, 2011. Statistical Yearbook of Beijing 2010. China Statistics Press, Beijing.
- Tang, G., Li, X., Wang, Y., Xin, J., Ren, X., 2009. Surface ozone trend details and interpretations in Beijing, 2001–2006. *Atmospheric Chem. Phys.* 9, 8813–8823.
- Tang, H., Liu, G., Han, Y., Zhu, J.G., Kobayashi, K., 2011. A system for free-air ozone concentration elevation with rice and wheat: control performance and ozone exposure regime. *Atmos. Environ.* 45, 6276–6282.
- UNECE, 2004. Revised Manual on Methodologies and Criteria for Mapping Critical Levels/loads and Geographical Areas Where They Are Exceeded. www.icpmapping.org (February 12, 2006).
- Wan, W., Xie, X.X., Zhang, S.Q., 2012. Health effect valuation of ground-level ozone control in Beijing and its surrounding areas, China. *Adv. Mater. Res.* 356, 585–589.
- Wang, J., Zhang, H.X., Wang, X.K., Mou, Y.J., 2011. Study on air pollutants in three representative regions of Beijing. *Environ. Chem.* 30, 2047–2053.
- Wang, X., Manning, W.J., Feng, Z., Yongguan, Zhu, 2007. Ground-level ozone in China: distribution and its effects on crop yields. *Environ. Pollut.* 147, 394–400.
- Wang, H., Zhou, W., Wang, X., Gao, F., Zheng, H., Tong, L., Ouyang, Z., 2012a. Ozone uptake by adult urban trees based on sap flow measurement. *Environ. Pollut.* 162, 275–286.
- Wang, Y., Konopka, P., Liu, Y., Chen, H., Müller, R., Plöger, F., Riese, M., Cai, Z., Lü, D., 2012b. Tropospheric ozone trend over Beijing from 2002–2010: ozonesonde measurements and modeling analysis. *Atmos. Chem. Phys.* 12, 8389–8399.
- Wang, X.K., Zhang, Q.Q., Zheng, F.X., Zheng, Q.W., Yao, F.F., Chen, Z., Zhang, W.W., Hou, P.Q., Feng, Z.Z., Song, W.Z., Feng, Z.W., Lu, F., 2012c. Effects of elevated O₃ concentration on winter wheat and rice yields in the Yangtze River Delta, China. *Environ. Pollut.* 171, 118–125.
- Xu, J., Zhang, X., Xu, X., Zhao, X., Meng, W., Pu, W., 2011. Measurement of surface ozone and its precursors in urban and rural sites in Beijing. *Proc. Earth Planet. Sci.* 2, 255–261.
- Xu, J., Zhang, Y.H., 2006. Process analysis of O₃ formation in summer at Beijing. *Acta Sci. Circumstantiae* 26, 973–980.
- Yuska, D.E., Skelly, J.M., Ferdinand, J.A., Stevenson, R.E., Savage, J.E., Mulik, J.D., Hines, A., 2003. Use of bioindicators and passive sampling devices to evaluate ambient ozone concentrations in north central Pennsylvania. *Environ. Pollut.* 125, 71–80.