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Foliar Sorption of Sulfur Dioxide, Nitrogen Dioxide, and Ozone by Ornamental Woody Plants[1]

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Additional index words. *Abies concolor*, white fir, *Acer platanoides*, Norway maple, *Betula pendula*, European white birch, *Ficus benjamina*, *Gleditsia triancanthos*, *Picea abies*, Norway spruce, *Pinus nigra*, Austrian pine, *Prunus sargentii*, *Pseudotsuga menziesii*, blue Douglas fir, *Sorbus aria*, mountain ash

***Abstract.* Excised shoots of 10 shade tree species were exposed for 6 hours to 40 pphm (vv^{-1}) sulfur dioxide (SO_2), 40 pphm nitrogen dioxide (NO_2), or 25 pphm ozone (O_3) separately or in mixture. Sorption rates were generally greater in coniferous than in deciduous shoots and higher for SO_2 than NO_2. Adsorption on leaf surfaces was greater than absorption through stomates for 4 of 5 species in which the 2 forms of sorption could be separated, while sorption from single gases was similar to that from mixed gases for these species. For the 5 species in which transpiration continued in darkness, sorption from the mixture was consistently less than from single gases.**

Vegetation may act as an important sink for air contaminants (15, 17). The planting of trees and shrubs is one strategy for reducing concentrations of urban atmospheric pollutants (16). Woody plants may effectively remove contaminants from the surrounding atmosphere, and there have been a number of studies of the capabilities of individual species (9). Martin and Barber (11) noted a loss of atmospheric sulfur dioxide (SO_2) near hawthorn foliage. Roberts (13) found that red maple, white birch, and sweetgum had a greater capacity to absorb SO_2 than did rhododendron, ash, and azalea, and Roberts and Krause (14) reported that firethorn removed greater quantities of SO_2 than did rhododendron. Jensen and Kozlowski (8) demonstrated that the SO_2-uptake rate in several woody species was affected by prefumigation with SO_2. Townsend (19) found that white oak and white birch sorbed larger quantities of O_3 than red maple or white ash. Some researchers have concluded that sorption of SO_2 at crown level by trees is negligible (10, 12).

The atmospheric environment may contain a complex mixture of pollutant gases. Most studies of gas sorption by leaves have been with single gases, and little attention has been given to the sorption of gases from mixtures. The objectives of this research were: to investigate the effectiveness of some ornamental woody plants in reducing the concentrations of SO_2, NO_2, and O_3 in the surrounding atmosphere; to distinguish between the rates of stomatal absorption and leaf surface adsorption for these gases; and to determine the sorption rates of these gases from a mixture of gases.

Sorption rates were determined using 4 cylindrical Plexiglas chambers (16 cm diameter × 25 cm height, 5 liters inside volume) through which air filtered with activated charcoal was circulated at a flow rate of 2 liters min^{-1}. The 4 cylinders were set on a laboratory bench and connected separately by an inlet to the air source and by an outlet to the analyzer. The filtered air was mixed with SO_2 or NO_2 in nitrogen from cylinders, or O_2 from an Elcar Viva high-voltage generator, or a mixture of the gases. Sulfur dioxide was monitored with a Beckman Model 952-A analyzer and NO_2 with a Beckman Model 953 analyzer, each calibrated with gases from calibration cylinders. Ozone was monitored with a Dasibi Model 1003AH monitor calibrated with a Monitor Labs 8500 calibration system.

Photosynthetically active radiation measured at the leaf canopy in the chambers was 350 $\mu Em^{-2}sec^{-1}$ (Li-Cor Model LI-185 quantum meter) provided by a high-pressure sodium lamp mounted above the laboratory bench. Temperature was 25 ± 2°C and relative humidity 65 ± 5% in both light and dark. The air stream was passed through distilled water for humidification prior to introduction of the gases. The leaf surface area was measured with a Lambda area meter Model LI-3050A.

The method of measuring the rate of absorption through stomata and adsorption on the leaf surfaces was adapted from Craker and Starbuck (2) and is reported elsewhere (4). In brief, the plant material was exposed to the pollutant in a transparent gas exchange chamber for 6 hr. Differences in pollutant concentrations between inlet and outlet were measured for 5 min at the end of a 2-hr light period (to determine stomatal absorption plus surface adsorption) or a 1-hr dark period (to determine surface adsorption).

Plant shoots used in these studies, with the exception of *Ficus* shoots, were obtained from woody plants growing in summer on the grounds of the University of Guelph. Shoots of *Ficus* plants were obtained from a greenhouse. Each shoot was detached from a plant, recut under water, and placed in each sorption chamber in a water-filled tube con-

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nected to a potometer, mounted on the wall of the chamber. Each shoot had a leaf area of 200 ± 15 cm^2. The potometer measured the water uptake by shoots and indirectly the transpiration rate as an approximate indicator of stomatal response to light and dark. A similar technique was used by Thorne and Hanson (18). The shoots were acclimated in the chamber for 2 hr (from 0800 to 1000 hr) with filtered air. All species were exposed to inlet concentrations of 40 pphm SO_2, 40 pphm NO_2, 25 pphm O_3, or a mixture of the 3 gases for 6 hr (1000 to 1600 hr). Sorption measurements were made at 1300 and 1600 hr. The determinations were conducted 3 times for each species with a new shoot for each determination.

No visible injury was noted on any species at the end of the 6 hr exposure period. Shoots of all species reduced the pollutant concentrations in the chamber to some degree, but there were marked differences among species (Table 1 and 2). The rates of absorption and adsorption were differentiated in the 5 species for which potometry indirectly indicated most stomates to be closed in the dark. The total sorption rates for the other 5 species, including all the coniferous species tested, could not be subdivided as stomates were apparently not closed in the dark. In general, the shoots from coniferous trees (*Abies, Picea, Pinus* and *Pseudotsuga*) sorbed more of the 3 single gases than did the shoots from deciduous trees (*Acer, Betula, Ficus, Gleditsia, Prunus, Sorbus*) (Table 1). There was some overlap of each of these groups and the relative sorption depended on the gas. For example, *Pseudotsuga* sorbed the least SO_2 among the conifers but the most O_3. Sorption rates of SO_2 were higher than for NO_2 in *Picea* and *Prunus* while O_3 rates were highest in relation to exposure concentration in most species.

In those species for which sorption could be subdivided, adsorption was greater than absorption in *Betula* for all 3 gases and in *Prunus* for SO_2 and O_3, while *Sorbus* had consistently more absorption than adsorption. Both absorption and adsorption from a gas mixture were generally similar to those for single gases in species for which sorption could be subdivided. In contrast, in the other species sorption of each gas from the mixture was consistently less than sorption from the single gas (Table 2). In petunia (4) and turfgrass (6) cultivars, absorption rates of individual gases were generally less from a mixture. Adsorption by petunia leaves was similar for both single and mixed gas exposures, while there was no consistent adsorption rate pattern for turfgrass leaves.

Species differences in sorption rates may reflect differences in surface-to-volume ratios (16) or different internal leaf geometry, which may affect the resistance to diffusive transport across the air spaces inside the leaf (7). Differences in adsorption rates could be due to variation in trichome numbers and leaf surface characteristics as in petunia (3) and *Rhododendron* and *Pyracantha* (14). Surface water and reactive cuticular components may also be important (1). Non-leafy portions of the shoots also may be responsible for some adsorption. Further study of these woody species is required to determine if such relationships exist. The amounts of pollutant gases sorbed by these woody plants are substantially less than for the herbaceous petunia (5) and turfgrasses (6). Similarly, Thorne and Hanson (18) demonstrated that herbaceous plants absorb more O_3 than woody plants. However, the relatively large total leaf area of mature woody plants could account for substantial pollutant sorption. Estimates are needed of the amounts of pollutants removed by woody plants of various species under field conditions together with methods for experimental confirmation of the amounts involved.

Table 1. Rates of adsorption and absorption (A) or total sorption (B) from single gases of 25 ppm O_3, 40 ppm SO_2, or 40 ppm NO_2 by leaves of selected woody plant species. Each value is the mean of 2 measurements of 3 replicates (plants) ± SD.

	SO_2		NO_2		O_3	
Species	ab–	ad–	ab–	ad–	ab–	ad–
A - Absorption or adsorption of single gases *($\mu l\ dm^{-2} min^{-1} 10^{-2}$)*						
Acer platanoides 'Schwedleri'						
Norway maple	1.2±0.2	1.8±0.4	2.2±0.3	0.8±0.2	1.4±0.2	1.4±0.2
Betula pendula						
European white birch	2.0±0.6	4.0±0.8	1.8±0.4	3.0±0.5	1.8±0.4	2.7±0.4
Sorbus aria 'Lutesceus'						
Mountain ash	3.6±0.6	1.6±0.3	4.6±0.9	0.7±0.2	2.9±0.5	1.7±0.2
Ficus benjamina	1.8±0.4	2.5±0.4	1.6±0.2	1.4±0.3	2.0±0.6	2.0±0.5
Prunus sargentii	2.0±0.3	3.6±0.6	2.0±0.4	2.0±0.2	1.2±0.2	3.0±0.5
B - Sorption of single gases ($\mu l\ dm^{-2} min^{-1} 10^{-2}$)						
Gleditsia triancanthos						
'Shademaster'	4.3±0.7		5.0±1.0		4.4±1.0	
Pinus nigra						
Austrian pine	6.1±0.5		7.2±1.0		4.8±1.0	
Picea abies						
Norway spruce	7.6±1.0		5.4±0.8		5.7±0.7	
Abies concolor						
White fir	6.4±0.7		6.6±1.0		6.8±1.0	
Pseudotsuga menziesii						
Blue Douglas fir	5.0±0.6		5.0±0.8		7.9±1.0	

Table 2. Rates of adsorption and absorption (A) or total sorption (B) from the gas mixture of 25 ppm O_3, 40 ppm SO_2, and 40 ppm NO_2 by leaves of selected woody plant species. Each value is the mean of 2 measurements of 3 replicates (plants) ± SD.

	SO_2		NO_2		O_3	
Species	ab–	ad–	ab–	ad–	ab–	ad–
A - Adsorption or absorption of gas mixture *($\mu l\ dm^{-2} min^{-1} 10^{-2}$)*						
Acer platanoides 'Schwedleri'						
Norway maple	1.4±0.2	1.7±0.3	1.0±0.4	0.8±0.1	1.0±0.1	1.4±0.2
Betula pendula						
European white birch	1.9±0.5	4.0±0.8	1.4±0.2	2.6±0.2	1.2±0.2	1.9±0.2
Sorbus aria 'Lutesceus'						
Mountain ash	3.0±0.6	1.2±0.2	2.0±0.1	1.2±0.2	2.2±0.6	1.6±0.3
Ficus benjamina	1.5±0.4	1.2±0.2	1.0±0.3	1.0±0.2	1.0±0.2	1.2±0.2
Prunus sargentii	1.8±0.2	3.5±0.6	1.0±0.1	2.2±0.2	1.0±0.2	2.6±0.2
B - Sorption of gas mixture ($\mu l\ dm^{-2} min^{-1} 10^{-2}$)						
Gleditsia triancanthos						
'Shademaster'	3.8±0.8		4.0±0.4		3.6±0.7	
Pinus nigra						
Austrian pine	5.6±0.5		4.4±0.7		3.7±0.4	
Picea abies						
Norway spruce	7.0±0.8		4.3±1.0		5.0±0.4	
Abies concolor						
White fir	5.4±0.6		3.3±0.4		5.1±0.6	
Pseudotsuga menziesii						
Blue Douglas fir	4.3±1.0		3.9±0.6		6.0±0.6	

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Selective Control of Trees by Pressure Injection of Herbicides[1]

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Abstract. **Herbicides were introduced into the vascular systems of 20-and 22-year-old Chinese elm (*Ulmus parvifolia* Jacq.), pin oak (*Quercus palustris* Muenchh.), and 20-year-old white ash (*Fraxinus americana* L.) with a syringe-type pressure injector. Concentrations of triclopyr [[(3,5,6,-trichloro-2-pyridinyl)oxy]acetic acid] triethylamine salt ranging from 90 to 360 g/liter were as effective on all species with 2 injection sites per tree as the combination of picloram (4-amino-3,5,6-trichloropicolinic acid) triisopropanolamine salt + 2,4-D [(2,4-dichlorophenoxy) acetic acid) triisopropanolamine salt at dosages ranging from 8 g/liter + 30 g/liter to 32 g/liter + 120 g/liter. Over 80% kill of Chinese elm tops occurred within 2 months after injection, whereas maximum kill of white ash and pin oak did not occur until the following growing season.**

It is advantageous to selectively control trees with herbicides for various reasons: to eliminate shade when tree removal is not possible, to facilitate stump removal by reducing stump sprouting to enhance decay, and to kill trees bordering power line rights-of-way that have the potential of growing or falling into the electrical conductors. Cut-surface treatments with tree injectors and hatchets have been used effectively for years by foresters to selectively remove undesirable tree species (5, 8, 9), but much of the herbicide solution introduced through cut-surfaces is not absorbed due to overflow or is washed out by rain, which reduces the effectiveness of the herbicide and can damage adjacent plants. Herbicides injected directly into the vascular system might be translocated more readily than cut-surface methods and without danger of being washed out especially in urban areas. Several kinds of pressure-type injection systems for growth retardants, insecticides, and fungicides are presently in use (2, 4, 7, 10). The combination of picloram and 2,4-D has been one of the most successful injection combinations (5, 8, 9). Triclopyr is a recent auxin-type herbicide recommended to control ash, oaks and root sprouting species such as black locust (*Robinia pseudoacacia* L.) and sumac (*Rhus* spp.), and can be applied through foliage or tree injection (3, 12). The objectives of this study were to determine if several species of deciduous trees can be killed when injected directly into the vascular system with herbicides and to compare the efficacy of triclopyr with a combination of picloram and 2,4-D.

The pressure injector used in this study is a large version of the miniature pressure injector described previously (10). It consists of a modified 28 cm, Vise-Grip[3] "C"-clamp with a tapered stainless steel injector barrel and disposable syringe designed to inject solutions into the vascular system of tree trunks (Fig. 1). Two, three, or four 3.9 mm diameter holes (injection sites) were drilled into the trunk with a cordless electric drill. The holes were spaced about 5 cm apart in a vertical direction and the lowest hole was located no closer than 10 cm above ground level. They were drilled equidistant around the trunk circumference and penetrated the phloem and xylem tangentially to a depth of about 9 cm in a manner similar to the technique used by Roberts et al. (7). The tapered injector barrel was inserted into each hole and wedged in place by closure of the Vise-Grip locking pliers. A pre-filled 5 ml polypropylene syringe was then inserted into a connector and the liquid herbicide mixture forced into the hole by hand. Species injected were 20 and 22 year old Chinese elm and pin oak, and 20 year old white ash that were planted on 3.05 m × 3.05 m spacing in the field at Frederick, Maryland. A total volume of 6 ml was used per tree regardless of the number of holes drilled. A 6 ml volume was used because it approximates the amount recommended for 10 to 18 cm diameter trees using cut-surface injection techniques. Herbicide concentrations were based on active ingredients. Experiments with similar concentrations of picloram + 2,4-D and triclopyr were conducted in July 1977 (11) and in July 1979. In addition, 2, 3, and 4 injection sites were evaluated in the 1977 experiment, and in the 1979 experiment several lower concentrations of each herbicide were evaluated using 2 injection sites. The percentage of tops killed was determined by visual estimate in September of the year treated and again the following growing season and was based on comparison with untreated trees at the experimental sites. Trees were selected with closely similar trunk diameters and tops, and a randomized block design was used. Treatments were replicated 5 times (1 tree per replication) and analyzed with Duncan's multiple range test and the rank sum test (1).

In the 1977 experiment most of the tops of Chinese elm were killed by September 1977

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