Absorption of Atmospheric Formaldehyde by Deciduous Broad-Leaved, Evergreen Broad-Leaved, and Coniferous Tree Species

Takayuki Kondo, Kiyoshi Hasegawa,* Ryutaro Uchida, Masanori Onishi,† Akihiro Mizukami,† and Kenji Omasa††

Department of Chemical and Biochemical Engineering, Faculty of Engineering, Toyama University, 3190 Gofuku, Toyama 930

†Toyama Prefectural Environmental Science Research Center, 17-1 Nakataikouyama, Kosugi, Toyama 939-03

††The National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305

(Received June 28, 1996)

To estimate the effect of tree planting on atmospheric formaldehyde, the absorption of formaldehyde by various tree species was examined. The absorption rates varied from 8.6 (Japanese black pine) to 137 $ng\,dm^{-2}\,h^{-1}\,ppb^{-1}$ (Lombardy poplar) at 1000 μmol of photons $m^{-2}\,s^{-1}$, and the absorption rate increased in the following order: deciduous broad-leaved tree species > evergreen broad-leaved tree species > coniferous tree species. In experiments in which the light intensity was varied, a linear relationship between the formaldehyde absorption rate and the transpiration rate was observed for three tree species. From the results obtained from a simplified gas diffusive resistance model, we can conclude that formaldehyde is absorbed through the stomata, and is rapidly metabolized by three tree species. Even at a high concentration of about 2000 ppb, trees have the ability to absorb atmospheric formaldehyde for at least 8 h without any visible foliar injury. We conclude that trees in general could act as an important sink for atmospheric formaldehyde.

Formaldehyde is a ubiquitous air pollutant that has been of great concern because of its adverse health effects. It causes irritation in humans,[1] and has been regulated because of its carcinogenic properties.[2]

Atmospheric formaldehyde is discharged from fuel combustion, garbage incineration, and the manufacture of formaldehyde, plastics, resins, and lacquers.[2] It is also produced by secondary reactions of hydrocarbons with O_3. Recently, Gabele[3] reported that atmospheric formaldehyde may increase as a result of switching from gasoline and diesel fuels to methanol fuels. Barker et al.[4] predicted that the maximum concentrations of atmospheric formaldehyde in California may be 42 ppb and 74 ppb for conventional and methanol fuels, respectively. On the other hand, the indoor concentration of formaldehyde has been found to be higher than outdoors because of indoor sources, such as wood products and furniture, which are pressed with formaldehyde-containing adhesives.[5]

Tree planting is one strategy for reducing the concentration of air pollutants in polluted urban and industrial areas.[6] Vegetation is also expected to reduce indoor air pollutants.[7] Vegetation is known to act as an important sink for inorganic air pollutants, such as SO_2,[8—10] NO_2,[8,11,12] O_3,[8,13,14] and Cl_2.[8] By contrast, few studies have been performed concerning the absorption of organic air pollutants, such as chlorinated hydrocarbons[15] and polycyclic aromatic hydrocarbons.[16,17]

There have been few reports documenting the uptake of gaseous formaldehyde by plants. Wolverton et al.[18] observed by chamber experiments that common room plants, in particular spider plant (*Chlorophytum comosum* L.), greatly reduce the concentration of gaseous formaldehyde. Girard et al.[19] and Giese et al.[20] reported that gaseous ^{14}C-formaldehyde is absorbed by sunflower (*Helianthus annuus* L.) leaves and spider plant shoots and is extensively metabolized.

However, the rate and mechanism of formaldehyde absorption by plants are still not well-understood.[20] To estimate the effect of tree planting on atmospheric formaldehyde, it is necessary to determine for various tree species the absorption rate, the absorption mechanism and plant tolerance to gaseous formaldehyde at high concentrations.

We have recently reported that atmospheric formaldehyde is absorbed by oleander (*Nerium indicum*) at an absorption rate similar to that of atmospheric NO_2.[21] However, it is not clear that other tree species have sufficient ability to absorb atmospheric formaldehyde.

This paper describes the absorption rate, the absorption mechanism, and plant tolerance to gaseous formaldehyde for deciduous broad-leaved, evergreen broad-leaved, and coniferous tree species.

Experimental

Plant Materials. Deciduous broad-leaved, evergreen broad-leaved, and coniferous seedlings were obtained from commercial nurseries in Toyama, including Lombardy poplar (*Populus nigra* var. *Italica*), locust (*Robinia pseudo-acacia* L.), Japanese maple (*Acer palmatum* Thunb.), Japanese elm (*Ulmus davidiana* Planch.

var. *japonica* Nakai), maidenhair tree (*Ginkgo biloba* L.), camellia (*Camellia japonica* L.), bamboo-leafed oak (*Quercus myrsinaefolia* Blume), Himalayan ceder (*Cedrus deodara* Loud.), and Japanese black pine (*Pinus thunbergii* Parl.). All of the seedlings were grown in a sunny laboratory under ambient light and temperature, were watered daily to maintain pot moisture near to field capacity and were fertilized weekly with liquid fertilizer (Hyponex).

Apparatus. Figure 1 shows the apparatus used for measuring the absorption rate of formaldehyde by trees. The operation was described in detail previously.[21] Humidity-controlled pure air and formaldehyde containing N_2 were introduced into a mixing chamber (G). The formaldehyde concentration of the gas mixture was controlled by the flow rate of N_2, and the humidity of the gas was regulated by the temperature of a H_2O bubbler (F).

The exposure chamber system consisted of a 120 L cylindrical acrylic chamber (J) equipped with 10 L buffer tanks (H) at its inlet and outlet. The rate of gas flow through the chamber was about 20 L min^{-1} and the chamber gas was mixed effectively by two internally mounted fans (K).

The mean inlet temperature and the relative humidity were 26±0.6°C and 50±5%, respectively. The photosynthetic photon flux density (PPFD) varied within the range of 0—1000 μmol of photons m^{-2} s^{-1} (Koito Co., Ltd., IKS-25; calibrated by Li-Cor Inc., Li-185A) at the height of the plant inside the chamber.

Measurement of Formaldehyde Absorption. Gas samples from the inlet and outlet buffer tanks were drawn at a flow rate of 1 L min^{-1} for 4 h through two bubblers in series, each containing 10 mL of 0.5% boric acid solution.[22] To 2 mL of the combined solution were added 2 mL of 5 M KOH solution (1 M = 1 mol dm^{-3}), 2 mL of 0.5% AHMT (4-amino-3-hydrazino-5-mercapto-1,2,4-triazole) solution, and 2 mL of 0.75% KIO_4 solution, successively. The inlet and outlet concentrations of formaldehyde were determined by measuring the colored solution spectrophotometrically at 550 nm.[23] The determination limit was 5 ppb of formaldehyde for a 240 L gas sample. The formaldehyde absorption rate was corrected by a "blank" experiment performed with an empty chamber. The corrected absorption rate was calculated by Eq. 1 using the procedure of Hanson et al.[12]

$$F_s = \frac{(C_i - C_o)}{A \cdot C_o} Q, \tag{1}$$

where F_s is the absorption rate of formaldehyde (ng dm^{-2} h^{-1}-ppb^{-1}), $(C_i - C_o)$ is the inlet/outlet concentration differential corrected for absorption to an empty chamber (ng m^{-3}), A is the leaf surface area (dm^2), Q is the flow rate through the exposure chamber (m^3 h^{-1}), and C_o is the outlet concentration of formaldehyde (ppb).

Measurement of the Formaldehyde Absorption Rate by Trees. The absorption rate of formaldehyde by each of nine tree species, listed in Plant Materials, was measured. The inlet concentrations of formaldehyde were within the range 65—75 ppb and the PPFD was 1000 μmol of photons m^{-2} s^{-1}. After conditioning for more than 1 h, the absorption rate of formaldehyde by the trees was measured for 4 h. The transpiration rate was determined from the decrease in the weight of the trees, which were planted in pots covered with plastic bags. The leaf temperature was measured with copper–constantan thermocouples. Shoot leaf areas for the broad-leaved species were measured with a image scanner (Sharp JX-2000), and those for conifers were computed by multiplying the total needle length by the average needle circumference which was determined from ocular micrometer measurements.

The effect of the light intensity on the rate of formaldehyde absorption by Japanese maple, bamboo-leafed oak, and Himalayan cedar was measured for 4 h while varying the light intensity from 0 to 1000 μmol of photons m^{-2} s^{-1}, at concentrations of 65—75 ppb formaldehyde.

The effect of the formaldehyde concentration on the rate of absorption by maidenhair tree, bamboo-leafed oak, and Himalayan cedar was measured while changing the formaldehyde concentration in the chamber from about 40 to about 2000 ppb at 1000 μmol of photons m^{-2} s^{-1}; the sampling time was 8 h and sampling flow rates were within the range 0.05—0.5 L min^{-1}.

Results

Absorption of Formaldehyde by Tree Species. Table 1 shows the absorption rate of formaldehyde by nine tree species, which are classified as deciduous broad-leaved, ev-

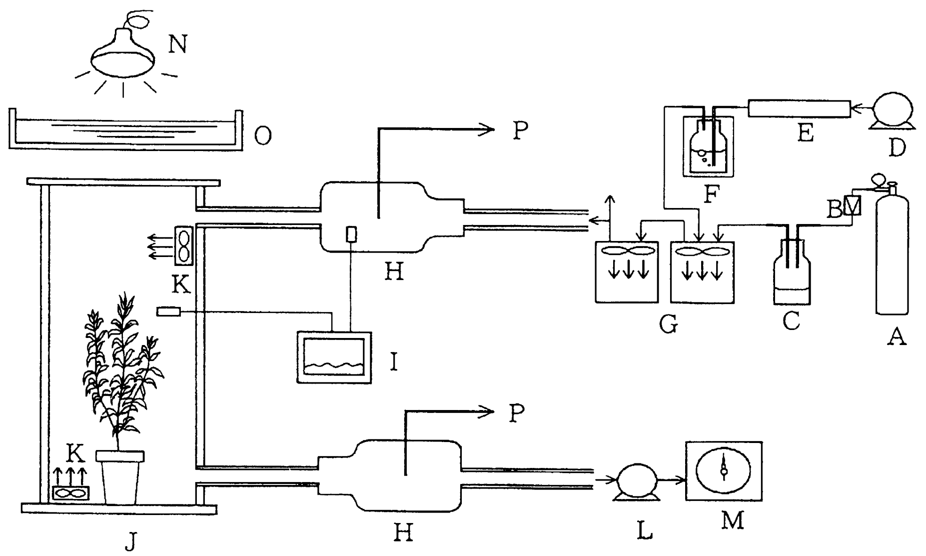

Fig. 1. Apparatus for measuring the absorption of formaldehyde by trees. A, N_2 gas; B, mass flow controller; C, formaldehyde solution (37%); D, pump; E, activated charcoal; F, H_2O bubbler; G, mixing chamber; H, buffer tank; I, thermometer and hygrometer; J, exposure chamber; K, fan; L, pump; M, dry gas meter; N, lamp; O, water filter; P, to bubblers for sampling of formaldehyde gas.

Table 1. Formaldehyde Absorption Rates and Transpiration Rates of Deciduous Broad-Leaved, Evergreen Broad-Leaved, and Coniferous Tree Species

Tree species	n	Absorption rate[a)] ng dm^{-2} h^{-1} ppb^{-1}	Transpiration rate[a)] mg dm^{-2} h^{-1} mmHg^{-1}
Deciduous broad-leaved trees			
Lombardy Poplar	8	137 ±14.4	123 ±10.5
Locust	8	113 ±28.5	99.9±21.6
Japanese Maple	11	56.1± 8.2	55.6± 7.2
Japanese Elm	8	55.2±10.2	55.3±10.2
Maidenhair Tree	8	44.3± 8.9	42.3± 4.2
Evergreen broad-leaved trees			
Camellia	9	46.2±11.6	41.3±12.1
Bamboo-leafed Oak	9	44.0± 7.9	44.1± 4.8
Coniferous trees			
Himalayan Cedar	8	25.7± 1.7	23.9± 2.0
Japanese Black Pine	8	8.6± 1.8	7.6± 1.2

a) Mean value and standard deviation. Photosynthetic photon flux density: 1000 µmol of photons m^{-2} s^{-1}.

ergreen broad-leaved, and coniferous tree species, under a near ambient formaldehyde concentration of 65—75 ppb at 1000 µmol of photons m^{-2} s^{-1}. The absorption rates varied from 8.6 (Japanese black pine) to 137 ng dm^{-2} h^{-1} ppb^{-1} (Lombardy poplar) and the absorption rates increased in the order of deciduous broad-leaved tree species > evergreen broad-leaved tree species > coniferous tree species. The trees exhibiting higher absorption rates of formaldehyde had greater transpiration rates.

The absorption rates were normalized for the outlet concentration of formaldehyde and the leaf surface area containing stomata, that is one side of each leaf for the broad-leaved species[24)] and the total leaf surface for the conifers. Since a uniform distribution of formaldehyde in the chamber must have been attained, the outlet concentration of formaldehyde was considered to be equal to that in the chamber, itself.[11)] The transpiration rate was normalized for the leaf area and the vapor pressure of the water differential between the interior of the leaf and the atmosphere.

Figure 2 shows the linear relationship between the absorption rates of formaldehyde and the transpiration rates of nine tree species (r=0.983, n=77). Interspecies variation in the absorption rate appeared to be based on the variation in the transpiration rate.

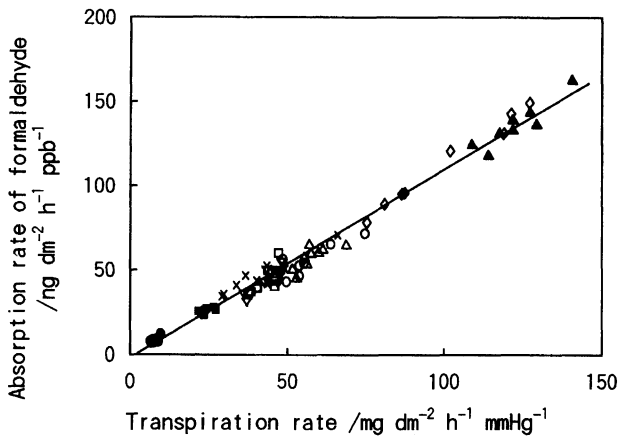

Fig. 2. Relationship between the formaldehyde absorption rate and the transpiration rate for nine tree species. ▲, Lombardy poplar; ◇, Locust; △, Japanese maple; ○, Japanese elm; □, Maidenhair tree; ×, Camellia; ▽, Bamboo-leafed oak; ■, Himalayan ceder; ●, Japanese black pine.

Effects of Light Intensity. It is known that the extent of stomatal conductance correlates with the light intensity.[11,12)] Accordingly, we examined the relationship between the absorption rate of formaldehyde and stomatal conductance by varying the light intensity for three representative tree species. Table 2 gives the absorption rate of formaldehyde by Japanese maple (deciduous broad-leaved tree), bamboo-leafed oak (evergreen broad-leaved tree), and Himalayan cedar (conifer) at 0, 600, and 1000 µmol of photons m^{-2} s^{-1}. The formaldehyde absorption rate of each species increased as the level of PPFD increased.

Figures 3a, 3b, and 3c show the relationship between the absorption rates of formaldehyde and the transpiration rates of the three tree species, which were obtained from experiments in which the light intensity was varied. A linear relationship between the absorption rate and the transpiration rate was observed for each of the species, Japanese maple (r=0.970, n=27), bamboo-leafed oak (r=0.967, n=25), and Himalayan cedar (r=0.979, n=23).

Effects of Formaldehyde Concentration on the Absorption Rate. The effect of the formaldehyde concentration on the absorption rate was examined for maidenhair tree (deciduous broad-leaved tree), bamboo-leafed oak, and Himalayan cedar. Figure 4 shows the relationship between the absorption rate of formaldehyde and its concentration for three tree species. Within the formaldehyde concentration range from near to the ambient concentration to about 2000 ppb, the absorption rate of formaldehyde increased linearly with increasing formaldehyde concentration for maidenhair

Table 2. Formaldehyde Absorption Rate by Japanese Maple, Bamboo-Leafed Oak, and Himalayan Cedar

PPFD[a)]	Absroption rate[b)]/ng dm^{-2} h^{-1} ppb^{-1}		
μmol of photons m^{-2} s^{-1}	Japanese Maple	Bamboo-leafed Oak	Himalayan Cedar
0	3.6±3.2	2.7±1.6	1.9±0.3
600	40.1±9.6	22.6±4.8	13.6±2.0
1000	56.1±8.2	44.0±7.9	25.7±1.7

a) Photosynthetic photon flux density. b) Mean value and standard deviation (*n*=7—11).

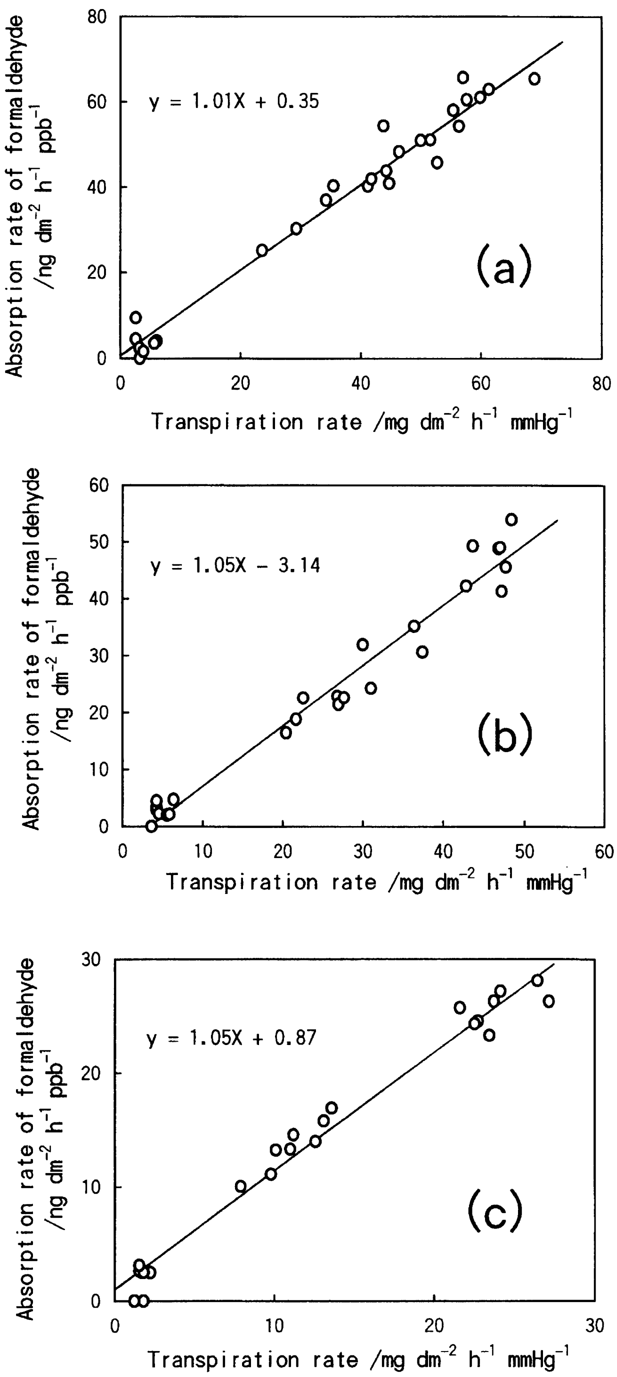

Fig. 3. Relationship between the formaldehyde absorption rate and the transpiration rate of three tree species. (a) Japanese maple; (b) Bamboo-leafed oak; (c) Himalayan cedar.

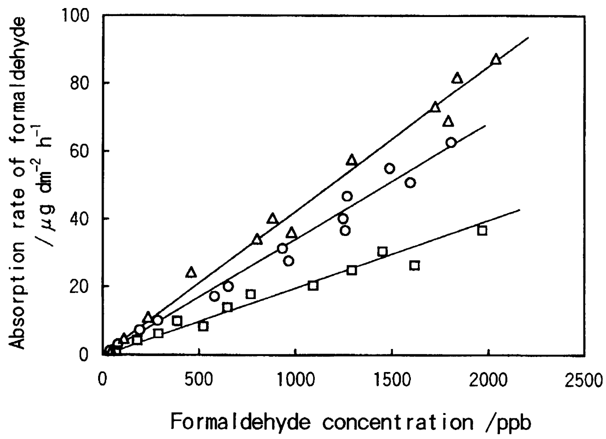

Fig. 4. Relationship between the formaldehyde absorption rate of three tree species and the formaldehyde concentration. □, Maidenhair tree; △, Bamboo-leafed oak; ○, Himalayan cedar.

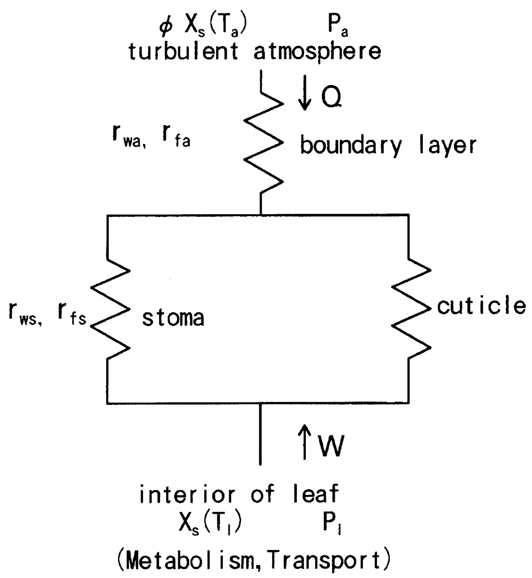

Fig. 5. Resistance network for formaldehyde absorption and transpiration.

tree, bamboo-leafed oak, and Himalayan cedar.

Discussion

Absorption Mechanism of Formaldehyde by Trees. Omasa et al.[25,26] previously reported that inorganic air pollutants, such as SO_2, NO_2, and O_3, are absorbed by plants through the stomata. By contrast, it has been reported that lipophilic organic chemicals, such as chlorinated hydrocarbons and polycyclic aromatic hydrocarbons, are absorbed by plants through the cuticle.[15—17] However, the absorption mechanism of formaldehyde is still not known[20]

As shown in Table 2, the absorption rates of formaldehyde by Japanese maple, bamboo-leafed oak, and Himalayan cedar increased as the level of PPFD increased. A measurement of formaldehyde absorption whilst varying the light intensity can provide information for evaluating the surface vs. internal absorption of formaldehyde. As shown in Figs. 3a, 3b, and 3c, in the dark neither absorption through the cuticle nor adsorption to the leaf surface were substantial, as judged from the *y*-intercepts of the absorption lines of formaldehyde.

We analyzed the absorption mechanism of formaldehyde using a simplified gas-diffusive resistance model, shown in Fig. 5, which was previously used to study the absorption mechanism of inorganic air pollutants such as SO_2, NO_2, and O_3.[25,26] The model consists of a boundary layer, stomatal, and cuticle resistances of formaldehyde and water vapor. Adjacent to the leaf surface there is an unstirred air layer called the boundary layer, the resistance of which depends on the wind speed and the leaf surface topography. The stomatal resistance depends on the degree of stomatal opening. It is unnecessary to take into account the cuticle resistance for the reason discussed in Figs. 3a, 3b, and 3c.

The transpiration rate and formaldehyde absorption rate of the leaves are given by the following equations,[25,26]

$$W = k\{X_s(T_l) - \phi \cdot X_s(T_a\}/\{k_w(r_{wa} + r_{ws})\}, \tag{2}$$

$$Q = k(P_a - P_l)/\{k_f(r_{fa} + r_{fs})\}, \tag{3}$$

where W is the transpiration rate ($g\,dm^{-2}\,h^{-1}$), Q is the absorption rate of formaldehyde ($g\,dm^{-2}\,h^{-1}$), k is a constant, $X_s(T)$ is the saturated vapor pressure of water at T °C (mmHg, 1 mmHg=133.322 Pa), T_l is the leaf temperature (°C), T_a is the ambient temperature in the chamber (°C), ϕ is the relative humidity in the chamber, k_w is the transformation coefficient for converting the density of saturated water vapor into saturated vapor pressure of water and equals 1.04×10^6 mmHg $cm^3\,g^{-1}$, r_{wa} is the boundary layer resistance to the transfer of water vapor ($s\,cm^{-1}$), r_{ws} is the stomatal resistance to the transfer of water vapor ($s\,cm^{-1}$), P_a is the formaldehyde concentration in the atmosphere (ppb), P_l is the formaldehyde concentration at the gas-liquid interface in the leaf (ppb), k_f is the transformation coefficient for converting the density of formaldehyde gas into formaldehyde concentration and equals 8.21×10^{11} ppb $cm^3\,g^{-1}$, r_{fa} is the boundary layer resistance to the transfer of formaldehyde gas ($s\,cm^{-1}$), and r_{fs} is the stomatal resistance to the transfer of formaldehyde gas ($s\,cm^{-1}$).

The resistances, r_{fa} and r_{fs}, for formaldehyde are obtained from the following equations:[27]

$$r_{fa} = r_{wa}(D_f/D_w)^{-2/3}, \tag{4}$$

$$r_{fs} = r_{ws}(D_f/D_w)^{-1}, \tag{5}$$

where D_f and D_w are the diffusivities of formaldehyde and water vapor in air, respectively. The quotient, D_f/D_w, is assumed to be equal to the square root of the ratio of the molecular mass of water to that of formaldehyde. This is in analogy to the relation commonly used to obtain the stomatal conductance for CO_2.[28]

The transpiration rate divided by the water vapor pressure differences between the interior of the leaf and the atmosphere, W', is calculated by

$$W' = W/\{X_s(T_l) - \phi \cdot X_s(T_a)\}. \tag{6}$$

The absorption rate divided by the formaldehyde concentration differences between the interior of the leaf and the atmosphere, Q', is calculated by

$$Q' = Q/(P_a - P_l). \tag{7}$$

If P_l is assumed to be zero, Eq. 7 may be written as

$$Q' = Q/P_a. \tag{8}$$

For simplification, if equalities $r_{fa}/r_{wa}=r_{fs}/r_{ws}=k_r$ are assumed, Q'/W' may be written as

$$Q'/W' = k_w/(k_f \cdot k_r). \tag{9}$$

If it is assumed that the transports of formaldehyde gas and water vapor depend only on the boundary layer resistance, $k_r=r_{fa}/r_{wa}$, and k_r is 1.19, then $k_w/(k_f \cdot k_r)=1.07\times10^{-6}$ mmHg ppb^{-1}. If it is assumed that the transports of formaldehyde gas and water vapor depend only on the stomatal resistance, $k_r=r_{fs}/r_{ws}$, and k_r is 1.29, then $k_w/(k_f \cdot k_r)=0.98\times10^{-6}$ mmHg ppb^{-1}. If the value of Q'/W' is within the range of that theoretically derived from gaseous diffusion, then P_l may be assumed to be zero.

The values of Q'/W', which are obtained from the slope of the absorption lines shown in Figs. 3a, 3b, and 3c, are 1.01×10^{-6} mmHg ppb^{-1} for Japanese maple (Fig. 3a), 1.05×10^{-6} mmHg ppb^{-1} for bamboo-leafed oak (Fig. 3b), and 1.05×10^{-6} mmHg ppb^{-1} for Himalayan cedar (Fig. 3c). These values of Q'/W' are within the range of values theoretically derived from gaseous diffusion. This result supports the assumption that P_l equals zero, and that the absorption rate of formaldehyde can be explained by the boundary layer and stomatal resistances. These facts suggest that formaldehyde is absorbed through the stomata and is rapidly metabolized or transported within the leaf tissue.

Girard et al.[19] found that gaseous ^{14}C-formaldehyde is absorbed and predominantly incorporated into amino acids of younger sunflower leaves. Giese et al.[20] reported that gaseous ^{14}C-formaldehyde taken up by spider plant shoots is extensively metabolized and that the metabolic rate is 12.8 $\mu g\,h^{-1}\,g^{-1}$ fresh leaf weight. Krall and Tolbert[29] reported that barley (*Hordeum vulgare* L.) shoots incorporate ^{14}C-formaldehyde into sugars, amino acids, and choline in the leaves and that the metabolic rate is 5 $\mu g\,h^{-1}\,g^{-1}$ fresh leaf weight. In our study, the absorption rates of formaldehyde by Japanese maple, bamboo-leafed oak, and Himalayan cedar corresponded to 2.5, 1.3, and 0.9 $\mu g\,h^{-1}\,g^{-1}$ fresh leaf weight at 1000 μmol of photons $m^{-2}\,s^{-1}$. It appears that these three tree species have the ability to metabolize formaldehyde absorbed from the atmosphere. From our experimental results, we cannot know the pathways of formaldehyde metabolism in leaf tissue, although we think that similar metabolic pathways to those described above[19,20,29] play important roles in the absorption of formaldehyde. Thus, we conclude that formaldehyde is absorbed through the stomata, and is rapidly metabolized by deciduous broad-leaved, evergreen broad-leaved and coniferous tree species.

Omasa et al.[25,26] reported that the absorption rates of SO_2, NO_2, and O_3 can be explained by boundary layer and stomatal resistances. Our results suggest that the absorption rates of those air pollutants may be comparable to those of formaldehyde, based on the ratios of the diffusivities of the air pollutants and formaldehyde; the ratios of the diffusivity of SO_2, NO_2, or O_3 and formaldehyde are as 0.68, 0.81, and 0.79, respectively, indicating that atmospheric formaldehyde may be absorbed by trees at a rate similar to those of atmospheric SO_2, NO_2, and O_3.

Differences in the Absorption Rates of Formaldehyde by Tree Species. As described in Table 1, the absorption rates of formaldehyde increased in the following order: deciduous broad-leaved tree species > evergreen broad-leaved tree species > coniferous tree species. Based on the absorption mechanism of formaldehyde, the tree species exhibiting higher absorption rate of formaldehyde should have lower leaf diffusive resistance, which corresponds to higher transpiration rate. This was confirmed by the linear relationship between the absorption rates of formaldehyde and the transpiration rates as shown in Fig. 2.

Hanson et al.[12] observed that the leaf diffusive resistance of almost broad-leaved tree species give lower values than conifers. Fujinuma et al.[30] measured the leaf diffusive resistance of 113 broad-leaved tree species (deciduous 78, evergreen 35) and reported that the deciduous tree species show significantly lower values than the evergreen tree species. By a comparison of the mean values of the stomatal density on the abaxial surface of the deciduous and evergreen tree species, they concluded that there is no significant correlation between the leaf diffusive resistance and the stomatal density. Accordingly, we can not evaluate the absorption rate of formaldehyde by the degree of stomatal density. Other factors, such as the degree of stomatal opening, may play an important role in the absorption rate of formaldehyde. At present, we can only say that the degree of the leaf diffusive resistance of tree species reflects the order of the formaldehyde absorption rate of the tree species.

Plant Tolerance to Gaseous Formaldehyde of High Concentration. The indoor concentration of formaldehyde has been found to be higher than that outdoors. Singh et al.[31] showed that the formaldehyde concentrations in urban sites in the USA are within the range 6.6—45.9 ppb. Zhang et al.[5] found that indoor formaldehyde concentrations in six residential houses were within the range 26.9—101.7 ppb. In particular, in some special environments, such as new mobile homes, very high levels of formaldehyde (2400 ppb) are occasionally observed.[32] Therefore, plant tolerance to formaldehyde of a high concentration (about 2000 ppb) was examined.

As shown in Fig. 4, increasing the concentration of formaldehyde did not affect the absorption ability of three tree species, and no visible foliar injury was observed during the 8 h exposure period, even at a high concentration of about 2000 ppb. These results are consistent with those of the limited reports on other plant species. Haagen–Smit et al.[33] observed that several plant species remained unchanged after a 2 h exposure to formaldehyde gas of 2000 ppb. Giese et al.[20] reported that no visible foliar injury to spider plants was observed after 5 h exposure to 10000 ppb. Mutters et al.[34] observed that plant growth is higher when plants are exposed to gaseous formaldehyde of high concentration (400 ppb), and that higher concentrations of sucrose and glycine in leaf tissue are associated with formaldehyde treatment. They concluded that atmospheric formaldehyde would probably have no harmful effect on short-term growth of beans at 400 ppb.

Even at very high concentrations of about 2000 ppb, trees can absorb atmospheric formaldehyde for at least 8 h. Therefore, trees have a sufficient ability to absorb atmospheric formaldehyde in urban areas or within the home. We conclude that trees in general could act as an important sink for atmospheric formaldehyde.

References

1) M. O. Amder, J. Doull, and C. D. Klaassen, "Air Pollutants. In Casarett and Doull's Toxicology: The Basic Science of Poisons," 4th ed, Pergamon Press, New York (1991), p. 866.

2) National Research Council, "Formaldehyde and Other Aldehydes," National Academy Press, Washington, D.C. (1981).

3) P. A. Gabele, *J. Air Waste Manage. Assoc.*, **40**, 296 (1990).

4) J. R. Barker, J. M. Lantis, and D. T. Tingey, "EPA/600/D-91/132 (1991)," Environmental Research Laboratory, U.S. Environmental Protection Agency.

5) J. Zhang, Q. He, and P. J. Lioy, *Environ. Sci. Technol.*, **28**, 146 (1994).

6) Environment Agency Government of Japan, "Guide for Tree Planting to Reduce Atmospheric Contaminants," Daiichi Hoki, Tokyo (1989).

7) I. Misaka, T. Ishiguro, T. Ro, M. Kiyota, T. Hirano, and I. Aiga, "Proc. of 33rd Annual Meeting of the Japan Soc. Air Pollut.," Osaka (1992), Abstr., p. 322.

8) A. C. Hill, *J. Air Pollut. Control Assoc.*, **21**, 341 (1971).

9) T. Elkiey, D. P. Ormrod, and B. Marie, *Hort Science*, **17**, 358 (1982).

10) B. R. Roberts, *Environ. Pollut.*, **7**, 133 (1974).

11) H. H. Rogers, H. E. Jeffries, and A. M. Witherspoon, *J. Environ. Qual.*, **8**, 551 (1979).

12) P. J. Hanson, K. Rott, G. E. Taylor, Jr., C. A. Gunderson, S. E. Lindberg, and B. M. Ross-Todd, *Atmos. Environ.*, **23**, 1783 (1989).

13) A. M. Townsend, *J. Am. Soc. Hort. Sci.*, **99**, 206 (1974).

14) Y. Fujinami, T. Furukawa, T. Totuka, and T. Tazaki, *Environ. Control Biol.*, **25**, 31 (1987).

15) E. Bacci and C. Gaggi, *Chemosphere*, **16**, 2515 (1987).

16) S. L. Simonich and R. A. Hites, *Environ. Sci. Technol.*, **28**, 939 (1994).

17) S. L. Simonich and R. A. Hites, *Nature*, **370**, 49 (1994).
18) B. C. Wolverton, R. C. McDonald, and E. A. Watkins, Jr., *Econ. Bot.*, **38**, 224 (1984).
19) F. Girard, P. Jolivet, and Y. Belot, *C. R. Acad. Sci.*, **309**, 447 (1989).
20) M. Giese, U. Bauer-Doranth, C. Langebartels, and H. Sandermann, *Plant Physiol.*, **104**, 1301 (1994).
21) T. Kondo, K. Hasegawa, R. Uchida, M. Onishi, A. Mizukami, and K. Omasa, *Environ. Sci. Technol.*, **29**, 2901 (1995).
22) Environment Agency Government of Japan, " Guide for Measurement of Air Pollutants," Environmental Agency, Tokyo (1988), p. 419.
23) R. G. Dickinson and N. W. Jacobsen, *J. Chem. Soc., Chem. Commum.*, **1970**, 1719.
24) W. Larcher, "Regulation of Gas Exchange by the Stomata. In: Physiological Plant Ecology," Springer-Verlag, Heidelberg (1975), p. 30.
25) K. Omasa and F. Abo, *J. Agric. Meteorol.*, **34**, 51 (1978).
26) K. Omasa, F. Abo, T. Natori, and T. Totsuka, *J. Agric. Meteorol.*, **35**, 77 (1979).
27) J. L. Monteith, "Principles of Environmental Physics," Edward Arnold, London (1973), p. 134.
28) P. G. Jarvis, "The Estimation of Resistances to Carbon Dioxide Transfer. In Plant Photosynthetic Production. Manual of Methods. Chapter 16," ed by Z. Sestak, J. Catsky, and P. G. Jarvis, Dr. W. Junk N. V., The Hague (1971), p. 566.
29) A. R. Krall and N. E. Tolbert, *Plant Physiol.*, **32**, 321 (1957).
30) Y. Fujinuma, T. Machida, K. Okano, T. Natori, and T. Totsuka, *Res. Rep. Natl. Inst. Environ. Stud.*, **82**, 13 (1985).
31) H. B. Singh, L. J. Salas, and R. E. Stiles, *Environ. Sci. Technol.*, **16**, 872 (1982).
32) National Research Council, "Indoor Pollutants," National Academy Press, Washington, D.C. (1981).
33) A. J. Haagen-Smit, E. F. Darley, M. Zaitlin, H. Hull, and W. Noble, *Plant Physiol.*, **27**, 18 (1952).
34) R. G. Mutters, M. Madore, and A. Bytnerowicz, *J. Air Waste Manage. Assoc.*, **43**, 113 (1993).