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Ozone Damage Assessment of Aspen at the Five Sites in Seoul Using a Computer Simulation Model of Individual Tree Growth, TREGRO

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TREGRO, a computer simulation model of individual tree growth, was applied to estimate ozone (O_3) effects on aspen (*Populus tremuloides*) growth under ambient and 1.7 times ambient O_3 of Seoul in 1996. The three highest O_3 (Kuui-dong, Ssangmun-dong, Sungsoo-dong) and the two lowest O_3 sites (Mapo-dong, Namgajwa-dong) were evaluated. The current ambient O_3 did not affect aspen growth compared to simulation without O_3. The only effect was 6.6 percent of total assimilated carbon loss at Ssangmun-dong where the level of O_3 was greatest among the 21 sites examined. Decrease as much as 50 percent of total carbon gain was calculated at 1.7 times ambient O_3 of the three highest sites. The carbon loss by O_3 came from biomass of tissues and total non-structural carbon (TNC) such as starch and sugar. The most sensitive fraction was TNC and the next was root biomass. Foliage mass was not affected by O_3. Structural biomass loss was at best 1 to 3 percent at 1.7 times ambient O_3 at the two lowest sites. The daily carbon simulation was affected by O_3 mainly during Growth Period 4 (Jul. 21-Oct. 26). Correlations between site, dose, and the simulated responses of aspen (tissue biomass, TNC, respiration, and senescence) ranged from -0.703 to -0.973 depending on the plant responses. The ozone effects on poplar in Seoul are not severe currently, but are probably measurable at Ssangmun-dong. However, severe O_3 effects on biomass would occur if O_3 levels increase to 1.7 times ambient O_3 in Seoul. In addition, O_3 could weaken the trees, thus increasing susceptibility to pathogens or insects.

***Keywords* :** aspen, ozone, total non-structural carbon, TREGRO.

Tropospheric ozone (O_3) is the most phytotoxic air pollutant in US and other places in the industrialized world (USEPA, 1996). The O_3 levels in Seoul were almost same as those in US (Yun et al., 1999) and possibly threaten vegetation. In order to assess the O_3 effects on plants, field exposure studies need to be conducted under ambient or greater levels using open top chambers. However, fumigation experiments are not to prove that ambient O_3 affects vegetation. Nowadays, computer models can simulate plant growth as affected by O_3 based on previous empirical or published data (Weinstein and Yanai, 1994; Weinstein et al., 1991).

TREGRO, a simulation model, has predicted growth and patterns of carbon allocation of an individual tree under various environmental stresses like O_3 (Laurence et al., 1993), nutrition (Weinstein et al., 1991), and climate change (Constable et al., 1996). In addition, it has been widely used for description of multiple stresses (Weinstein and Yanai, 1994), root biomass change (Retzlaff et al., 1997), and acidic rain (Laurence et al., 1989) related to O_3 stress. The model can examine the mechanisms of plant response to stress alone or combination. The basic concept of TREGRO is to describe physiologically the plant responses using hourly meteorological data including ambient O_3 (Weinstein et al., 1992). The model simulates detailed carbon assimilation in leaves and carbon allocation among the tissues. A tree is divided into several compartments: leaves, branches, stem, and coarse and fine roots by soil horizon. The three types of carbon, living structural (structural carbon), dead structural (wood), and total non-structural carbon (TNC) are stored in the compartments. The daily carbon budget in a whole plant can be calculated as the sum of foliar photosynthesis minus maintenance and growth respiration of each compartment. Total carbon assimilation is calculated hourly and summed over the entire day. Net carbon is subtracted from the tissue lost daily to senescence (Weinstein et al., 1992).

The TREGRO simulation in this study, based on the empirical O_3 exposure, has several merits. First, damage due to O_3 can be predicted or estimated without fumigation experiments in the field. Second, the simulated results can guide to direct research on O_3 effects in the future. Third, TREGRO can estimate plant response under the O_3-free conditions, which is not possible to achieve in the field. The comparison between simulations under the ambient and O_3-free air can quantify the potential O_3 damage under the

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ambient O_3. Finally, the model can track the disturbed flow of carbon dioxide due to O_3 through detailed carbon budgets and redistribution on daily basis. However, it is desirable to conduct actual experiments to verify simulation results.

TREGRO has two hypothesized mechanisms of O_3 damage. First, mesophyll conductance can be reduced according to cumulative O_3 dose. Second, respiration can be tied to an instantaneous O_3 dose to simulate the cost of repairing tissue damage. The cumulative O_3 effects do not occur in the second method (Weinstein et al., 1992). TREGRO must be parameterized for growth of a specific species to simulate O_3 effects under various environments. Although field fumigation studies at Seoul have not conducted, TREGRO can simulate the O_3 impact in Seoul from previously parameterized aspen at Suwon.

Poplar, a fast growing and pioneer species, is one of the most sensitive trees to O_3 and significant reductions of growth have been documented (Karnosky et al., 1996; Matyssek et al., 1993; Yun and Laurence, 1999; Woodbury et al., 1994). The effects of O_3 come from reduction of photosynthesis in the leaves and alteration of carbon allocation among the tissues. Since aspen has a high carbon demand for growth, most assimilated carbon is allocated for maintenance and growth. Although aspen is only 0.6 percent of the street trees in Seoul, the simulation can warn the phytotoxicity of O_3 under ambient condition in Seoul.

The objective of this study is to estimate O_3 effects on aspen growth under ambient or higher O_3 in Seoul using TREGRO simulations. Increasing O_3 levels are of concern for street trees and vegetation in Seoul. Since TREGRO describes aspen carbon gain and allocation under O_3 stress, we investigated various responses such as changes in structural carbons, TNC, and respiration for growth and maintenance.

Materials and Methods

Carbon allocation of TREGRO simulation. Carbon assimilation was simulated and the newly assimilated carbohydrate was allocated to various tissues for respiration, growth, and TNC storage. The priority of carbon allocation was set first for maintenance respiration, second for refilling leaf storage, then for the growth of each compartment according to a programmed priority based on actual observations. The growth of tissue was limited by carbon availability, nutrition availability, and maximum growth rate in each tissue. If carbon supply was not sufficient due to serious O_3 effects, available resources were distributed to each tissue by priority. The excess carbon after growth demand is stored in TNC pools in each tissue. The maximum growth rate and the order of growth priority were established based on the previous field study (Yun and Laurence, 1999).

One-year growth simulation. TREGRO simulated the growth of a one-year old aspen from root-cuttings. The measured initial biomass with pre-developed root structure were 2.7 g carbon of stem and 11.0 g carbon of root. The TNC proportion to structural carbon was estimated by Tewari (1993). The final dry weights of one-year growth in each tissue were the averages measured from two clones of aspen, one sensitive and one tolerant to O_3. Temperature, relative humidity, rainfall, and photosynthetic photon flux density data were collected at the Boyce Thompson field located at Ithaca, NY (42.7°N, 74.5° W) in 1996.

TREGRO allocates available carbon (new photosynthate and TNC) according to distinct seasonal growth periods determined by phenological data (Noh et al., 1994). Before new leaf production, carbon distribution, root growth and bud swelling were already fueled by TNC storage. After leaf fall, carbon was redirected to root development. Five distinct growth periods (GP) were determined by the environment (accumulated growing degree days) or by tree status (TNC content) based on phenological data. The degree-day (0°C base temperature) intervals associated with pre-growth (storage) (GP 1), spring root growth (GP 2), leaf growth and shoot elongation (GP 3), secondary growth of root, branch and stem (GP 4), and leaf fall and root storage (GP 5) were used.

The O_3 effects on aspen for TREGRO simulation were based on measurements in a field experiment (Yun and Laurence, 1999). A field exposure study was conducted at the Boyce Thompson Institute field with ambient (1.0 x), 1.7 times (1.7 x), and 3.0 times (3.0 x) of ambient O_3 at Ithaca, NY in 1996. In the model, mesophyll conductance was reduced by O_3 to match observed photosynthetic rates at known doses of O_3.

Ambient ozone in Seoul sites. The Korean government has monitored ambient O_3 at 21 sites in Seoul. Based on the sum of hourly concentrations of O_3 greater than or equal to 0.06 ppm (SUM06) and the accumulated O_3 exposure over a threshold of 40 ppb (AOT40) in 1996 (Yun et al., 1999), five sites in Seoul (within a radius of 8.5 km) were chosen. The three highest sites were Ssangmun-dong, Kuui-dong, and Sungsoo-dong. The two lowest sites were Mapo-dong and Namgajwa-dong. The hourly data for temperature, relative humidity, precipitation, and radiation in the Seoul area were obtained from the Korea Meteorological Administration. Except for the ozone data, the other parameters such as growth rates, phenological data, meterological data, were held constant in the TREGRO simulations for the 5 sites (Table 1).

Dose-response relation. The various simulated plant responses to O_3 stress were related to the two ozone indices, SUM06 and AOT40. Based on the five sites O_3 data at 1.0 x and 1.7 x, the two indices were calculated depending on the period of O_3 exposure. The five different periods were decided depending on the Growth Period (GP) of the simulation (Table 2). The high O_3 episodes occurred during June in Seoul.

Results

One year growth simulation. The TREGRO simulations in Seoul were based on the Suwon parameterization. Since Seoul is located about 40 km north of Suwon, the environments for aspen growth in both cities were similar.

Table 1. The meteorological and ozone data at the five monitoring sites of Seoul in 1996

Month	Temperature	Relative Humidity	Vapor pressure	Radiation	Precipitation	Ozone (nl L^{-1})				
	(C)	(%)	(kPa)	(μmol m^{-2} s^{-1})	(mm)	Kuui-dong	Ssangmun-dong	Sungsoo-dong	Namgajwa-dong	Mapo-dong
1	-2.13	49.89	0.286	82.99	0.022	13.39	15.39	6.26	4.05	4.81
2	-1.69	45.88	0.275	112.74	0.001	20.56	16.47	10.07	7.91	5.92
3	4.91	53.20	0.461	126.80	0.105	29.69	20.95	7.36	6.95	4.86
4	10.21	52.48	0.688	197.10	0.086	37.09	29.56	18.89	7.88	8.06
5	18.33	57.60	1.171	206.11	0.039	28.35	32.30	20.75	8.17	11.73
6	22.28	74.69	1.970	130.63	0.347	28.98	31.17	22.17	12.66	12.71
7	24.35	75.64	2.294	141.56	0.689	21.31	22.31	14.86	13.06	12.15
8	26.00	72.72	2.441	136.25	0.178	28.01	28.14	22.13	20.43	13.14
9	21.97	65.26	1.682	158.98	0.015	21.96	22.04	18.28	17.74	15.50
10	14.49	62.46	1.036	113.14	0.121	19.36	12.60	9.19	12.25	7.52
11	6.08	63.18	0.627	79.17	0.087	17.08	10.46	5.78	7.83	2.93
12	1.62	58.50	0.409	68.65	0.015	12.51	8.52	4.68	6.52	1.59
					SUM06[a]	3.826	4.990	3.354	0.801	0.890
					AOT40[b]	9.724	12.035	8.111	1.011	2.501

[a] SUM06 (ppm·hr) is the sum of the hourly concentration of O_3 greater than or equal to 0.06 ppm during June, July and August in 1996.
[b] AOT40 (ppm·hr) is the accumulated hourly O_3 exposure over a threshold of 40 ppb during June, July and August in 1996.

Table 2. Correlation[a] coefficients between the TREGRO simulated carbon allocations and ozone indices for various periods of aspen growth at five sites of Seoul in 1996

Ozone Index[b]	Period	Allocated carbon in each part							Average
		Respiration	Senescence	Root	Stem	TNC[c]	Structural carbon	Total	
SUM06	Jan.-Dec.	-0.893	-0.965	-0.884	-0.802	-0.664	-0.874	-0.909	-0.856
SUM06	Jun.-Sep.	-0.911	-0.978	-0.897	-0.845	-0.684	-0.892	-0.926	-0.876
SUM06	Jul.-Sep.	-0.899	-0.964	-0.883	-0.835	-0.674	-0.878	-0.913	-0.864
SUM06	GP[d] 2-4	-0.914	-0.985	-0.905	-0.834	-0.688	-0.896	-0.931	-0.879
SUM06	GP 4	-0.902	-0.966	-0.887	-0.837	-0.679	-0.881	-0.917	-0.867
AOT40	Jan.-Dec.	-0.922	-0.972	-0.911	-0.839	-0.712	-0.903	-0.935	-0.885
AOT40	Jun.-Sep.	-0.941	-0.982	-0.923	-0.873	-0.734	-0.918	-0.951	-0.903
AOT40	Jul.-Sep.	-0.922	-0.963	-0.906	-0.862	-0.721	-0.901	-0.933	-0.887
AOT40	GP 2-4	-0.946	-0.989	-0.933	-0.872	-0.743	-0.926	-0.958	-0.91
AOT40	GP 4	-0.925	-0.965	-0.911	-0.866	-0.728	-0.906	-0.937	-0.891
	Average	-0.918	-0.973	-0.904	-0.847	-0.703	-0.897	-0.931	-0.882

[a] Correlations were based on ten O_3 levels which were the ambient and 1.7 times ambient of 5 Seoul sites.
[b] SUM06 is sum of the hourly O_3 concentration greater than 0.06 ppm. AOT40 is the accumulated hourly exposure over the threshold of 40 ppb.
[c] TNC is total non-structural carbon which consists of various sugars and starch.
[d] Growth Period (GP) is based on TREGRO simulation. GP 2-4 was from March 9 to October 26. And GP 4 was from July 21 to October 26.

The structural carbon estimated under ambient O_3 concentration and TNC were 56.88 g carbon and 13.21 g carbon, which were approximately 81 percent and 19 percent, respectively of total carbon after one-year simulation (Table 3). Since the simulated tree was young, the structural carbon of all tissues did not include wood. The TNC storage and fine root growth approximately initiated from March 8 at Growth Period (GP) 2; leaf bud swelling and tissue growth started from April 18 (GP 3). After growing the foliage completely, the plants assimilated carbon vigorously and excessive carbon was stored in branch, stem, and coarse root after July 21 (GP 4). Although leaves started to fall on October 27, carbon was continuously allocated to each tissue until November 2 (GP 5).

Simulated growth under higher O_3. The highest SUM06 for 3 months (June, July, and August) among 21 sites in Seoul was 4.99 ppm·hr at Ssangmun-dong (Table 3); the lowest SUM06 was 0.89 ppm·hr at Mapo-dong. A carbon

Table 3. Carbon (g carbon) partitioning among the various tissues after one year simulation of aspen tree

Site	Ozone[a] Level	Foliage	Branch	Stem	Coarse Root	Fine Root	Structural carbon	TNC	Total
	0 x	16	3.5	17.02	25.16	8.42	56.88	13.21	70.09
Kuui-dong	1.0 x	16	3.23	16.15	20.25	7.06	56.19	6.51	62.70
	1.7 x	16	3.07	15.29	17.62	0.69	47.97	4.71	52.68
	0 x	16	3.50	17.02	25.16	8.42	56.88	13.21	70.09
Mapo-dong	1.0 x	16	3.50	17.06	25.19	8.39	56.80	13.22	70.02
	1.7 x	16	3.43	16.85	24.12	7.96	56.59	11.76	68.35
	0 x	16	3.50	17.02	25.16	8.42	56.88	13.21	70.09
Namgajwa-dong	1.0 x	16	3.52	17.20	25.18	8.34	56.98	13.26	70.24
	1.7 x	16	3.17	15.86	19.59	6.03	54.96	5.70	60.66
	0 x	16	3.50	17.02	25.16	8.42	56.88	13.21	70.09
Ssangmun-dong	1.0 x	16	3.21	16.01	20.27	6.05	55.20	6.33	61.53
	1.7 x	16	3.06	14.70	16.66	0.54	46.35	4.61	50.96
	0 x	16	3.50	17.02	25.16	8.42	56.88	13.21	70.09
Sungsoo-dong	1.0 x	16	3.49	17.32	24.90	7.86	56.79	12.79	69.58
	1.7 x	16	3.07	15.35	19.47	1.52	50.64	4.76	55.40

[a]The ambient ozone levels were in Table 1.

loss of 6.6 percent under ambient condition was simulated at Ssangmun-dong. Under the condition of 1.7 times ambient O_3, most of the effect came from loss of TNC and reduction of tissue biomass except foliage. Fine root was the most sensitive tissue to O_3 stress. The total carbon was decreased by about 27 percent due to 1.7 x O_3 at the 3 highest sites, Kuui-dong, Ssangmun-dong and Sungsoo-dong. There were no apparent carbon decrease at the two lowest sites, Mapo-dong and Namgajwa-dong (Table 3). The foliage biomass was not affected by O_3 at any site (Table 3).

Carbon allocation pattern. The carbon allocation pattern of aspen at Ssangmun-dong is illustrated in Figure 1. Since O_3 effects at this site were the most severe among the five sites, this pattern is typical of O_3 stress. The maxima of respiration and root carbon allocation around September without O_3 disappeared at the greater O_3 level. Carbon reduction caused by O_3 started at GP 4 with the assimilated carbon mainly allocated to root and stem at that time. The foliage growth was not affected by O_3. The total biomass was not significantly different and it mainly came from biomass of roots. Thus, it is difficult to detect damage due to O_3 under the ambient air compared to O_3-free air.

Dynamic changes in allocable carbon due to O_3. Figure 2 shows the daily change of allocable carbon as a percent of O_3-free conditions at Ssangmun-dong and Mapo-dong where the highest and the lowest ambient O_3 was recorded, respectively. At Ssangmun-dong, carbon assimilation was estimated to decrease by approximately 30 percent from early May, and then it became severely reduced from July until the end of growth. On the other hand, the serious carbon reduction started on August 27 at Mapo-dong. The O_3 impact on allocable carbon during 108-201 day (GP 3) even at Ssangmun-dong did not result in any biomass. However, ambient O_3 at both sites obviously affected carbon assimilation at GP 4 (202-299 day). At the end of growth, the TNC of 1.0 x at Ssangmun-dong was reduced to 50 percent compared to O_3-free air, whereas the structural carbon loss was at best 0.5 g carbon/day. The daily allocable carbon of 1.7 x at Mapo-dong was similar to that of 1.0 x at Ssangmun-dong.

Biomass changes at Ssangmun-dong. Figure 3 describes the changes in biomass of each structural tissue over the growing season at Ssangmun-dong. Except for foliage, biomass of all tissues were expected to decrease due to O_3. Roots were the most sensitive. The fine root biomass was significantly decreased at 1.7 x.

Comparisons among four carbon parameters. Allocable carbon, total biomass, foliage biomass, and fine root biomass were more or less affected by O_3 exposure (Fig. 4). Allocable carbon was the most sensitive to O_3 stress among the parameters. Allocable carbon was decreased about 50 percent even at 1.0 x of Ssangmun-dong compared to O_3-free air. However, there was no significant reduction in all carbon variables at Mapo-dong even under 1.7 x of the ambient O_3 concentration. Total biomass of Ssangmun-dong shows a linear relationship between O_3 dose and total biomass.

Figure 5 shows the total of all assimilated carbon in each compartment at the five Seoul sites. Since these are the sum of all carbon variables, the O_3 damage can be integrated on carbon assimilation. Respiration had the largest portion and contributed to a major change due to O_3 stress. At 1.7 x of

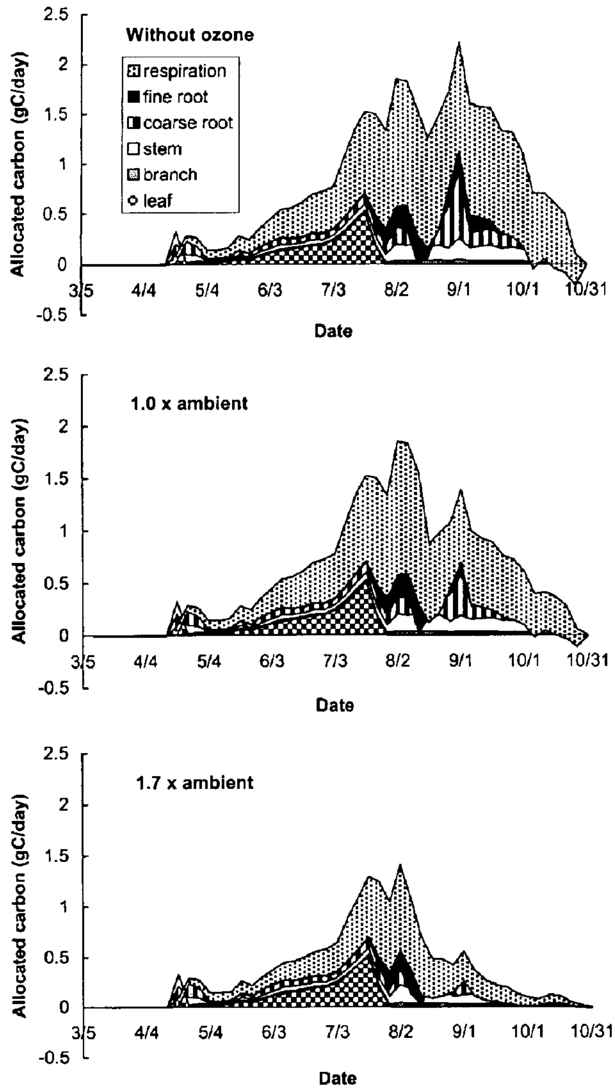

Fig. 1. Pattern of annual carbon allocation predicted by TREGRO run with the three different levels O_3 at Ssangmun-dong site.

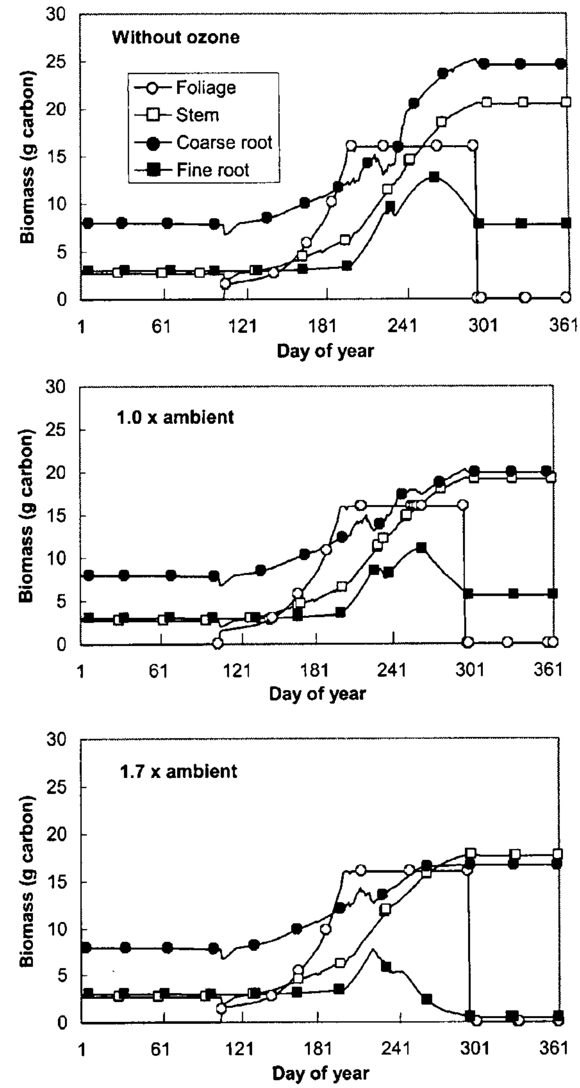

Fig. 3. The TREGRO simulation of biomass tree compartments of aspen over a growing season in 1996 at Ssangmun-dong under three levels of O_3 in the air.

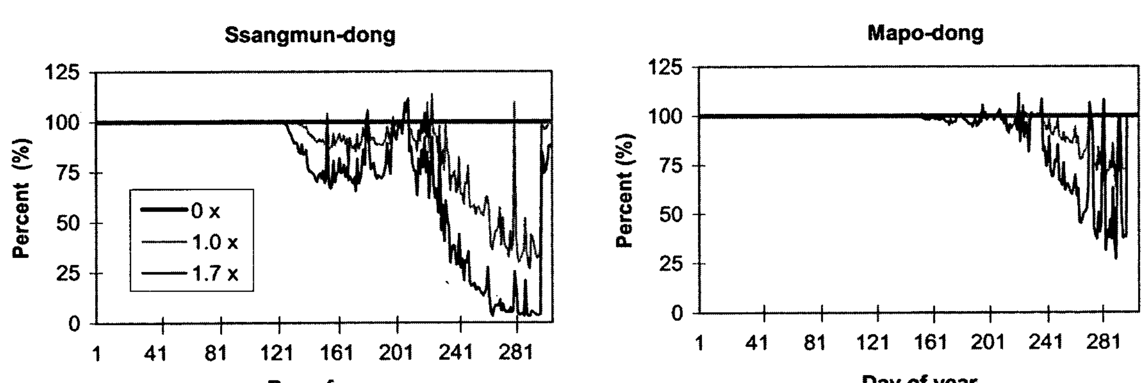

Fig. 2. Allocable carbon as a percent of base-ozone free condition for one-year simulation at 1.0 x and 1.7 x ozone based on the ambient ozone levels in Seoul.

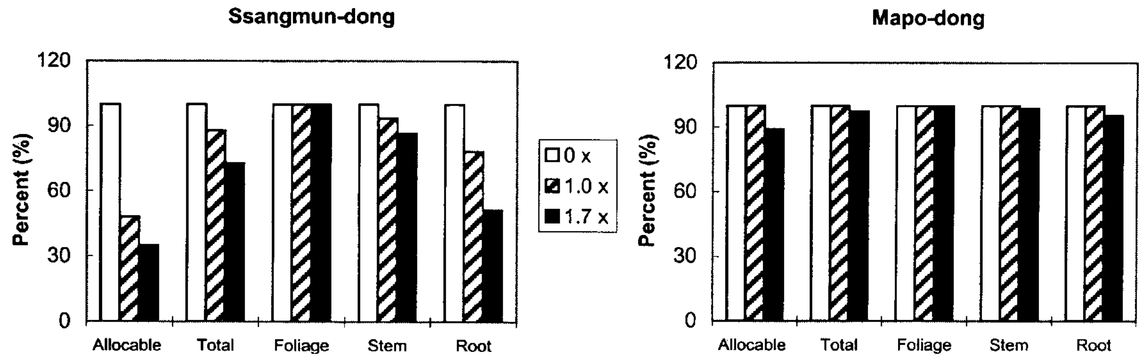

Fig. 4. The effects of ozone on the allocable carbon, total biomass, and growth of foliage, stem, and root resulted from the TREGRO simulation of one year growth at the Ssangmun-dong and Mapo-dong in 1996.

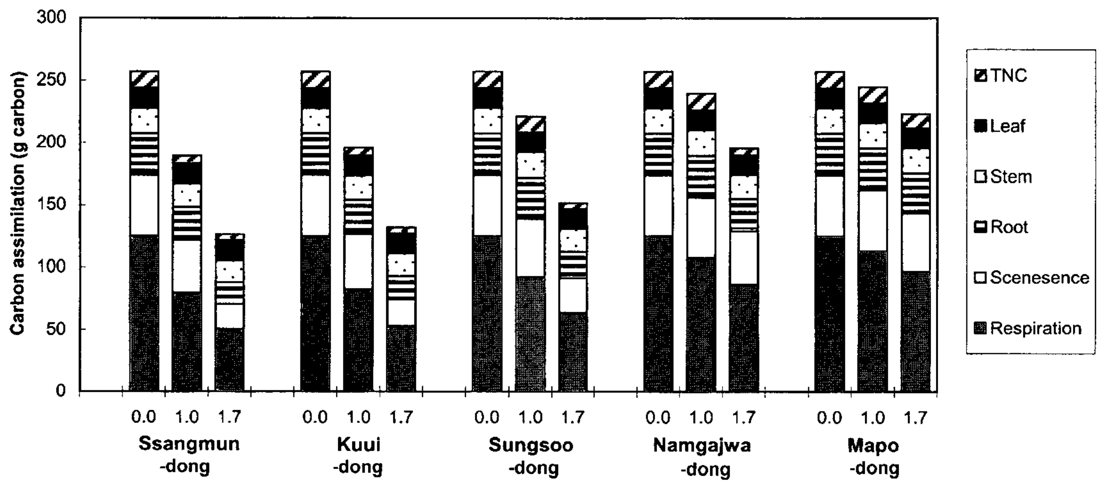

Fig. 5. Allocation of total simulated carbon to structural growth and maintainance at three different levels of O_3 treatments among the five monitoring sites of Seoul.

Ssangmun-dong site, total carbon was reduced by approximately 50 percent. On the other hand, the total carbon at 1.7 x of Mapo-dong was reduced only 10 percent.

Dose-response correlation coefficients. Most of the dose-response correlations were highly negative. The correlation coefficient was significantly different depending on the tissue. The coefficient of TNC was only -0.703. On the other hand, that of senescence was -0.973. However, the variations between two indices or among 5 different periods was small (Table 2). The growth period 2-4 had the highest correlation coefficient among the 5 periods. And the correlation coefficient of AOT40 was a little greater than that of SUM06 (0.027-0.023).

Discussion

The TREGRO simulations in this study described aspen growth under various O_3 levels in Seoul. If O_3 fumigation studies are conducted in Seoul, poplar O_3 damage would be detected on roots and total biomass. If extremely high O_3 episode occurs, the typical O_3 foliar symptom would occur. However, the more important point in this study is to show the potential chronic O_3 effects on growth. Ozone effects are already present under current ambient O_3 at Ssangmun-dong; 6.6 percent of carbon loss would be expected mainly on fine root and TNC in the tissue according to the simulation. This damage would occur without a typical visible symptom. Most of current O_3 levels in Seoul area was not threatening aspen growth; only 1-2 sites may have the potential to damage trees among 21 sites in Seoul. Among the 21 monitoring sites in Seoul, the O_3 damage at the 16 non-investigated sites would be between Sungsoo-dong and Namgajwa-dong. Thus, O_3-induced biomass reduction in most of Seoul would not be easy to detect. However, carbon assimilation apparently decreased under current levels of O_3 in Seoul.

Although current ambient O_3 is not a serious threat to aspen growth in Seoul, the O_3 level is continuously increasing (Yun et al., 1999). If Seoul O_3 increases to 1.7 times of current ambient levels, chronic O_3 damage at the three sites, Kuui-dong, Ssangmun-dong and Sungsoo-dong, would occur. The greater O_3 would reduce carbon assimilation and change carbon allocation to each tissue. From our results, root/shoot ratio will be decreased and carbon assimilation will be reduced up to 25 percent compared to the current O_3 levels. However, a reduction in foliar mass would not occur at this level. Rather, root reduction will be 35 percent and stem reduction will be less than 10 percent. Since root damage is more severe than above ground tissues, O_3 effects such as reducing carbon assimilation and altering carbon allocation in a tree are carried over for many years. In addition, O_3 damaged trees may be more susceptible to pathogens or insects, weakened by winter injury, or be affected by drought because of poor vigor (USEPA, 1996).

Before the simulation, the three highest and two lowest O_3 sites were chosen based on two accumulated O_3 indices, SUM06 and AOT40. According to the dose-response relationships, both indices described O_3 damage on aspen growth adequately (Table 2). The various correlation coefficients among the tissues were due to the different carbon priority. For instance, TNC was easy to change by the limited carbon allocation from O_3 stress because it had the lowest carbon availability among the carbon tissues. However, the five different periods of O_3 exposures did not affect the dose-response relations if GP 4 is included.

To expand the O_3 damage study to more popular species of Seoul street trees like oriental plane (*Platanus orientalis*, 44.1%) and ginkgo (*Ginkgo biloba*, 43.0%), O_3 fumigation studies are needed to be conducted. Our results are showing not noly the potential O_3 phototoxity on aspen species under simulated 1.7 times ambient O_3 at Seoul but the severe loss of total carbon assimilation under ambient O_3 at the three highest sites. The damage due to O_3 was occurred during GP 4 after the leaves were fully expanded. Although O_3 enters through the stomata of the leaf, the foliar damage due to O_3 could not simulate in this study. Moreover, most of the damage occurred on invisible tissues, like fine root and coarse root because of the less carbon availability according to the carbon priority. Thus, aspen in this study could be an indicator plant for warning of chronic damages from O_3 levels currently occurring in Seoul.

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