

Tolerance of Several Woody Plants to Sulphur Dioxide

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The photosynthetic and stomatal responses of several woody plants (*Powlonia coreana*, *Firmiana simplex*, *Quercus acutissima*, *Q. variabilis* and *Q. serrata*) to SO₂ were investigated in order to understand their ecophysiological tolerance to SO₂. Of the plants, *P. coreana* showed the largest reduction in its photosynthesis in response to exposure of 0.4 ppm SO₂ for 20 h. Fumigation of 0.7 ppm SO₂ for 20 h caused complete leaf necrosis of *P. coreana* and *F. simplex*, which made them unavailable for the measurement of photosynthesis. *Q. variabilis* exhibited the smallest reduction in photosynthesis following exposure of 0.7 ppm SO₂ for 20 h. Both stomatal- and non-stomatal inhibition of the plants by SO₂ were determined according to equations by Ikeda et al. (1992). When exposed to 0.4 ppm SO₂ for 20 h, *F. simplex* and *P. coreana* showed the lowest stomatal and non-stomatal inhibition, respectively, while *Q. variabilis* and *Q. serrata* exhibited the lowest stomatal and non-stomatal inhibition, respectively, in response to 0.7 ppm SO₂ for 20 h. The data are discussed with regard to resistance mechanisms of other plants to SO₂ exposure and implications for restoration of declined Korean forests.

Sulfur dioxide has been known not only as an air pollutant but also as a precursor of the acid rain in industrialized countries, causing direct damages to the plant metabolism and growth (Malhorta and Hocking, 1976). Furthermore, it may be considered as a chronic environmental stress responsible for forest decline in Western Europe and North America (Krouse et al., 1986; Steubing and Fangemeier, 1991). For instance, air pollutants including SO₂ and O₃ suppress photosynthesis and biomass accumulation, and change biomass allocation pattern of the plants (McLaughlin and McConathy, 1983; Natori, 1988; Furukawa, 1991). Stomatal conductance is also affected by SO₂ positively or negatively, depending on the species exposed (Black and Unsworth, 1980; Winner and Mooney 1980a).

According to Taylor (1978), two mechanisms of plant resistance to SO₂ pollution are proposed. One is 'stress avoidance' mechanism mediated by closing stomata in response to SO₂ exposure, which may reduce the extent to which SO₂ is taken into the plants, and thereby alleviate negative and direct effects of an air pollutant on internal plant tissues. The other is 'stress tolerance' mechanism facilitated by higher capacity of mesophyll tissue to assimilate, detoxify, or

repair biochemical damages by SO₂. Particularly, in chronically air-polluted areas, the plants with tolerance mechanism are more probable to survive than those with avoidance mechanism (Fitter and Hay, 1987). However, little attention has been drawn to assess resistance mechanisms of Korean woody plants to air pollutants, which may provide essential information toward establishment of restoration schemes on the declined forests in Korea.

The objectives of this study are 1) to evaluate SO₂-resistance mechanisms of several woody plants (*P. coreana*, *F. simplex*, *Q. acutissima*, *Q. variabilis* and *Q. serrata*) through investigating photosynthesis and transpiration in response to SO₂, and 2) to address some basic criteria for selection of woody plants appropriate for transplant-mediated restoration of the forests affected by air pollution.

Materials and Methods

Plant growth and measurement

Seeds of *Quercus* species (*Q. acutissima*, *Q. variabilis* and *Q. serrata*) and other two species (*P. coreana* and *F. simplex*) were collected from Seosan, Chungcheong Nam Do and Yeo-Cheon Industrial Complex, Cheonla Nam Do, respectively, in October 1993. They were germinated in pots (44×30×12 cm) in April 1994, and seedlings received Hoagland solution (50% strength)

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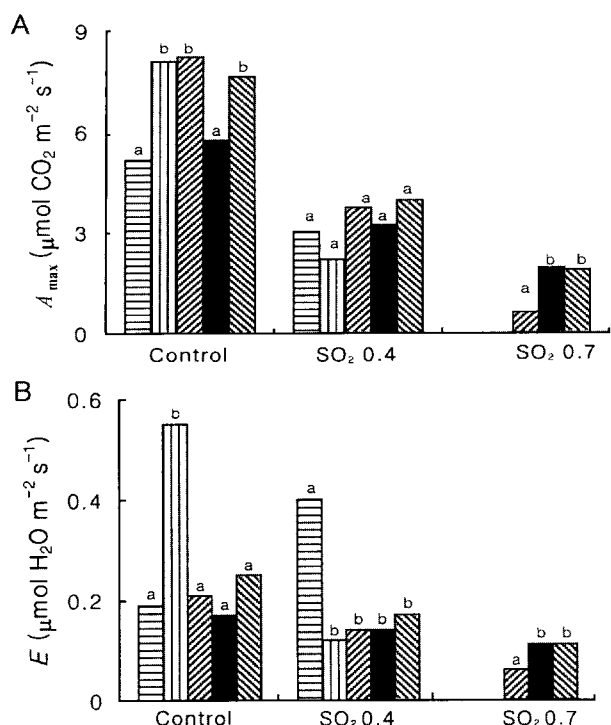


Fig. 1. Light saturated-photosynthetic rate (A_{max} , A) and transpiration (E) of *F. simplex* (□), *P. coreana* (▨), *Q. acutissima* (▧), *Q. variabilis* (■) and *Q. serrata* (▩) after fumigation with concentrations (ppm) of SO₂ 0.4 or SO₂ 0.7 (B). Control indicates plants without SO₂ fumigation. Bars with the same letters are not significantly different within each treatment.

monthly. Exposure of the plants to SO₂ was carried out using SO₂ fumigation system of National Institute of Environmental Research (NIER). All plants were 4 months old at the time of exposure to SO₂, and 5 replicates were used for each plant. Concentrations of SO₂ applied to the plants were 0.4 or 0.7 ppm with 20 h of exposure. Temperature and humidity inside the chamber were 25°C and 70%, respectively. Half an hour after the termination of SO₂ fumigation, CO₂ exchange rate was measured with infrared gas analyzer (IRGA, LCA2, ADC, U.K.), and light-saturated photosynthetic rate and transpiration were calculated on a leaf area basis using the equations of von Cammerer and Farquhar (1981). Three consecutive instantaneous measurements were taken at 30 s intervals and averaged in analysis. During the measurement, temperature was maintained between 25 and 28°C, and 2.5 mmolm⁻²s⁻¹ of additional light (Halogen lamp, ADC, U.K.) was supplied.

Calculations

Photosynthetic rates of plants decrease as a consequence of either SO₂-induced stomatal closure, or SO₂-induced inhibition on biochemical functions of photosynthetic systems (Winner and Mooney, 1980a). The former is called stomatal inhibition, and the latter non-stomatal inhibition. Expected photosynthetic rate (P_e), and stomatal- and non-stomatal inhibitions were determined by equations 1, 2, and 3, respectively

(Ikeda et al., 1992). The expected photosynthetic rate indicates a calculated photosynthetic rate, which is determined only by considering alterations in stomatal conductance due to exposure to SO₂ 0.4 or 0.7 ppm.

Expected photosynthetic rate (P_e) = $(P_o \times C_c) / C_o$ (1)

Stomatal inhibition (%) = $(1 - P_e / P_o) \times 100$ (2)

Non-stomatal inhibition (%) = $(1 - P_c / P_e) \times 100$ (3)

(C_c : transpiration of the plants with exposure to SO₂ 0.4 or 0.7, C_o : transpiration of the control plants, P_c : photosynthetic rate of the plants with exposure to SO₂ 0.4 or 0.7, P_o : photosynthetic rate of the control plants, P_e : expected photosynthetic rate of the plants with exposure to SO₂ 0.4 or 0.7). Higher stomatal inhibition indicates that the plants adopt avoidance mechanism mediated by stomatal closure in order to minimize SO₂ uptake. Lower non-stomatal inhibition indicate that they are able to tolerate deleterious effects of SO₂ on photosynthetic tissues via rapid detoxification of SO₂ or recovery from SO₂-induced damages (Ikeda et al., 1992). Data were analyzed by one-way ANOVA (Tukey test).

Results

Of the control plants, *P. coreana*, *Q. acutissima* and *Q. serrata* showed significantly higher light-saturated photosynthetic rate per unit leaf area (A_{max}) than the other plants (Fig. 1A, $P < 0.05$). After 20 h of exposure to 0.4 ppm SO₂, all the tested plants showed decreases in their photosynthesis, of which *P. coreana* had the largest reduction (72%) in its photosynthesis and *F. simplex* the smallest (41%) (Fig. 1A). Fumigation of 0.7 ppm SO₂ for 20 h also considerably decreased photosynthesis of the plants, with *P. coreana* and *F. simplex* unavailable for the measurement due to SO₂-induced complete leaf necrosis. Photosynthetic rates of *Q. variabilis* and *Q. serrata* were significantly higher than that of *Q. acutissima* after exposure to 0.7 ppm SO₂ for 20 h (Fig. 1A, $P < 0.05$). As shown in photosynthesis, transpiration rate (E) of the plants showed a tendency to decrease in response to both 0.4 and 0.7 ppm SO₂ fumigations, except for *F. simplex* fumigated with 0.4 ppm SO₂ (Fig. 1B). In addition, both *Q. variabilis* and *Q. serrata* showed significantly higher transpiration rates compared to *Q. acutissima* (Fig. 1B, $P < 0.05$).

In order to assess photosynthetic resistance of the plants to SO₂ fumigation, stomatal- and non-stomatal inhibition were calculated by equations developed by Ikeda et al. (1992). When exposed to 0.4 ppm SO₂, *F. simplex* and *P. coreana* showed the lowest stomatal and non-stomatal inhibition, respectively (Table 1). However, when exposed to 0.7 ppm SO₂ for 20 h, *Q. variabilis* and *Q. serrata* exhibited the lowest stomatal and non-stomatal inhibition, respectively (Table 1).

Table 1. Expected photosynthesis (Pe), and stomatal and non-stomatal inhibition (%) of photosynthesis by fumigation of 0.4 and 0.7 ppm SO₂

	<i>F. simplex</i>	<i>P. coreana</i>	<i>Q. acutissima</i>	<i>Q. variabilis</i>	<i>Q. serrata</i>
Expected photosynthesis (Pe, $\mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$)					
SO ₂ 0.4	11.2	1.77	5.43	4.70	5.08
SO ₂ 0.7	-	-	2.36	3.70	3.28
Actual photosynthesis ($\mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$)					
SO ₂ 0.4	3.02	2.19	3.74	3.22	3.96
SO ₂ 0.7	-	-	0.60	1.93	1.86
Stomatal inhibition (%)					
SO ₂ 0.4	0	78	35	18	33
SO ₂ 0.7	-	-	71	35	57
Non-stomatal inhibition (%)					
SO ₂ 0.4	72	0	31	31	22
SO ₂ 0.7	-	-	74	47	43

Discussion

Plant responses to SO₂ exposure

One of the most common responses of the plants to SO₂ fumigation is the reduction in their photosynthesis (Heath, 1980; Natori, 1988; Furukawa, 1991). This is also true in this study. Regardless of SO₂ concentrations, they showed reductions in their photosynthesis, which was accounted for by stomatal- and/or non-stomatal inhibition, depending on species (Winner and Mooney, 1980a).

P. coreana showed the highest stomatal inhibition at 0.4 ppm SO₂. This indicates that the reduction of photosynthesis mainly results from stomatal closure in response to SO₂ exposure, which probably minimizes direct damages by SO₂ on photosynthetic tissues via reducing SO₂ uptake. This is referred to as avoidance mechanism. However, this type of resistance is unlikely to be strong enough to allow it to survive higher SO₂ concentration, since complete necrosis was observed shortly after exposure to 0.7 ppm SO₂. In contrast, *Q. variabilis* and *Q. serrata* showed relatively lower stomatal- and non-stomatal inhibition at both concentrations of SO₂, indicating that they did not resist to SO₂ exposure by closing their stomata. Instead, they may be able to tolerate SO₂ mainly by either detoxification of SO₂ or biochemical repair of damages from SO₂ (Ziegler, 1973), which may facilitate rapid recovery of their photosynthetic functions from the deleterious effects of SO₂. This is referred to as tolerance mechanism. Reduction in photosynthetic rate of *F. simplex* after exposure to 0.4 ppm SO₂ was not due to stomatal inhibition, but due to the highest non-stomatal inhibition. Furthermore, its transpiration rate increased in response to exposure to 0.4 ppm SO₂, which may allow more SO₂ to enter through stomata. It is therefore suggested that *F. simplex* may not have either avoidance or tolerance mechanism to SO₂ exposure, at least, in this experiment.

According to Ikeda et al. (1992), plants with tolerance mechanism to air pollutants would be better candidates in the selection of plant species appropriate

for transplant than those with avoidance mechanism. This might be due to the fact that the plant resistance to SO₂ by stomatal closure is not suitable for long-term survival in chronically SO₂-polluted areas (Lee and Bae, 1991). Taken together, it seems that *Q. variabilis* and *Q. serrata* with tolerance mechanism to air pollutants are highly probable to survive air pollution than other woody plants in this study.

Implications for restoration of air pollution-damaged forests via transplant

In 1980's, most forests in the vicinity of metropolitan cities and industrialized complexes in Korea began to show symptoms of forest decline, which became a widespread phenomenon over the country in 1990's (NIER, 1993; Rhyu, 1994). Restoration of the declined forests may be achieved through either removing the pollution sources or transplanting tolerant plants to the polluted areas. Species tolerant to environmental pollution can persist through growth and reproduction or even expand their distribution range in the polluted environment (Dobson et al., 1997). The transplantation of tolerant species to the polluted areas should be preceded by such processes as the selection of plants with high resistance to anthropogenic pollutants. However, relatively little has been studied about the ecophysiological plant resistance mechanisms to air pollutants and/or acid rain in Korea, which serves to establish basic criteria for selection of plant species for restoration of declined vegetation via transplant.

In terms of evolutionary responses to environmental stresses including anthropogenic pollutants, slow-growing plants with lower photosynthetic rates could be the most successful in resisting anthropogenic stresses (Chapin III, 1991). This might be partly due to the fact that plants with higher photosynthetic rates absorb more air pollutants via stomata (Winner and Mooney, 1980b). If this is the case, intrinsically and relatively lower photosynthetic rates of *Q. variabilis* with lower transpiration as shown in this study may play an additional role in improving their resistance to SO₂ exposure through reducing SO₂ uptake. It might be therefore concluded that *Q. variabilis* with these traits and *Q. serrata* with high tolerance to SO₂ would be more appropriate as candidates for transplantation than others in restoration schemes of air-polluted forests. Indeed, they showed better growth in polluted sites within Yecheon Industrial Complex Area in Korea, and were thereby classified as tolerant species in a transplant study by You et al. (1998).

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