Impacts of urban greenspace on offsetting carbon emissions for middle Korea

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Carbon dioxide is an important greenhouse gas and a major agent of climate change. This study quantified carbon (C) emissions from energy consumption and C storage and uptake by greenspace for three cities in middle Korea: Chuncheon, Kangleung, and Seoul. Carbon emissions were estimated using C emission coefficients for fossil fuels consumed. Carbon storage and uptake by woody plants were computed applying biomass equations and radial growth rates. The soils in Chuncheon were cored to analyze organic C storage. Annual C emissions were 37·0 t/ha/yr in Kangleung, 47·2 t/ha/yr in Chuncheon, and 264·9 t/ha/yr in Seoul. Mean C storage by woody plants ranged from 26·0 to 60·1 t/ha for natural lands within the study cities, and from 4·7 to 7·2 t/ha for urban lands (all land use types except natural and agricultural lands). Mean annual C uptake by woody plants ranged from 1·60 to 3·91 t/ha/yr for natural lands within the cities, and from 0·53 to 0·80 t/ha/yr for urban lands. There were no significant differences (95% confidence level) between the cities in C storage and uptake per ha for urban lands. Organic C storage in Chuncheon soils (to a depth of 60 cm) averaged 31·6 t/ha for natural lands and 24·8 t/ha for urban lands. Woody plants stored an amount of C equivalent to 6·0–59·1% of total C emissions within the cities, and annually offset total C emissions by 0·5–2·2%. Carbon storage in soils was 1·2 times greater than that by woody plants in Chuncheon. The C reduction benefits of woody plants were greater in Chuncheon and Kangleung, where areal distribution of natural lands was larger and the population density lower than in Seoul. Strategies to increase C storage and uptake by urban greenspace were explored.
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Introduction

Climate change is one of the most serious concerns of our society. The gases causing the greenhouse effect are carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, tropospheric ozone, and stratospheric water vapor (Ciborowski, 1989; Ramanathan, 1989). Among them, CO_2 is the most significant greenhouse gas contributing about half of the total greenhouse effect (Ciborowski, 1989; Rodhe, 1990). The recent concentration of atmospheric CO_2 is 25% higher than the preindustrial level (Post *et al*., 1990). This increase is primarily due to fossil fuel combustion and deforestation. Climate change might pose a serious threat to our ecological and socio-economic systems (Kemp, 1990; Melillo *et al*., 1990; Karl *et al*., 1997), unless measures are investigated to mitigate the rising accumulation of atmospheric CO_2.

Increasing concern about climate change has recently generated studies about the effects of urban greenspace on the reduction of atmospheric carbon (C). Nowak (1994) quantified C storage and uptake by urban trees in Chicago, IL, and explored the effects of tree plantings in urban areas on atmospheric C levels. Jo and McPherson (1995) estimated C uptake and release by greenspace of residential neighborhoods in Chicago, and suggested effective planting and management strategies for the reduction of atmospheric C. McPherson (1998) quantified the benefits of Sacramento, CA's urban forest in offsetting C emissions from human energy consumption, and presented guidelines of urban forest management to improve these benefits.

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Greenspace in urban ecosystems can reduce atmospheric C levels in three ways. Here, greenspace is defined as soil surface area capable of supporting vegetation and the vegetation being supported. First, urban trees and shrubs directly sequester and accumulate atmospheric C in the process of their growth through photosynthesis. Second, urban vegetation decreases building cooling demand by shading and evapotranspiration, and heating demand by windspeed reduction, thereby reducing C emissions associated with fossil fuel use. Third, urban soils store organic C from litterfall, until it is returned to the atmosphere by decomposition. On the other hand, buildings, factories, and automobiles in urban landscapes release C through fossil fuel consumption.

In Korea, little is known about C storage and uptake by urban greenspace. The reduction of atmospheric C by urban greenspace could be significantly variable both within and among nations due to differences in land use distributions, greenspace sizes and structures, and fossil fuel uses. Diverse regional or national studies will help increase our understanding of urban greenspace effects on atmospheric C levels. The objectives of this study were to assess the impacts of (1) C storage and uptake by woody plants and (2) organic C storage in soils on offsetting C emissions from energy consumption for several cities of middle Korea. The study did not consider shading, evapotranspiration, and wind-reduction effects of vegetation on the reduction of C emissions. In this study, C storage indicates total C accumulated as vegetation growth over time, and C uptake refers to the annual rate of C fixation.

Methods

Study area

Chuncheon, Kangleung, and Seoul, located in the middle of Korea, were selected as the study cities (Figure 1), based on differences in population density, climate, and land uses. For both Chuncheon and Kangleung, all administrative districts were included as the study area. For Seoul with its larger size, the two administrative districts of Kangnam and Junglang were chosen based on areal distribution of land use types, socio-economic characteristics, and building construction dates. The two districts represented Seoul's land use characteristics. Kangnam represented districts with a higher income and newer residential buildings, while

Junglang had lower income and older residential buildings (City of Seoul, 1997). The differences in income and construction date were assumed to influence areal cover and age structure of, and accordingly C storage and uptake by, woody plants.

Ground sampling of vegetation and land use analysis

Data on urban vegetation were collected on plots which were located using a stratified systematic sample of grid points. After delineating land use types on a 1:10 000-scale map covering the study area, the grid was laid out by latitude and longitude at an interval of 600 m for agricultural and natural lands and 400 m for other land use types. This resolution was a compromise between the competing concerns for a large sample size and the availability of labor and expense. The resolution provided 234 grid points for Chuncheon, 271 for Kangleung, 121 for Kangnam, and 91
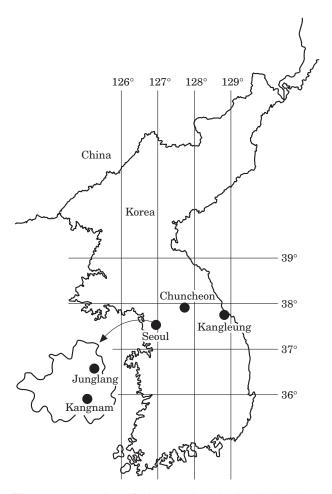

Figure 1. Location of three study cities in middle Korea and two study districts in Seoul.

for Junglang. All the grid points were selected for vegetation sampling in the study cities. Plot structure varied by land use type. The entire lot was measured on residential, commercial, industrial, and building-dominant institutional (e.g. schools, hospitals) lands. For natural and vegetation-dominant institutional lands, 225-m^2 plots were measured. Field-surveyed vegetation data included species, total height, crown width, crown height, areal cover, and stem diameter at breast height of 1·2 m (dbh) for trees and at 15 cm above ground for shrubs (here, shrubs indicate woody plants 2 cm or less in dbh). Plot information was used to produce average estimates per unit area on C storage and uptake by woody plants for each land use type (except agricultural lands).

Land use types in the study cities were analyzed using black and white aerial photographs (1:15 000 for Chuncheon, Kangleung, and Kangnam, and 1:20 000 for Junglang). An acetate 1 × 1 cm dot grid (0·5 × 0·5 cm dot grid for Junglang) was placed on the photos for interpretation. This resolution generated 2392 grid points for Chuncheon, 2823 for Kangleung, 1661 for Kangnam, and 1428 for Junglang. Land use types for all the grid points were identified with an eight times magnifier interfaced with a mirror stereoscope (Sokkisha MS-27, Tokyo). Land use proportions were calculated by dividing the number of dots in the category of land use type by the total number of dots in each study city or district. Areal distribution of land use types was used to produce total estimates of C storage and uptake by greenspace for each land use type.

Fossil fuel consumption and carbon emissions

Annual consumption of fossil fuels for 3 years from 1994 to 1996 was quantified based on statistical data published for each study city (City of Chuncheon, 1997; City of Kangleung, 1997; City of Seoul, 1997). Fossil fuels of each type consumed were converted to an estimate of C emitted using data on C emission coefficients (Korea Energy Management Corporation, 1996). Carbon emissions from oil consumption were calculated using a ratio of 0·63 kg/L (liter) for gasoline, 0·68 kg/L for kerosene, 0·73 kg/L for diesel, and 0·82 kg/L for bunker-C oil. Carbon emissions from gas consumption were computed applying a ratio of 0·64 kg/m^3 for natural gas, 0·82 kg/kg for propane, and 0·83 kg/kg for butane. Carbon emissions from briquet use were estimated at the rate of 0·48 kg of C/kg. Carbon emissions

from electricity use were calculated at the rate of 0·22 kg/kWh, based on the ratio of power production sources (personal communication with Korea Electric Power Corporation, 1997). Hydroelectric and nuclear power were assumed to emit no C.

Carbon storage and uptake by vegetation

Carbon storage

Above-ground biomass of common tree and shrub species in Chuncheon was measured to develop biomass equations. Tree species selected were *Pinus densiflora*, *Pinus koraiensis*, and *Quercus* spp. (*Q. mongolica* and *Q. aliena*) in the Research Forests of Kangwon National University, and open-grown *Populus tomentiglandulosa* on the campus of the university. Forty trees (10 of each species) were randomly sampled to represent the range of diameters. A total of 277 shrubs for 5 species (45–60 of each species) was randomly sampled around each plot located in natural lands for ground sampling of vegetation.

Sample trees and shrubs were felled at 10–15 cm above ground and at ground level, respectively, in fall when leaves remained (except *Populus tomentiglandulosa*, cut in late winter). Stem and branch fresh weights of trees felled were measured in the field. A stem disk (5–10 cm thick) at breast height of 1·2 m and random branches of 0·5–1 kg (with foliage) were sampled from each tree, and oven-dried at 65°C to constant weight to measure dry weight. The ratios of dry weight to fresh weight for stem and branch samples were calculated to obtain the entire above-ground biomass of each tree. Shrubs cut were sealed in double plastic bags and transported to the laboratory where fresh weight was measured within 4 hours. Ten random shrubs of each species were oven-dried at 65°C to constant weight to compute the average ratio of dry weight to fresh weight. A biomass equation for each species was generated using diameter (at breast height for trees and at 15 cm above ground for shrubs) and total height as independent variables. An iterative linear and nonlinear approach was used to determine the most appropriate parameter and equation. The biomass equation obtained for each species was used to calculate above-ground biomass of the same species ground-sampled in the study cities.

Below-ground biomass of the above-mentioned species and total biomass of the other woody species were estimated using biomass equations from the

literature (Telfer, 1969; Whittaker and Marks, 1975; Ohmann *et al*., 1976; Stanek and State, 1978; Monteith, 1979; Roussopoulos and Loomis, 1979; Ker, 1980; Connolly, 1981; Ker and van Raalte, 1981; Phillips, 1981; Yim *et al*., 1981; 1982; Tritton and Hornbeck, 1982; Smith and Brand, 1983; Hahn, 1984; Wenger, 1984; Czapowskyj *et al*., 1985; Park, 1985; Smith, 1985; Lee and Park, 1987; Harrington *et al*., 1989; Park and Lee, 1990; Choi and Park, 1993; Jo, 1993; Jo *et al*., 1995; Park *et al*., 1996). Biomass estimates of a given species may not be consistent for different growing sites. Therefore, the use of published equations was limited to the diameter range for which they were applicable, and the equations of more than one author (a maximum of 5 equations) were used to average biomass values. If there was no biomass equation available for a particular species, the biomass average derived from equations for the same genus or group (hardwood or conifer) was substituted. The dry-weight biomass of trees and shrubs was converted to a C estimate by multiplying by 0·5 (Ovington, 1956; Reichle *et al*., 1973; Pingrey, 1976; Ajtay *et al*., 1979; Chow and Rolfe, 1989; Song *et al*., 1997).

Above-ground herbaceous plants in natural lands of Chuncheon were harvested within 1-m^2 quadrats of each plot located for ground sampling of vegetation. After measuring fresh weight in the field, the samples were bagged, transported to the laboratory, and oven-dried at 65°C for 24 hours to obtain dry weights. The above-ground dry weight was divided by 1·39 (Körner and Renhardt, 1987) to estimate below-ground biomass. Total biomass of herbaceous plants was converted to a C storage estimate by multiplying by 0·45 (Olson, 1970; Ajtay *et al*., 1979).

Carbon uptake

Carbon uptake of deciduous tree species sampled in urban lands (all land use types except natural and agricultural lands) was computed using C uptake equations derived from monthly measurements for two years' growing seasons of CO_2 exchange rates by a portable Infrared Gas Analyzer (Jo and Cho, 1998). Carbon uptake of the other woody species in urban lands and all woody plants in natural lands was quantified applying annual radial growth rates and the above-mentioned biomass equations. The growth rates were used to calculate diameters in year $y-1$ (y: present year), and the diameters to calculate biomass in year $y-1$. Biomass in year $y-1$ was subtracted from biomass in year y to

estimate C uptake. All foliage C was subtracted for deciduous species, and 25% of foliage C was subtracted for evergreen species assuming 3-year leaf retention (Dirr, 1977; Rowntree and Nowak, 1991).

Annual dbh growth rates of *P. densiflora*, *P. koraiensis*, and *Quercus* spp. felled in the Research Forests of Kangwon National University were obtained by averaging measurements from 4 cross-sectional directions of stem disks sampled. To supplement sample size and enhance data reliability, the growth rates of *P. densiflora* and *P. koraiensis* were again averaged across existing data (Park, 1987) for the same species in the Research Forests. For deciduous tree species (except *Quercus* spp.), annual dbh growth rates (Jung *et al*., 1983), measured for forest trees in the middle of Korea, were used. For shrubs for which no data were available for Korea, annual diameter (at 15 cm above ground) growth rates were used for open-grown (Jo, 1993) and forest-grown (Whittaker, 1962; Whittaker and Woodwell, 1968; Whittaker and Marks, 1975; Harrington *et al*., 1989) shrubs in the United States. If no radial growth rate could be found for an individual species, the average from the same genus or group (hardwood or conifer) was substituted.

Carbon storage in soils

Of the grid points laid out in Chuncheon for ground sampling of vegetation, 60 points (30 in urban lands and 30 in natural lands) were randomly selected for soil sampling. The soils were cored to a depth of 60 cm in fall using a multi-stage soil sampler (AMS, Idaho) of 5·1 cm in diameter. Soil samples were air-dried for a week, sieved through a 2 mm mesh size, and weighed to 0·1 g. Organic C in the samples was analyzed using the Walkley–Black method (Jackson, 1958).

Results and discussion

Land uses

Total area of each study city was about 52 km^2 for Chuncheon, 76 km^2 for Kangleung, and 606 km^2 for Seoul. The population density was 175 persons/ha in Seoul, 5–8 times higher than in Chuncheon and Kangleung (Table 1). Mean annual temperature was a little lower in Chuncheon than in Kangleung and Seoul. Kangnam and Junglang covered, respectively, 6·5% (39·6 km^2) and 3·1% (18·5 km^2)

Table 1. Population* and climate** for study cities

City	Area (km²)	Population	Pop. density (persons/ha)	Mean annual temp. (°C)	Mean annual precip. (mm)
Chuncheon	52	182 850	35	11·0	1217
Kangleung	76	156 900	21	13·2	1327
Seoul	606	10 595 950	175	12·5	1312

* As of Dec. 31, 1995.
** For 5 years from 1991 to 1995 (City of Chuncheon, 1997; City of Kangleung, 1997; City of Seoul, 1997).

of total area in Seoul. The population density was 141 persons/ha and 246 persons/ha in Kangnam and Junglang, respectively.

Chuncheon and Kangleung were much less urbanized than Seoul, the capital of South Korea. Natural and agricultural lands were the predominant land uses (75–80% of the total area) in Chuncheon and Kangleung, with residential lands (8%) the other major land use (Table 2). Residential lands comprised the largest area (32–37%) in Kangnam and Junglang, followed by natural (19–22%) and institutional (13–17%) lands.

Vegetation

Dominant tree and shrub species in urban lands of the study cities (based on importance values) were *Ginkgo biloba*, *Acer palmatum*, *Juniperus chinensis*, and *Buxus microphylla* var. *koreana*. Natural lands in Chuncheon and Kangleung were dominated by *Pinus* spp., with *Quercus* spp. and *Robinia pseudo-acacia* the dominant species in Kangnam and Junglang. Tree-age structure was largely characterized by a young, growing tree population. Trees less than 30 cm in dbh dominated

the forest structure in both urban (94–99%) and natural (95–100%) lands.

There were no obvious differences in density or cover of woody plants between Chuncheon and Kangleung, nor between Kangnam and Junglang (Table 3). For urban lands, tree and shrub cover was quite similar among the study cities (12–13%), while tree density was 2 times higher in Kangnam and Junglang than in Chuncheon and Kangleung. Basal area of trees per unit area of natural lands in Chuncheon was about half that in the other cities.

Carbon emissions

The use of electricity, oil, and gas increased annually from 1994–1996, while briquet consumption declined during this period (Table 4). Carbon emissions to the atmosphere showed an annual increase of 10–20% among the study cities. Mean annual C emissions for the 3 years were 47·2 t/ha/yr (246 kt/yr) in Chuncheon, 37·0 t/ha/yr (281 kt/yr) in Kangleung, and 264·9 t/ha/yr (16 047 kt/yr) in Seoul. Of the total, 87–96% was accounted for by oil and electricity use. Oil consumption in Korea was largely attributed to transport and industry, which occupied 62% of total (Korea Energy Economics

Table 2. Percentages of land use types in study cities

Land use	Chuncheon	Kangleung	Seoul	
			Kangnam	Junglang
Residential: Detached	5·78	6·97	16·74	29·77
Multifamily	2·59	0·67	15·24	7·14
Commercial	0·96	1·84	7·83	5·11
Industrial	0·42	0·19	1·50	0·63
Institutional: Building-dominant	3·30	1·66	11·02	10·79
Veg.-dominant*	0·88	0·11	2·29	6·16
Recreational: Facility-dominant	1·25	1·89	4·45	0·84
Veg.-dominant*	0·62	0·35	2·11	4·62
Transportation	5·18	2·59	8·73	7·56
Agricultural	23·12	35·78	7·10	5·18
Natural	54·06	43·82	21·67	19·19
Other**	1·84	4·13	1·32	3·01

* Dominated by vegetation, such as forested areas or natural parks.
** Military and vacant areas.

Table 3. Density, basal area (cm^2), and cover (m^2) of woody plants per 100 m^2 in study cities (mean±SE)*

City	Land use**	$N^\wedge$	Density	Basal area	Cover
Chuncheon	Urban	107	1·5±0·2	179±30	12·2±1·4
	Natural	42	9·9±0·8	1103±99	118·3±8·3
Kangleung	Urban	108	1·5±0·2	207±28	13·2±1·3
	Natural	65	10·0±0·6	2492±193	109·2±6·4
Seoul Kangnam	Urban	80	3·3±0·4	212±21	13·0±1·2
	Natural	31	12·9±1·4	2089±196	143·1±16·8
Junglang	Urban	65	3·1±0·4	267±52	12·9±1·4
	Natural	21	13·2±1·4	1999±140	186·8±10·4

* Density and basal area exclude shrubs. SE denotes standard error (the same with Table 5).
** Urban indicates all land use types except natural and agricultural lands (the same with Table 5).
$^\wedge$ N denotes the number of samples (the same with Table 6).

Table 4. Annual carbon emissions from fossil fuel use in study cities from 1994–1996*

City	Year	Emission (t/ha)	Electricity (%)	Oil (%)	Gas (%)	Briquet (%)
Chuncheon	1994	39·7	31·2	52·1	5·6	11·1
	1995	45·2	33·4	53·4	6·3	6·9
	1996	56·8	42·7	47·7	5·7	3·9
	Mean	47·2	35·8	51·1	5·9	7·3
Kangleung	1994	31·9	55·3	41·1	0·0	3·6
	1995	36·5	51·7	44·5	1·4	2·4
	1996	42·5	50·8	45·8	1·3	2·1
	Mean	37·0	52·6	43·8	0·9	2·7
Seoul	1994	240·1	34·4	52·9	8·4	4·3
	1995	257·0	34·0	53·3	10·3	2·4
	1996	297·5	32·0	56·9	9·9	1·2
	Mean	264·9	33·5	54·4	9·5	2·6

* Source: City of Chuncheon (1997), City of Kangleung (1997), City of Seoul (1997).

Table 5. Mean carbon storage (t) and uptake (t/yr) per ha by woody plants for each land use type (mean±SE)

Land use		Chuncheon	Kangleung	Seoul	
				Kangnam	Junglang
Urban	Storage	4·70±0·70	6·30±0·80	6·60±0·70	7·20±1·30
	Uptake	0·56±0·08	0·71±0·10	0·53±0·06	0·80±0·12
Natural	Storage	26·00±2·70	46·70±3·90	60·10±5·70	58·70±5·60
	Uptake	1·71±0·17	1·60±0·09	3·77±0·36	3·91±0·32

Institute, 1996). Major sources of electricity use were commerce and residences (66–81%) in Chuncheon and Seoul, and industry (65%) in Kangleung.

Carbon storage and uptake by woody plants

Mean C storage by woody plants for urban lands was 4·7±0·7 t/ha in Chuncheon, 6·3±0·8 t/ha in Kangleung, 6·6±0·7 t/ha in Kangnam, and 7·2±1·3 t/ha in Junglang (Table 5). There were no significant differences (95% confidence level) in the C storage of urban lands among the study cities. Carbon storage by woody plants for natural lands averaged 26·0±2·7 t/ha in Chuncheon, 46·7±3·9 t/ha in Kangleung, 58·7±5·6 t/ha in Junglang, and 60·1±5·7 t/ha in Kangnam. Carbon storage for natural lands was significantly lower (95% confidence level) in Chuncheon, where basal area of trees per unit area was smaller than in the other cities. However, there were no differences (95% confidence level) in C storage for natural lands among Kangleung, Kangnam, and Junglang.

Nowak (1994) found that C storage by woody plants in Chicago was 13·5 t/ha for urban lands and 35·5 t/ha for natural lands. Carbon storage averaged across these study cities was approximately half that of urban lands, and a little greater in natural lands, than Nowak's (1994) estimate.

Mean C uptake per ha by woody plants for urban lands was 0·56±0·08 t/yr in Chuncheon, 0·71±0·10 t/yr in Kangleung, 0·53±0·06 t/yr in Kangnam, and 0·80±0·12 t/yr in Junglang. There were no differences (95% confidence level) in C uptake for urban lands among the study cities. Carbon uptake was similar to the 0·7 t/ha/yr reported for a residential district in Chicago, where tree and shrub cover were similar to these study cities (Jo and McPherson, 1995). Carbon uptake by woody plants for natural lands averaged 1·60±0·09 t/ha/yr in Kangleung, 1·71±0·17 t/ha/yr in Chuncheon, 3·77±0·36 t/ha/yr in Kangnam, and 3·91±0·32 t/ha/yr in Junglang. Carbon uptake for natural lands was significantly greater (95% confidence level) in Kangnam and Junglang than in Chuncheon and Kangleung. This might be due to differences in tree density and species composition. As mentioned previously, broad-leaved tree species were dominant in natural lands of Kangnam and Junglang, while conifers were common in Chuncheon and Kangleung. Broad-leaved tree species had higher growth rates and, therefore, greater C uptake than conifers (Jung et al., 1983; Park, 1987; Jo, 1993; Jo et al., 1995).

Table 6 shows biomass equations generated to estimate above-ground biomass of common tree and shrub species in Chuncheon. All the equations had r^2 values greater than 0·96 for trees and 0·71 for shrubs. The dbh of sample trees ranged from 4 cm to 27 cm, and the diameter at 15 cm above ground of sample shrubs was between 0·4 cm and 4·0 cm. Tree age averaged 14 years for P. koraiensis, 20 years for P. densiflora, and 29 years for Quercus spp. Mean annual dbh growth rates were 0·75±0·08 cm for P. koraiensis, 0·51±0·03 cm for P. densiflora, and 0·38±0·04 cm for Quercus spp. Of the 3 species, the youngest, P. koraiensis, showed the greatest growth rate. Park (1987) reported that mean annual dbh growth rates for 40-year old P. koraiensis and P. densiflora in forest areas of Chuncheon were 0·33 cm ($n = 160$) and 0·29 cm ($n = 160$), respectively. On the other hand, Jung et al. (1983) found that annual dbh growth rates for various deciduous tree species (40–65 years old) in forest areas of middle Korea averaged 0·68 cm ($n = 734$). The growth rate for deciduous trees from Jung's study was at least twice that of Park's estimates for evergreens.

Carbon uptake by trees per m^2 of crown cover ranged from 0·39 kg to 0·61 kg in urban lands and from 0·13 kg to 0·26 kg in natural lands. An open-grown urban tree for the same species and age as a forest-grown tree could have a wider crown due to lower competition and better maintenance, and have greater C uptake. However, poor growing conditions, such as soil disturbances, air pollution, and heat might lower C uptake in an urban tree. Carbon uptake by open-grown deciduous trees was compared with that of forest-grown deciduous trees within the same diameter ranges. This comparison assumed no severe pruning for open-grown urban trees. Carbon uptake by open-grown urban A. palmatum was half that of forest-grown trees. However, C uptake by G. biloba, Platanus occidentalis, and Zelkova serrata, which

Table 6. Biomass equations generated to calculate total above-ground biomass of common tree and shrub species in Chuncheon

	Species	Equations*	r^2	N	Diameter (cm)
Tree	Pinus densiflora	lnDW=−1·8436+2·1199 lnD	0·98	10	4·3–26·0
	Pinus koraiensis	lnDW=−2·9097+2·5362 lnD	0·99	10	5·0–22·0
	Populus tomentiglandulosa**	DW=−77·58+10·05 D	0·98	10	8·3–23·8
	Quercus mongolica & aliena	lnDW=−3·2648+0·9828 lnD^{2}H	0·96	10	5·2–26·5
	General softwoods^	lnDW=−2·2796+2·2874 lnD	0·98	20	4·3–26·0
Shrub	Lespedeza bicolor	lnDW=4·4155+1·8061 lnD	0·82	59	0·4–2·5
	Pinus densiflora & rigida	lnDW=4·0685+2·1892 lnD	0·90	54	0·6–3·6
	Quercus mongolica	lnDW=4·2763+2·2189 lnD	0·90	59	0·5–4·0
	Rhododendron mucronulatum	lnDW=3·8212+2·3652 lnD	0·87	60	0·5–3·4
	Rhododendron schlippenbachii	DW=−133·28+181·74 D	0·71	45	0·4–2·6
	General hardwoods^^	lnDW=4·1813+1·9494 lnD	0·77	223	0·4–4·0

* DW: Dry weight in kg for trees and g for shrubs. D: Diameter at breast height of 1·2 m for trees and at 15 cm above ground for shrubs. H: Height in m.
** Leaf biomass excluded.
^ Pinus densiflora and Pinus koraiensis.
^^ Lespedeza bicolor, Quercus mongolica, Rhododendron mucronulatum, and Rhododendron schlippenbachii.

have relatively high photosynthetic capacities even under adverse urban environments (Jo and Cho, 1998), was approximately 2 times greater for open-grown trees than for forest-grown trees.

Carbon storage in soils

Chuncheon soils were gravelly loams or sandy loams. Soil bulk density averaged $1.40 \, g/cm^3$ for urban lands and $1.22 \, g/cm^3$ for natural lands. Mean pH of soils was 6.6 for urban lands and 5.0 for natural lands. Organic matter in these soils averaged 0.6% for urban lands and 1.0% for natural lands, which was much lower than the average of 3.2% for forest soils of Korea (Lee, 1981).

Mean organic C storage in Chuncheon soils was 24.8 ± 1.6 t/ha of soil surface area for urban lands and 31.6 ± 1.6 t/ha for natural lands, which was 1.3 times greater than for urban lands. About 65% $(16.2\pm1.2$ t/ha) of the total amount of organic C in urban lands was stored in the top 30 cm of soils and the remaining 35% (8.6 ± 0.9 t/ha), in the 30- to 60-cm depth. Organic C storage has been estimated at 130–160 t/ha for forest areas in north central and northeastern US (Birdsey, 1992), and 163 t/ha for residential lands in Chicago (Jo and McPherson, 1995). Soil C storage for urban lands in Chuncheon was 6.5 times lower than the Chicago estimate (to a depth of 60 cm). The estimate for natural lands in Chuncheon was at least 4 times lower than that for forest areas in the US.

The lower soil C storage in Chuncheon might be associated with younger forest stands and lower ecosystem production in natural lands, and with lower organic matter accumulations from poorer plantings and less composting in urban lands. The majority of soil C results from above- and below-ground litterfall. Most tree roots in natural lands of Chuncheon are found within the upper 60 cm of soil depth (Chun and Oh, 1994), the sampling depth used in this study.

Role of urban greenspace in offsetting carbon emissions

Total C storage by urban greenspace (woody plants and soils) in Chuncheon was estimated at approximately 139 kt, which equaled 56.5% of the C emissions from fossil fuel use (Figure 2). Soils in both urban and natural lands accounted for 54.9% of the total C storage. Forest ecosystems of the United States stored about 52 Gt of C, with 59% in soils, 31% in trees, 9% in litter above soil

surfaces, and 1% in understory vegetation (Birdsey, 1990). In the natural lands of Chuncheon, soils accounted for 54% of total C storage (58.2 t/ha), 45% for woody plants, and the remaining 1% for herbaceous plants. Total C storage by woody plants was 166 kt in Kangleung, 60 kt in Kangnam, and 42 kt in Junglang. Woody plants stored the amount of C equivalent to 59.1% of the C emissions in Kangleung, 7.1% in Kangnam, and 6.0% in Junglang.

Total C uptake by woody plants was 4.3 kt/yr in Chuncheon, 6.2 kt/yr in Kangleung, 4.1 kt/yr in Kangnam, and 3.2 kt/yr in Junglang. Woody plants annually offset the C emissions by 2.2% in Kangleung, 1.8% in Chuncheon, and 0.5% in Kangnam and Junglang (Figure 2). The total C uptake equaled the amount of C annually emitted by 3310 persons in Chuncheon, 3440 persons in Kangleung, 2740 persons in Kangnam, and 2130 persons in Junglang. Discrepancies in income and building construction dates between Kangnam and Junglang did not result in a significant difference between the two administrative districts in C storage and uptake by woody plants on a land area basis. Based on estimates of C storage and uptake per ha in Kangnam and Junglang, Seoul's woody plants stored a total of 1195 kt, 7.4% of the C emissions, and annually fixed 84 kt/yr, 0.5% of the C emissions. In Sacramento, total C uptake (including the reduction of C emissions from building energy savings) by urban trees offset regional C emissions by 1.8% (McPherson, 1998), less than in Kangleung. The benefits of woody plants in offsetting C emissions were greater in Chuncheon and Kangleung, where areal distribution of natural lands was relatively larger and the population density was lower, than in Kangnam and Junglang.

Implication and management strategies

Greenspace in the study cities played an important role in reducing atmospheric C levels, although C storage and uptake against C emissions were not as significant in Kangnam and Junglang as in Chuncheon and Kangleung. Urban greenspace makes only a partial contribution to atmospheric C reduction. However, urban greenspace planning and management could be one of more time-saving and cost-effective ways to slow climate change, as compared to the development of alternative energy sources. To increase C storage and uptake by urban greenspace, the following strategies are suggested.
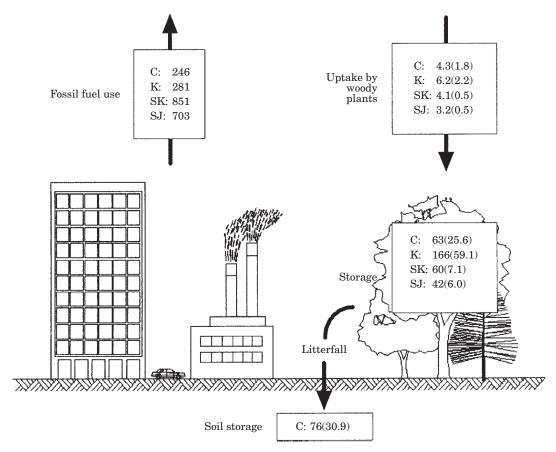
Figure 2. Total annual flows and total storage of carbon (kt) for components considered in study cities (C: Chuncheon, K: Kangleung, SK: Seoul Kangnam, SJ: Seoul Junglang)*.
*Percentages of carbon uptake or storage against emissions are given in parentheses.

First, hard surfaces were predominant in the urban lands of the study cities. Available growing space and planting potential could be increased by locating parking lots and above-ground utility lines below ground.

Second, plantings in urban lands were characterized by a single layer of grass, shrubs, or trees and a young, even-aged tree population. Multi-layered plantings, in which herb, shrub, and tree layers overlap, would increase C storage and uptake per unit area, and maintain a multi-aged tree structure to promote continuous C uptake over time.

Third, ordinances should be amended to increase greenspace area in urban lands. Based on current landscape-related ordinances in Korea (Kwon *et al.*, 1996), no plantings are required within a residential lot smaller than $200\,m^2$, and urban parks should be $1500\,m^2$ or larger. This large size could limit establishment of parks in urban sectors where land prices are usually high. Residences smaller than $200\,m^2$ in lot area accounted for 40–50% of total detached residences sampled among the study cities. Areal distribution of facility-dominant parks

was only 1–4% of total area. The present regulations should be amended to improve tree cover in residential lands, and to provide an opportunity to establish smaller and more numerous parks in urban lands.

Fourth, tree species that have high growth rates, even under adverse urban growing conditions, should be planted. Broad-leaved tree species have higher growth rates than conifers and shrubs.

Finally, natural lands, in which C storage and uptake per unit area are significant, should be conserved. It goes without saying that disturbing natural lands will release the C stored in vegetation and soils back to the atmosphere. Each city needs to establish a target for C emissions offset by greenspace to control developments of natural lands.

Vegetation will fix atmospheric C during its growing period. However, all the C stored in vegetation will ultimately be lost upon the death or removal of the vegetation. Thus, vegetation is not a permanent C sink. Immediate replacement is necessary to compensate for the C emitted from

previously removed vegetation. The appropriate plantings and maintenance of trees are needed to ensure longer productive lifespans and to avoid rapid C release. Soils are a relatively long-term C sink with slow turnover rates. Carbon storage in soils was greater than that by woody plants in Chuncheon even with poor soil conditions. Although annual rates of soil C accumulation were not quantified in this study, the turnover time of soil C was estimated to be approximately 41 years in residential lands of Chicago (Jo and McPherson, 1995).

This research did not consider the reduction of C emissions from building energy savings by vegetation, and C release from vegetation maintenance, such as pruning and fertilization. If the effects of building energy savings are added, the C reduction benefits of greenspace would be greater in the study cities, although C release from vegetation maintenance is included (McPherson, 1998; Jo, 1999). Carbon storage and uptake by some open-grown trees, except common species in the study cities, were estimated using biomass equations and growth rates from forest areas, because data for urban sites were lacking. More detailed studies, including annual C fluxes for grass and soils, would improve our understanding of greenspace impacts on C cycling in urban landscapes.

Acknowledgements

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