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Estimation of the Effects of Air Pollutants on Tree Ring Growth in Black Pines (*Pinus thunbergii*)

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ABSTRACT: Tree-ring width analysis has been used to assess the effects of air pollution on tree growth around industrial complexes. Our study was conducted to elucidate the effect of air pollutants on annual ring growth in black pines *(Pinus thunbergii)* of age 41～48 years around Ulsan Metropolitan City. The growth data were analyzed by multiple regression and the results are as follows: 1. The annual ring increment of black pines increased with tree age until age 40 years and then decreased gradually after age 40 years. 2. The increment of annual ring width of black pines was affected more by precipitation and evapotranspiration than air temperature. An annual ring decline appeared in the years 1968～1983, when annual ring indices below zero were observed. Decreased annual ring growth during this period may have been due to air pollution. 3. The heavy metal with the strongest effect on annual ring growth of black pines in the experimental stand was lead (Pb). The concentration of lead in the stand was estimated as over 6 ppm. 4. The technique of tree-ring width analysis may be useful for estimation of the extent of pollution in forest areas near industrial complexes.

Key words: Air pollutant, Black pine, Dendrochronology, Heavy metal, Tree ring

INTRODUCTION

Environmental changes in forest habitats in terrestrial ecosystems give rise to heterogeneity in the width of annual rings in trees (Schweingruber 1988). Many studies have tried to explain abrupt decreases in ring growth rates and heterogeneity in annual ring width as the result of environmental factors such as drought and environmental pollution (Fritts 1976, Hughes et al. 1982, Cramer 1984, Weiss et al. 1985, Johnson et al. 1986).

Severe droughts affect tree growth in both polluted and unpolluted areas, but trees in unpolluted areas recover more easily than those in polluted areas. Factors such as drought or contamination by pollutants can lead to tree death or lower tree growth rates. The accumulation of pollutants has given rise to widespread and severe forest decline in many parts of Europe and North America (Leblanc and Loehle 1993).

For many years, air pollutants have been recognized as a factor influencing tree growth and there is now an extensive literature on the subject. Industrial plants emitting gases such as sulfur dioxide and hydrogen fluoride or particulates such as soot, copper, and nickel have caused severe reductions in tree growth and even mortality of trees (Suzuki 1975, Thompson 1981, Innes and Cook 1989, Yasuda et al. 1993, Smith 1980).

Whereas air pollution is clearly involved in growth depression and mortality around point sources of pollution, its exact role in recent declines remains unproven. Tree-ring analysis represents a possible technique for assessing the reduction in growth associated with both forms of decline.

Since the inception of studies of climate and tree growth by means of annual ring analysis (Douglass 1919), tree ring analysis has been used to measure the effects of pollution in many parts of the world (Inners and Cook 1989, Majumdar et al. 1991, Cutter and Guyette 1993, Bert 1993, West et al. 1993, Kim and Fukazawa 1997). The tree-ring technique can provide useful information about the age distribution and the ratio of damaged trees in polluted areas.

Ulsan Metropolitan City was the first industrial complex established in Korea in 1962 and is now the center of the heavy chemical industry in Korea, and as a result, air pollution in the vicinity of Ulsan has become a serious problem. Studies on the effects of air pollutants on terrestrial ecosystems in the area since the 1980's have been conducted in a piecemeal manner by several different workers.

The floristic composition and biodiversity of plant communities located near sources of pollution have decreased and black pines (*Pinus thunbergii*), in particular, exhibit symptoms of substantial damage from exposure to airborne pollutants. However, to date, studies on the effects of air contaminants on the growth patterns of annual rings of black pines have not been conducted. In this paper, we report the results of our study of the relationship between air

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pollutants and growth patterns of annual rings of black pines living near pollution sources.

MATERIALS AND METHODS

Sampling Site

The sampling site is located on a ridge adjacent to the road connecting Ulsan to Busan Metropolitan City. The vegetation on the ridge, which belongs to the warm-temperate forest zone, is mainly composed of black pines (*P. thunbergii*). The site is affected directly or indirectly by air pollutants emitting from the Onsan industrial complex, a heavy industrial complex and a petrochemical industrial complex. In addition, air pollutants emitted from vehicles on the road may affect the vegetation. We collected five disks from black pines aged 41～48 years living on the ridge 3～5 m from the road (Fig. 1).

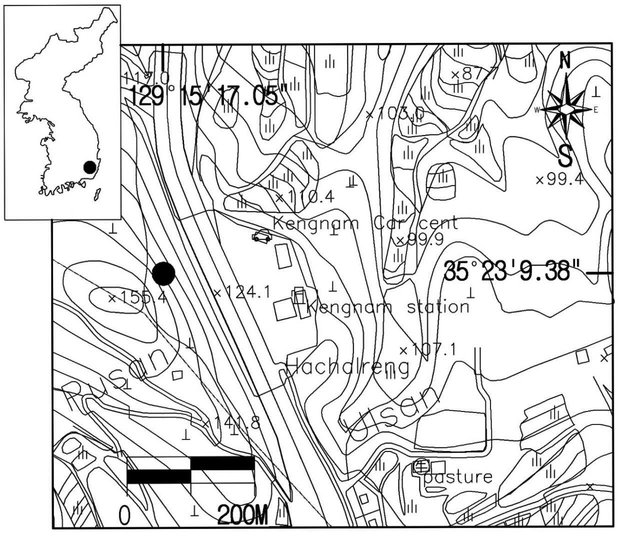

Fig. 1. Map of the sampling site. (●: sampling site)

Measurement of Annual Ring Growth

Tree-ring analysis involves the measurement of the annual radial growth of trees. We measured the annual ring widths of eight disks collected from black pines in eight directions from the center of disks to the nearest 1/100 mm, and estimated the radial growth of trees in each year as the mean of the increment values.

Analysis of Growth Patterns

We plotted the radial increment values measured from five disks against tree age, and then calculated growth patterns and changes in annual ring growth by multiple regression analysis (the package for computer calculation and analysis SPSS PC^+ 7.0).

Analysis of Declines in Ring Growth Associated with Pollution

According to Graybill's hypothesis (Schweingruber 1988), factors affecting tree growth include tree age, physiological condition, climate, and damage by insects and synthetic factors (e.g. pollution, contamination). We only analyzed the effects of synthetic factors on growth of black pines, while controlling for the effects of the other factors described above.

Analysis of Heavy Metal Content

To elucidate the effects of heavy metals such as Cu, Cr, Pb, Ni, Fe, Zn, Mg, Ca and Mn on annual ring growth, we analyzed annual ring growth for each three-year period in the disks, and measured

Table. 1. Heavy metal contents of disks analyzed by Inductively Coupled Plasma-Mass Spectrometry Unit: ppm

Year	No.	Cu	Cr	Pb	Ni	Fe	Zn	Mg	Ca	Mn
1961～1963	12	1.00	1.63	3.39	1.35	18.77	10.93	102	664	70.79
1964～1966	11	1.30	3.02	5.97	2.38	20.99	39.07	109	710	73.95
1967～1969	10	1.40	2.90	5.60	2.95	23.52	46.88	121	688	72.41
1970～1972	9	1.08	1.94	5.23	1.92	14.59	13.18	97	582	57.93
1973～1975	8	1.17	3.96	9.22	4.01	27.80	23.34	103	572	61.03
1976～1978	7	1.36	0.55	9.44	0.40	9.49	27.72	105	591	65.36
1979～1981	6	1.06	1.83	6.42	1.91	15.52	30.61	100	552	58.09
1982～1984	5	1.58	0.41	4.75	0.22	13.26	25.52	127	634	76.98
1985～1987	4	1.34	1.87	1.47	1.93	17.44	9.20	97	533	58.92
1988～1990	3	1.34	3.17	2.96	3.34	23.69	13.68	89	442	48.35
1991～1993	2	1.32	3.20	2.48	3.44	26.50	15.46	95	456	48.13
1994～1995	1	1.74	3.05	2.90	3.18	40.52	13.83	151	505	67.84

their heavy metal levels using Inductively Coupled Plasma-Mass Spectrometry (ICP, HP4500 G1820, USA). We collected heavy metal data from samples encompassing three-year intervals from each disk, resulting in a total of 66 samples.

RESULTS AND DISCUSSION

Variation in Annual Ring Width and Growth Patterns

The increment of annual ring width in the five disks varied with the physiological and environmental conditions of each tree (Fig. 2). Ring width increment decreased in disk 1 and disk 5 during the early growth stage, at ages 10 years to 20 years. In the other disks, however, annual ring width growth increased in the early growth stage and decreased in the late growth stage (Fig. 3).

The relationship between annual ring width and tree age can expressed as:

Estimated annual ring width

$$= 0.98 + 0.10755\ (\text{age}) - 2.037 \times 10^{-5}\ (\text{age})^3 \cdots\cdots \text{Equation 1}$$

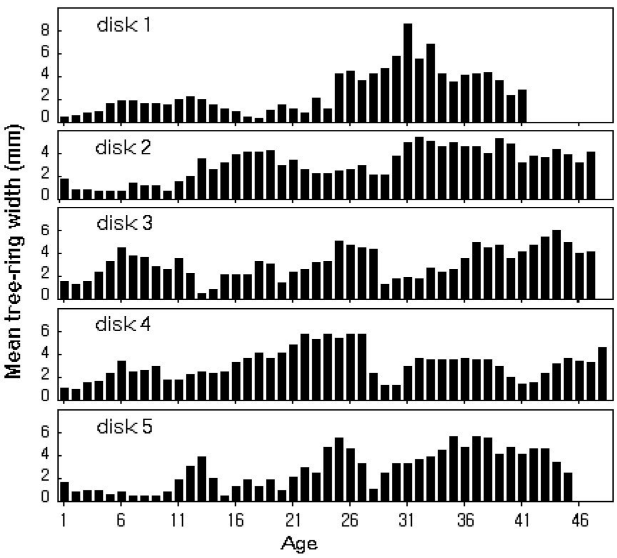

Fig. 2. Annual ring width for each tree age for disks 1～5.

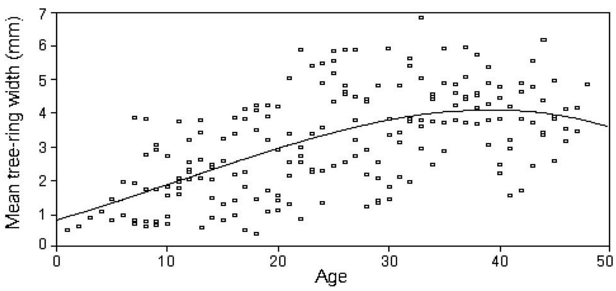

Fig. 3. Estimated relationship between annual ring width and tree age.

From equation 1, we estimated the maximum width of annual ring as 5.35 mm. Accordingly, Equation 1 predicts that the annual ring growth of black pines will increase until age 42 years and width 5.4 mm, and decrease subsequently.

Analysis of Growth Factors by Graybill's Hypothesis

Graybill's equation (below) incorporates a number of factors affecting annual ring growth.

$$R(t) = Ct + Bt + D_1t + D_2t + Et \cdots\cdots\cdots\cdots \text{Equation 2}$$

$R(t)$: ring width
Bt: biological growth trend (age)
Ct: climatic growth trend
D_1t: disturbance signal unique to the individual tree
D_2t: disturbance signal common to most individual trees
Et: Error

To ascertain whether pollution influenced the ring-growth of trees in our sample, it is necessary to control for the effects of climatic and biological factors such as air temperature, precipitation and relative humidity, evapotranspiration and insect damage. To control for the effects of age (Bt), climate (Ct) and insect damage (D_1t), we used the estimated annual ring width and the minimal value of annual ring width measured in five disks, respectively. We ignored the effects of error (Et) because we were able to analyze a large sample of annual rings.

Annual Ring Index

We calculated the annual ring index as mean annual ring increment/estimated annual ring width according to the equation 2.

Fig. 4 and Fig. 5 show the annual ring indices for each disk plotted against tree age and year, respectively. The distribution of annual ring indices for each tree age differs from that of the annual ring widths (Figs. 3 and 4), which indicates that the trees have experienced some factors promoting irregular growth such as climatic variation or pollution.

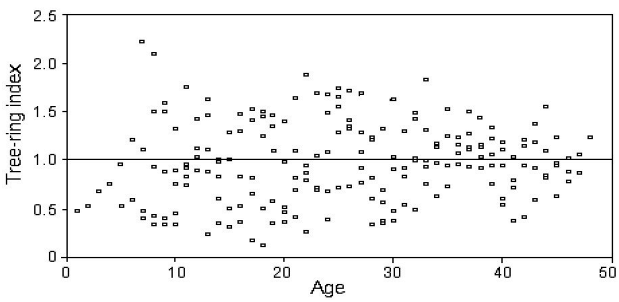

Fig. 4. Annual ring indices plotted against tree age.

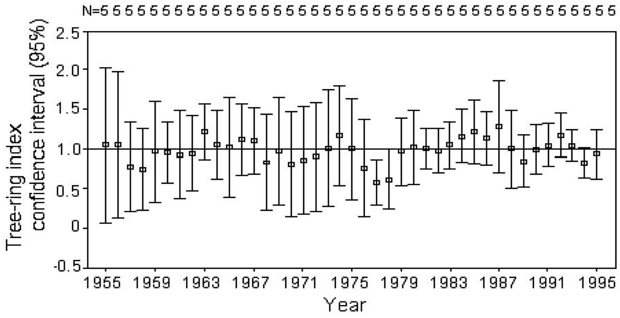

Fig. 5. Annual ring indices plotted against year.

The annual ring indices were relatively low, with values below 1, from 1968 to 1978 (Fig. 5), while the distribution of values was irregular (Fig. 4). Values below 1 may reflect the effects of pollution, rather than climatic variation. Increases and decreases in the annual ring index resulting from climatic factors should be sudden, but variation in the annual ring indices resulting from contamination is gradual (Fig. 5).

Climatic Factors and Annual Ring Indices

Thornthwaite(1948) described the relationship between the annual ring index and climatic factors (potential evapotranspiration and precipitation) as follows:

Annual ring index

$$= 0.001024\ (\text{precipitation yr}^{-1}) - 0.01667\ (\text{potential evaporation yr}^{-1}) + 0.944 \quad \text{Equation 3}$$

Air temperature and precipitation are critical factors affecting the distribution of vegetation over the Korean peninsula. These two factors also affect tree ring growth, but our study site, Ulsan Metropolitan City, is included in the warm-temperate forest zone where temperatures are optimal for plant growth. Accordingly, we assumed that only precipitation and potential evaporation affected the annual ring growth of black pines.

Fig. 6 shows the relationship between precipitation, potential evaporation and the annual ring index.

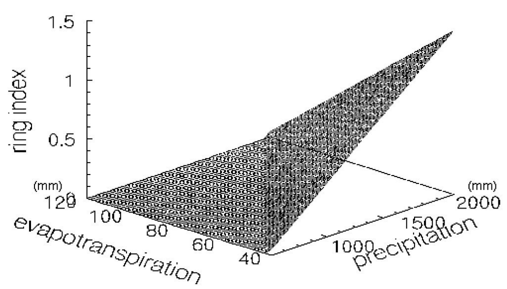

Fig. 6. Relationship between precipitation and potential evaporation and annual ring indices.

Pollution and Tree Ring Indices

If the effects of tree age and climatic factors on annual ring growth are eliminated, we can infer that the observed declines in the tree ring indices were due to the remaining factor, that is, pollution. Tree ring indices from 1968 to 1983 were relatively low, with most values below zero (Fig. 7). We conclude that the lower indices during this 30-year period were due to environmental pollution.

Relationship between Air Pollutants and Annual Ring Indices

Sulfur dioxide (SO_2), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO) and TSP (total suspended particulate) were the main air pollutants in the stand. However, the impact of these air pollutants on the annual ring index was insignificant. In particular, the drastic changes in emissions of sulfur dioxide that have occurred since the early 1980's did not show a pronounced effect on annual ring growth.

Relationship between Heavy Metals and Annual Ring Indices

Lead and zinc concentrations in the stand followed similar patterns over time, and tree-ring indices also changed drastically with changing concentrations of lead from 1962 to 1994 (Fig. 8). Accordingly, we

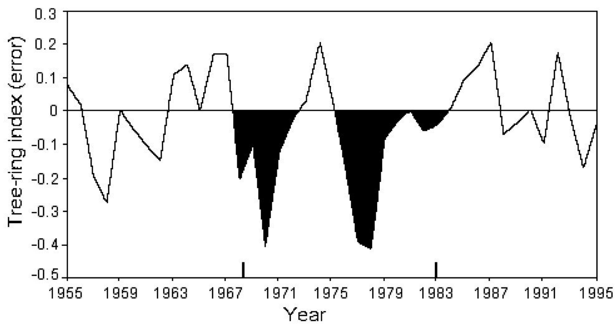

Fig. 7. Variation in tree-ring indices (error) from 1955 to 1995.

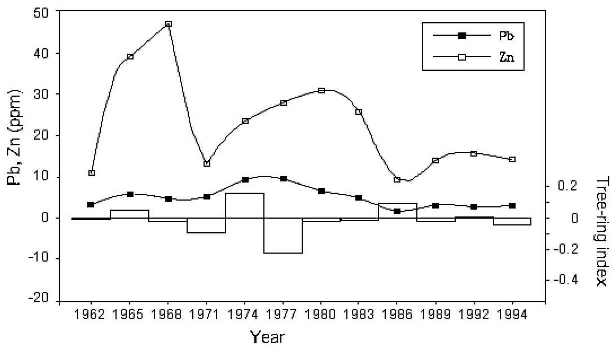

Fig. 8. Relationship between concentrations of heavy metals (Pb and Zn) and tree-ring indices.

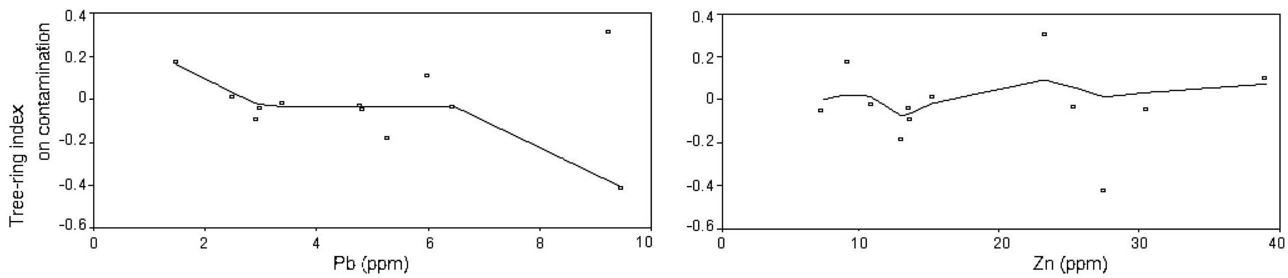

Fig. 9. Effects of heavy metals (Pb and Zn) on tree-ring growth.

infer that annual ring growth was affected by the concentration of lead in the stand. From 1973 to 1975, the tree-ring index increased, a phenomenon that may have resulted from unusually heavy precipitation (100～300 mm) in April to July of those years, the period of optimum plant growth, despite the heavier pollution occurring during this period.

Effects of Lead and Zinc on Tree Growth Indices

The effects of lead and zinc on the growth indices of trees expressed by weighted regression scatter plot smoothing are shown in Fig. 9. Lead concentrations below 6 ppm in the stand did not influence the growth of black pine (*Pinus thunbergii*) but concentrations of lead over 6 ppm had remarkable effects on the growth of black pine, resulting in tree-ring decline. Zinc pollution, conversely, did not appear to cause annual ring declines in the black pines.

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