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ORIGINAL ARTICLE

Evaluation of CO_2 Storage and Uptake by Forest Landscapes in the Middle Region of Korea

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Abstract

Anthropogenic increases in greenhouse gas concentrations, primarily through radiative forcing from carbon dioxide, continue to challenge earth's climate. This study quantified CO_2 storage and uptake by dominant forest types and age classes in the middle region of Korea. In addition, the role of forest landscapes in reducing atmospheric CO_2 against CO_2 emissions based on energy consumption was evaluated. Mean CO_2 storage and uptake per unit area by woody plants for three forest types and four age classes were estimated applying regression equations derived to quantify CO_2 storage and uptake per tree; and computations per soil unit area were also performed. Total CO_2 storage and uptake by forest landscapes were estimated by extrapolating CO_2 storage and uptake per unit area. Results indicated mean CO_2 storage per unit area by woody plants and soils was higher in older age classes for the same forest types, and higher in broadleaved than coniferous forests for the same age classes, with the exception of age class II (11-20 years). CO_2 storage by broadleaved forests of age class V (41-50 years) averaged 662.0 t/ha (US$331.0 hundred/ha), highest for all forest types and age classes evaluated. Overall, an increased mean CO_2 uptake per unit area by woody plants was evident for older age classes for the same forest types. However, decreased CO_2 uptake by broadleaved forests at age class V was observed, compared to classes III and IV with an average of 27.9 t/ha/yr (US$14.0 hundred/ha/yr). Total CO_2 storage by woody plants and soils in the study area was equivalent to 3.4 times the annual CO_2 emissions, and woody plants annually offset the CO_2 emissions by 17.7%. The important roles of plants and soils were associated with 39.1% of total forest area in South Korea, and CO_2 emissions comprised 62.2% of the total population. Therefore, development of forest lands may change CO_2 sinks into sources. Forest landscape management strategies were explored to maintain or improve forest roles in reducing atmospheric CO_2 levels.

Key words : Forest type, Age class, Equation, CO_2 emission, Offset, Strategy

1. Introduction

Carbon dioxide is one of the primary greenhouse gases resulting in climate change, and a serious concern for the earth's future. Atmospheric CO_2 concentrations were approximately 379 ppm in 2005, a 35% increase over preindustrial levels, and showed a 1.9 ppm increase per year from 1995 to 2005 (IPCC, 2007). Continued climate change poses serious threats to global ecological and socio- economic systems unless measures are explored to mitigate the increasing accumulation of atmospheric CO_2 (IPCC, 2007; Karl et al., 1997; Kemp, 1990; Melillo et al., 1990). Increased atmospheric CO_2 is primarily the result of fossil fuel combustion and deforestation (Detwiler and Hall, 1987; Schneider, 1990).

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Forest landscapes contribute to a reduction in atmospheric CO_2 concentration in the following two ways: i) forest trees and shrubs directly sequester and accumulate atmospheric CO_2 during growth via photosynthetic processes; atmospheric CO_2 sequestration continues until the plants are cut or die; and ii) soils store CO_2 in litter fall until it is returned to the atmosphere through decomposition; the majority of soil carbon is derived from fallen plant organic matter, biomass accumulated during photosynthetic processes.

Rising concerns regarding climate change have generated studies evaluating the effects of forest ecosystems on atmospheric CO_2 levels. Birdsey (1990) reported that United States forest ecosystems stored approximately 190 Gt of CO_2, which was equivalent to 4% of the CO_2 stored in the world's forests (Atjay et al., 1979). Approximately 59% of the estimate was stored in soils, 31% in trees, 9% in above soil litter surfaces, and 1% in understory vegetation (Birdsey, 1990). Milne and Brown (1997) estimated the respective amount of CO_2 stored in vegetation and soils in Great Britain was 418 Mt and 36,073 Mt; and broadleaved woodlands and Scottish peat soils were major sinks for CO_2. Jo (2002) determined that total CO_2 storage by woody plants and soils equaled about 57% of the total CO_2 emissions from fossil fuel consumption in Chuncheon, a city in middle Korea, and suggested forest lands with significant CO_2 storage per unit area should be conserved. The urban forests in Hangzhou, China annually offset 18.6% of the amount of CO_2 emitted by industrial energy use within the city (Zhao et al., 2010).

Forest landscapes clearly play an important role in reducing atmospheric CO_2 levels, however it is likely the role of forest landscapes varies with type, age, and productivity. Quantifying CO_2 storage and uptake for different forest types and ages will contribute to determining the relative values among forest types and ages, and consequently serve in preservation, conservation, and in the decision making process, as a part of a low carbon, green growth policy. In Korea, little information is available regarding the effects of forest landscapes on offsetting CO_2 emissions at local, regional, and national levels. The purpose of this study was to quantify CO_2 storage and uptake by forest type and age class, and evaluate the role of forest landscapes in reducing atmospheric CO_2 levels against CO_2 emissions based on energy consumption in the middle region of Korea.

2. Materials and Methods

2.1. Study area and biomass equation selection

Temperate forest landscapes in the middle region of Korea were selected as the study area, including the following seven administrative provinces: Chungbuk, Chungnam, Daejeon, Gangwon, Gyeonggi, Incheon, and Seoul (Fig. 1). The provinces largely fall in the 85-100^{o}C warmth index (Yim, 1977). Daejeon, Incheon, and Seoul are metropolises with high population density in Korea (see population in Results and Discussion), and each of the other provinces contains various cities or counties with lower population density.

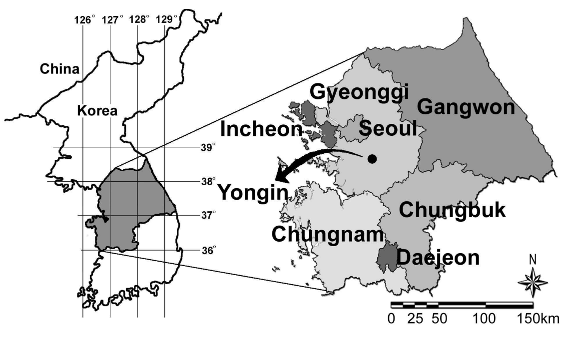

Fig. 1. Location of seven study provinces in the middle region of Korea and Yongin City in which forest structure was field-surveyed.

Quercus and *Pinus* are the dominant native genera in the region (Song and Jang, 1997); *Quercus* is comprised of deciduous species, and *Pinus* species are evergreen. The species representative of these genera, and the community types (broadleaved, mixed, or evergreen) will be determined as a part of this study (see Forest structure ground sampling). Various biomass equations for the major species, which were derived from trees growing in the study area, were obtained from the literature (Table 1) to estimate CO_2 storage and uptake. The biomass equations were tested and verified against different references, to exclude any equation with extreme deviations from the median biomass estimates of a given species and to enhance the reliability of biomass estimates. All equations selected had r^2 values of 0.97-0.99.

Table 1. Biomass equation sources selected to calculate CO_2 storage and uptake of major tree species in the study provinces

Species	Dbh range[a] (cm)	Reference
Quercus dentata	11.7[b]	Park et al. (1996)
Quercus mongolica	6.0-42.0	Song and Lee (1996)
	6.9-18.6	Lee and Park (1987)
	15.0[b]	Park et al. (1996)
	5.0-40.0	Jo and Ahn (2003)[c]
Quercus variabilis	14.9[b]	Park et al. (1996)
Pinus densiflora	12.4-42.9	Park and Lee (1990)
	4.3-26.0	Jo (2002)
	5.0-40.0	Jo and Ahn (2003)[c]
Pinus koraiensis	5.0-22.0	Jo (2002)
	9.3-20.8	Lee and Park (1987)
Pinus rigida	7.2-16.5	Yim et al. (1982)
	4.1-10.9	Yim et al. (1982)
Larix leptolepis	4.7-15.2	Yim et al. (1981)

[a] Dbh denotes stem diameter at breast height of 1.2 m (see Table 4)
[b] Mean value
[c] Equation for CO_2 uptake, not biomass

2.2. Forest structure ground sampling

Forest structure data was field-surveyed in Yongin City within the study provinces (Fig. 1), which contains diverse forest types and age classes in large natural forest areas. The data was collected in 100-m^2 quadrats, which were located using a systematic random sample of grid points. Following delineation of forest types and age classes on a 1:25,000-scale map, a grid was established by latitude and longitude at 250 m intervals. A total of 120 grid points was randomly selected with 20-39 samples for each forest age class. This sample size was a compromise between competing concerns for a desirable level of statistical significance, and labor and funding limitations.

Survey data included species, stem diameter, height, crown width, and density of woody plants. Stem diameter was measured at breast height of 1.2 m (dbh) for trees, and at 15 cm above ground for shrubs (woody plants 2 cm or less in dbh). Plot data was used to generate estimates of CO_2 storage and uptake per tree and unit area.

2.3. Estimates of CO_2 storage and uptake by woody plant species

The biomass equations obtained for each tree species were used to calculate average dry-weight biomass based on dbh growth of the same species ground-sampled in forest areas of Yongin City. Biomass was converted to carbon storage by multiplying by 0.5 (Ajtay et al., 1979; Chow and Rolfe, 1989; Ovington, 1956; Pingrey, 1976; Reichle et al., 1973; Song et al., 1997), and subsequently to CO_2 storage by multiplying by 3.6667. Based on these CO_2 estimates, regression equations to easily quantify CO_2 storage per broadleaved and coniferous tree species were developed using dbh as the independent variable. An iterative linear and nonlinear approach was applied to determine the most appropriate equation. Shrub CO_2 storage was estimated applying the biomass equations for each species derived by Jo (2002).

Tree CO_2 uptake was computed applying the annual dbh growth rates and regression equations of Jo and Ahn (2003) (Table 1). Equations were derived from seasonal CO_2 exchange rate measurements using a portable Infrared Gas Analyzer. In the former case, stem diameter in year y-1 (y: present year) was calculated using growth rate; and biomass in year y-1 was calculated applying stem diameter to the biomass equation. Biomass in year y-1 was subtracted from biomass in year y to estimate CO_2 uptake. Mean annual dbh growth rates of 0.67 cm (Chung et al., 1983; Jo, 2002; Son et al., 1997) and 0.64 cm (Chung, 1985; Jo, 2002; Park, 1987; Son et al., 1997) were applied to broadleaved and coniferous tree species, respectively. Complete foliage CO_2 was subtracted for deciduous species, and 25% foliage CO_2 was subtracted for evergreen species assuming three-year leaf retention (Dirr, 1977; Rowntree and Nowak, 1991). Consistent with CO_2 storage, regression equations to quantify average CO_2 uptake per broadleaved and coniferous tree species were developed using dbh as the independent variable. Shrub CO_2 uptake was estimated for each species using biomass equations derived by Jo (2002), and annual stem diameter growth rates at 15 cm above ground. Data for Korea was unavailable for several shrubs, therefore annual growth rates for forest-grown shrubs in the United States were substituted (Harrington et al., 1989; Whittaker, 1962; Whittaker and Marks, 1975; Whittaker and Woodwell, 1968).

The derived CO_2 equations were applied to each field-surveyed woody plant to quantify CO_2 storage and uptake per unit area. The CO_2 estimates per unit area per woody plant were rated across forest types and age classes via statistical analyses; the level of significance (p-value) was determined through an ANOVA and a t test using SPSS 12.0 (SPSS Inc., 2004).

2.4. Soil CO_2 storage estimates

Soil samples were collected from within the grid points established in Yongin City for ground sampling of forest structures; 85 points were randomly selected for soil sampling that included different forest types and age classes. The soils were cored to a depth of 60 cm during spring using a multi-stage soil sampler (AMS, Idaho, USA) of 5.1 cm in diameter. Soil samples were air-dried for one-week, sieved through a 2 mm size mesh, and weighed to 0.1 g. Soil organic CO_2 was analyzed per sample using the Walkley-Black method (Jackson, 1958). Significant differences in soil CO_2 storage per unit area was assessed among forest types and age classes via above-mentioned statistical analyses.

3. Results and Discussion

3.1. Study provinces: population and forest area

Total area and population in the study provinces (Table 2) was approximately 4,530 thousand ha and 30,942 thousand people, respectively with a population density of 6.8 people/ha (Korea Ministry of Public Administration and Security, 2010). The area and population comprised 45.2% and 62.2% of South Korea, respectively. Total forest area in the study provinces was roughly 2,828 thousand ha (Korea Forest Service, 2010), which occupied 45.8% of the total forest area in South Korea, and 62.4% of the total study province area. Mean annual temperatures and precipitation during a 30-year period from 1971 to 2000 ranged from 8.5°C (Taebaek City in Gangwon Province) to 12.9°C (Gangneung City in Gangwon Province), and from 1,114 mm (Inje County in Gangwon Province) to 1,402 mm (Gangneung City) (Korea Meteorological Administration, 2010).

Mean tree density by forest type field surveyed in Yongin City showed a decreased trend as age classes increased, which was particularly notable for age class

V (age classes are delimited in Table 3). Tree density was similar between broadleaved and coniferous forests within the same age class, with higher density exhibited in mixed forest relative to broadleaved and coniferous forests for age classes II and III. Older age classes exhibited decreased tree density; however mean basal area per unit area increased with age, consistent with diameter growth. Dominant tree species included *Quercus mongolica*, *Q. aliena*, *Q. variabilis* (mean importance values of 37.7%), *Pinus rigida*, *P. densiflora* (17.4%), *Rhus trichocarpa* (5.5%), *Larix leptolepis* (4.6%), and *Castanea crenata* (4.4%). *Rhododendron mucronulatum* (5.6%) and *R. schlippenbachii* (4.0%) comprised the dominant shrub species.

Table 2. Population and forest area for the study provinces

Province	Administrative area (ha)	Population	Forest area (ha)
Chungbuk	743,317	1,527,478	476,552
Chungnam	862,898	2,037,582	421,198
Daejeon	53,986	1,484,180	29,804
Gangwon	1,687,394	1,512,870	1,342,683
Gyeonggi	1,018,675	11,460,610	506,183
Incheon	102,701	2,710,579	37,812
Seoul	60,528	10,208,302	13,672
Total	4,529,499	30,941,601	2,827,904

As of Dec. 31, 2009 (Korea Ministry of Public Administration and Security, 2010; Korea Forest Service, 2010)

Table 3. Density and basal area of trees by forest type and age class in Yongin City

Forest type	Age class	Density (tree/100m^2)	Basal area (cm^2/100m^2)
Broadleaved	II	31.2 ± 4.5	1,552 ± 158
	III	30.3 ± 3.6	2,333 ± 202
	IV	28.3 ± 4.4	2,726 ± 212
	V	20.1 ± 3.4	2,955 ± 248
Coniferous	II	31.4 ± 3.7	2,284 ± 142
	III	30.1 ± 3.1	2,767 ± 197
	IV	29.8 ± 3.8	3,229 ± 186
	V	23.1 ± 4.1	3,657 ± 232
Mixed	II	37.0 ± 3.9	1,805 ± 175
	III	35.0 ± 3.0	2,409 ± 104
	IV	28.0 ± 1.9	2,876 ± 147

Figures indicate mean ± standard error. II: 11-20 years, III: 21-30, IV: 31-40, V: 41-50 (the same with subsequent tables)

3.2. CO_2 storage and uptake by woody plants

Carbon dioxide storage and uptake per broadleaved and coniferous tree species were positively correlated to diameter growth (dbh in cm) (Table 4). The increase in CO_2 storage between diameter classes was relatively higher at larger tree diameters. For example, CO_2 storage for a 10 cm dbh coniferous tree increased by approximately 68 kg with 5 cm growth, but by 205 kg with 5 cm growth in a 30 cm dbh tree (3-times higher). Carbon dioxide storage and uptake for broadleaved species was higher than coniferous species of the same diameter, and differences increased as diameters increased, particularly in CO_2 storage. The storage and uptake of a 20 cm dbh broadleaved tree was a respective and approximate 1.8 and 1.4 times higher than a coniferous tree of the same dbh. One liter of gasoline consumption emits approximately 2.12 kg of CO_2 (Ahn, 2010); therefore the CO_2 storage of a 20 cm dbh broadleaved tree was equivalent to the amount of CO_2 emitted from the use

Table 4. CO_2 storage (kg) and uptake (kg/yr) per tree by diameter growth in the study provinces

Species		Dbh (cm)							
		5	10	15	20	25	30	35	40
Broadleaved	Storage[a]	12.7	69.8	189.2	384.0	664.9	1,041.6	1,522.4	2,115.1
	Uptake[b]	2.8	12.7	22.8	33.2	43.7	54.5	65.6	76.8
Coniferous	Storage[c]	11.0	48.6	116.4	214.9	344.3	521.6	726.9	940.2
	Uptake[d]	2.7	8.9	16.2	24.5	33.7	44.0	55.3	67.5

[a] Equation: $\ln CO_2 = -1.4134 + 2.4581 \ln dbh$ ($r^2 = 0.99$)
[b] $CO_2 = -6.8539 + 1.9082\ dbh + 0.0046\ dbh^2$ ($r^2 = 0.99$)
[c] $\ln CO_2 = -1.0470 + 2.1436 \ln dbh$ ($r^2 = 0.99$)
[d] $CO_2 = -2.6257 + 0.9572\ dbh + 0.0199\ dbh^2$ ($r^2 = 0.99$)

of approximately 181 liter of gasoline.

Mean CO_2 storage per unit area by woody plants in Yongin City was higher in older age classes within the same forest types, and was higher in broadleaved forests than coniferous or mixed forests of the same age classes, with the exception of age class II (Table 5). CO_2 storage by broadleaved forests of age classes IV and V averaged 367.1 t/ha, significantly higher than all other forest types and age classes evaluated ($p < 0.01$). This CO_2 storage level was roughly 2.5 times higher than all forest types of age class II, 1.4 times higher than broadleaved forests of age class III, mixed forests of age class IV, and coniferous forests of age class V. Mean CO_2 uptake per unit area by woody plants tended to be higher at older age classes for the same forest types (Table 6). However, CO_2 uptake by broadleaved forests was lower at age class V than age classes III and IV. A higher respiration rate of woody organs (Jo and Ahn, 2003) and lower tree density at age class V are a plausible explanation for this result. Carbon dioxide uptake in broadleaved forests age classes III and IV, and mixed forests age class IV averaged 27.9 t/ha/yr, significantly higher than all forest types and age classes ($p < 0.05$).

Table 5. CO_2 storage per ha by woody plants for each forest type and age class in Yongin City

Forest type/age class	*n*	Storage (t/ha)	*p*
BL/II, CN/II, M/II	32	148.6 ± 6.3	< 0.0001
CN/III & IV, M/III	32	207.7 ± 7.3	< 0.0001
BL/III, CN/V, M/IV	32	261.4 ± 10.3	< 0.0002
BL/IV & V	18	367.1 ± 23.3	

BL: Broadleaved, CN: Coniferous, M: Mixed. *n* denotes the number of samples (the same with subsequent tables)

Table 6. CO_2 uptake per ha by woody plants for each forest type and age class in Yongin City

Forest type/age class	*n*	Uptake (t/ha/yr)	*p*
BL/II, CN/II, M/II	32	21.0 ± 0.6	0.0412
CN/III	13	23.4 ± 1.2	0.0328
BL/V, CN/IV & V, M/III	38	26.1 ± 0.7	0.0441
BL/III & IV, M/IV	31	27.9 ± 0.8	

3.3. CO_2 soil storage

Forest soil bulk density in Yongin City averaged 1.3 ± 0.0 (standard error) g/cm^3, and moisture and gravel mean content (> 2 mm in diameter) were 12.9 ± 0.4% and 18.8 ± 1.6%, respectively. Mean soil pH was 4.8 ± 0.0, and organic matter averaged 2.0 ± 0.1%. Mean soil CO_2 storage per unit area was higher at older age classes for each forest type (Table 7), consistent with CO_2 storage by woody plants. Soil CO_2 storage for the same age classes was higher in mixed forests than in broadleaved or coniferous forests, with the exception of age class II. Mean soil CO_2 storage in mixed forests of age class IV, and broadleaved forests of age class V averaged 294.9 t/ha, exhibiting the highest value of all forest types and age classes evaluated ($p < 0.05$). This estimate was 1.3-1.5 times greater than for broadleaved and coniferous forests of age classes II and III.

Table 7. CO_2 storage per ha in soils for each forest type and age class in Yongin City

Forest type/age class	*n*	Storage (t/ha)	*p*
BL/II, CN/II, M/II	20	200.6 ± 5.4	0.0110
BL/III, CN/III	14	226.3 ± 8.6	0.0241
BL/IV, CN/IV & V, M/III	31	250.6 ± 8.0	0.0463
BL/V, M/IV	17	294.9 ± 23.2	

Carbon dioxide storage for forest soils in Korea averaged approximately 246 t/ha (Jeong et al., 1998), which fell in the middle range of estimates for forest types and age classes in this study. Mean CO_2 storage for agricultural soils in Korea were determined at 110 t/ha from fields and orchards (Korea Institute of Agricultural Science and Technology, 1999; Korea Rural Development Administration, 1989), and urban soils from gardens, streets, and parks in a middle Korean city were approximately 92 t/ha (Jo, 2002). Soil CO_2 storage in agricultural and urban lands was much lower than even forest types of age class II, which was the lowest of the forest types and age classes assessed in this study. This indicates that changes in land use from forest lands to agricultural or urban lands have the potential to act as a significant source of CO_2 release.

3.4. Role of forest landscapes to reduce atmospheric CO_2 levels

Broadleaved forests of age class V exhibited the highest CO_2 storage per unit area by woody plants and soils with an average of 662.0 t/ha, followed by broadleaved (617.7 t/ha) and mixed (556.3 t/ha) forests of age class IV. Recent annual CO_2 emissions per capita from energy consumption were 11.3 t/yr in Korea (Korea Energy Economics Institute, 2010). The CO_2 storage per ha for broadleaved forests of age class V was equivalent to the amount of CO_2 annually emitted by approximately 59 people.

Based on a control cost of nearly US$50/t CO_2 (Korea Forest Research Institute, 2007), economic values of CO_2 storage from woody plants and soils ranged from $174.6 hundred/ha for forest types of age class II to $331.0 hundred/ha for broadleaved forests of age class V (Table 8). Economic values of CO_2 uptake by woody plants ranged from $10.5 hundred/ha/yr for forest types of age class II to $14.0 hundred/ha/yr for broadleaved forests of age classes III and IV, and mixed forests of age class IV. This information is clearly valuable in evaluating forest loss costs and benefits from various development projects, and in securing budgets for reforestation and management.

Table 8. Economic value of CO_2 storage by woody plants and soils for each forest type and age class in Yongin City (US$ hundred/ha)

Forest type	Age class			
	II	III	IV	V
BL	174.6	243.9	308.9	331.0
CN	174.6	217.0	229.2	256.0
M	174.6	229.2	278.2	-

Urban sprawl associated with residential development and industrial facilities has caused forest tree removal and reduction in forest landscapes. For example, Chuncheon forest area, one of the cities in the study provinces decreased by approximately 33% during the past 31 years (i.e. 1974 to 2005) (Ahn, 2010; Jo and Kim, 2001). If forest land disturbances are inevitable due to developmental pressures, appropriate land use policies are required to minimize adverse impacts. Policy should reflect the relative capacity of CO_2 storage and uptake among forest types and age classes.

It is essential to avoid haphazard development and preserve broadleaved forests of age classes III-V and mixed forests of age class IV, which exhibited increased CO_2 storage or uptake. Alternatively, a conservative development approach could be instituted for age class II forest types and age class III coniferous forests. However, younger forests have the potential to grow into important CO_2 reservoirs, therefore it is desirable to levy a reforestation or replacement cost equivalent to the above economic values to offset young forest losses. This measure is similar to a system of CO_2 emission trading.

Based on extrapolation of the average CO_2 estimates per unit area by forest type and age class, total woody plant and soil CO_2 storage in forest areas of the study provinces was estimated at 1,171 Mt, and total CO_2 uptake by woody plants was 61.6 Mt/yr (Table 9). Total annual CO_2 emissions from fossil fuel consumption were recently measured at 348 Mt/yr in the study provinces (Korea Energy Economics Institute, 2010). Forest landscapes distributed in the study provinces stored a CO_2 amount equivalent to approximately 3.4 times the CO_2 emissions, and annually offset the CO_2 emissions by 17.7% (Fig. 2). These important interactions were associated with 39.1% of the total South Korean forest area, and CO_2 emissions from 62.2% of the total population. Total CO_2 storage and uptake did not include ground-sampling of each forest type of age classes I and VI, and mixed forest of age class V due to rare or small distributions in Yongin City. These forest types and age classes accounted for 14.5% of the total forest area in the study provinces. Therefore, the addition of these samples might result in an increased reduction in atmospheric CO_2 levels.

Table 9. Total CO_2 storage and uptake by forest landscapes in the study provinces

Forest type	Age class	Area (ha)	Storage[a] (Mt)	Uptake[b] (Mt/yr)
BL	II	85,681	29.9	1.8
	III	264,062	128.8	7.4
	IV	295,741	182.7	8.3
	V	155,602	103.0	4.1
CN	II	237,137	82.8	5.0
	III	400,730	173.9	9.4
	IV	263,665	120.8	6.9
	V	70,050	35.9	1.8
M	II	87,507	30.6	1.8
	III	293,536	134.5	7.7
	IV	265,448	147.7	7.4
Total		2,827,904	1,170.6	61.6

[a] Storage by woody plants and soils
[b] Uptake by woody plants

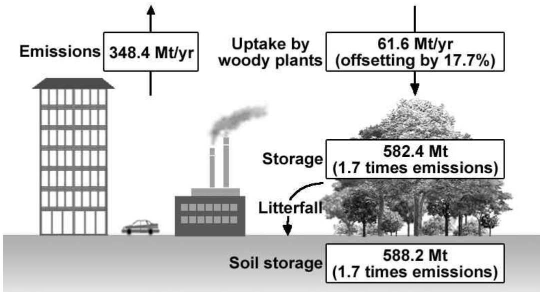

Fig. 2. The role of total CO_2 storage and uptake by forest landscapes in offsetting total CO_2 emissions in the study provinces.

The results from this study indicated forest landscapes significantly contribute to CO_2 uptake and storage, which should aid in curbing the effects of climate change. However, destruction of forest lands due to urban expansion could accelerate the rising accumulation of atmospheric CO_2 by reducing potential CO_2 uptake by trees and releasing CO_2 stored in trees and soils. Establishing a target for CO_2 emissions offset by forests is required at the local and regional scales to control development pressures on forest lands. A designated target is vital to establish the magnitude of forest conservation, preservation, or the number of plantings to maintain or improve the effects of CO_2 reduction. This study provides the indicators to evaluate CO_2 storage and uptake per tree, and per unit area for forest landscapes. These indicators can serve, in part, as decision-making criteria for forest management, including CO_2 offset targets, land use regulations, and reforestation policies.

4. Conclusion

Reduction of atmospheric CO_2 concentration is one of the most challenging and controversial issues our society faces for environmental soundness and economic progress. Quantifying CO_2 reduction in forest landscapes at the local and regional scales is necessary to develop desirable management policies with improved value systems for higher-level CO_2 emission trading between governments. This study put an emphasis on answering environmental concerns about what CO_2 storage and uptake by forest type and age class are, and what the effects of forest landscapes on atmospheric CO_2 reductions against CO_2 emissions are in the middle region of Korea. Woody plants and soils in the forested areas of the study region stored an amount of CO_2 equivalent to approximately 3.4 times the annual CO_2 emissions from energy consumption, and woody plants annually offset the CO_2 emissions by 17.7%. These significant roles were associated with 39.1% of the total forest area in South Korea, and CO_2 emissions from 62.2% of the total population.

The results of this study result in the recommendation of three management strategies to maintain or improve the roles of forest landscapes. First, a CO_2 emissions target offset by forests to control development pressures on forest lands should be established. Forest land development will likely accelerate atmospheric CO_2 levels by releasing the CO_2 stored in trees and soils, and limiting CO_2 uptake opportunities by trees. The target for CO_2 offset will serve to determine an areal size of forest preservation for sustainable development. The CO_2 storage and uptake per unit area by forest type and age class from this study can be applied to establish a target.

Second, forest management must place high priority on preservation of forest types and age classes with higher levels of CO_2 storage and/or uptake, such as broadleaved forests of age classes III-V, and mixed forests of age class IV (in this study). Inevitably, land use must be permitted for forest types and age classes with lower CO_2 storage and/or uptake, such as age class II forest types and age class III coniferous forests. However, mitigation measures, including soil conservation and immediate replantation are required for developers to compensate for losses.

Third, replacement with broadleaved trees is preferable to coniferous species, particularly for the study region, because the former sequester more CO_2 annually for comparable age classes. Carbon dioxide storage and uptake per tree by diameter growth of broadleaved and coniferous species can be easily calculated and compared using the regression equations derived for species in this study. Assuming heterogeneous landscape diversity, it is desirable to establish mixed forests partially including coniferous species.

Climate change is the result of continuing cumulative CO_2 emissions worldwide. Mitigation or curbing climate change requires comprehensive measures for national and regional reductions in CO_2 emissions. The measures should not only include a reduction in the use of fossil fuels and alternative energy development, but forest preservation, conservation, and replantation. Forest planning and management has great potential as a more time-saving and cost-effective means to reduce atmospheric CO_2 levels, compared to the development of alternative energy. The results of this study are expected to be useful in evaluating CO_2 storage and uptake capacity by forest type and age class, and to guide forest landscape policy and improve the effects of atmospheric CO_2 reduction.

Total CO_2 storage and uptake by forest landscapes in the study region were estimated based on field surveys of species composition, tree size, and tree density in a city with relatively diverse forest types and age classes. In Korea, detailed information from ground surveys is still limited regarding spatial distributions of tree stem diameters and density by forest type and age class. The total CO_2 storage and uptake need to be compared with additional studies that include wider sampling of forest structures and soils spanning the entire study region. Research on annual litterfall and soil decomposition is also required to help understand annual CO_2 accumulation in soils by forest type and age class, which was not considered in this study. In particular, similar forest landscape research should be conducted in the southernmost region of Korea to elucidate the impacts of forest landscapes on atmospheric CO_2 reduction at the national scale.

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