Changes in annual CO_2 fluxes estimated from inventory data in South Korea

Lee Dowon[1], Yook Keun Hyung[1], Lee Dongseon[1], Kang Sinkyu[2], Kang Hojeong[3], Lim Jong Hwan[4] & Lee Kyeong Hak[5]

1. Environmental Planning Institute, Graduate School of Environmental Studies, Seoul National University, Seoul 151-742, Korea;
2. School of Forestry, University of Montana, Missoula, MT 59812, USA;
3. Department of Environmental Science and Engineering, Ewha Womans University, Seoul 120-750, Korea;
4. Division of Forest Ecology, Korea Forest Research Institute, Seoul 130-712, Korea;
5. Division of Forest Resources, Korea Forest Research Institute, Seoul 130-712, Korea

Correspondence should be addressed to Lee Dewon (email: leedw@snu.ac.kr)

Received May 14, 2002

Abstract Using a slightly modified IPCC method, we examined changes in annual fluxes of CO_2 and contributions of energy consumption, limestone use, waste combustion, land-use change, and forest growth to the fluxes in South Korea from 1990 to 1997. Our method required less data and resulted in a larger estimate of CO_2 released by industrial processes, comparing with the original IPCC guideline. However, net CO_2 emission is not substantially different from the estimates of IPCC and modified methods. Net CO_2 emission is intimately related to GDP as Korean economy has heavily relied on energy consumption and industrial activities, which are major sources of CO_2. Total efflux of CO_2 was estimated to be 63.6 Tg C/a in 1990 and amounted to 112.9 Tg C/a in 1997. Land-use change contributed to annual budget of CO_2 in a relatively small portion. Carbon dioxide was sequestered by forest biomass at the rate of 6.5 Tg C/a in 1990 and 8.5 Tg C/a in 1997. Although CO_2 storage in the forests increased, the sink effect was overwhelmed by extensive energy consumption, suggesting that energy-saving strategies will be more effective in reducing CO_2 emission in Korea than any other practices. It is presumed that plant uptake of CO_2 is underestimated as carbon contained in plant detritus and belowground living biomass were not fully considered. Furthermore, the soil organic carbon stored in forest decomposes in various ways in rugged mountains depending on their conditions, such as slope, aspect and elevation, which could have an effect on decomposition rate and carbon stores in soils. Thus, carbon sequestration of forests deserves further attention.

Keywords: CO_2 emission and removal, energy consumption, forest regrowth, land use, simplified IPCC method.

Earth's climate is greatly influenced by carbon dioxide concentrations in the atmosphere. From a global perspective, elevated atmospheric CO_2 is attributed to accelerated fossil fuel combustion and deforestation[1], both intimately related to economic growth.

In South Korea, the annual economic growth-rate was 8.4% on average from 1981 to 1997. The economic growth has been fueled by primary energy, relied on the consumption of a large amount of solvent and other materials and industrial processes, and resulted in solid and liquid wastes into the environment. Relevant documents of governmental institutes, such as the Ministry of Commerce and the Ministry of Environment in Korea, indicate the increasing uses of energy sources and raw materials and production of wastes. For example, primary energy consumption increased by approximately 3.8 times[2]. Such statistics suggests that there must be a rapid increase of CO_2 released to the atmosphere during the period of time.

In addition, vegetated areas are declining as urban areas are sprawling out into uplands to support a large population and economy. Over the past decades, a lot of forests were converted to residential and industrial areas. Hence, the land-use change might also be another source of atmospheric CO_2.

A major sink of CO_2 is driven by forest regrowth because a fraction of carbon is absorbed and held by living biomass and detritus in terrestrial ecosystems[3]. Forests in Korea are mainly in the cool-temperate forest zone dominated by *Pinus*, *Quercus* and *Acer* species, and occupy about 65% of the total land area[4]. Most of the forest stands had been degraded by over-harvesting for fuel wood and timber production over the period of Japanese occupation (1910—1945), Korean War (1950—1953) and up until 1960s. Forest stock volume of South Korea was only 10.6 m^3/ha in 1960.

Korea Forest Service established “Reforestation Project” twice between 1973 and 1987. As a result of the efforts, the stock reached 63.5 m^3/ha in 2000[4]. Forest biomass is still increasing since more than 40% of the forest is younger than 40 a. Thus forests in Korea are expected to have a large potential to sequester the atmospheric CO_2 into forest ecosystems.

Currently, Korean government has proposed and applied several institutional programs to meet the Kyoto Protocol targets. Strategies to save energy and raw materials, reduce solid and liquid wastes, and enhance forest regrowth are encompassed in the programs. Hence, we need to assess how effective relevant strategies and practices are in reducing the amount of CO_2 released in the air and suggest which approaches emphasis would be placed on.

In the present paper, we aim at estimating the major CO_2 fluxes on a national scale in South Korea and addressing the effects of land-use changes and reforestation on the annual carbon budget. For the energy consumption, emission of CO_2 was estimated by a simplified IPCC method.

1 Methods

Major sources of CO_2 can be grouped into energy consumption, solvent/other product use, industrial processes, waste, land-use change, and forestry[5].

1.1 Energy consumption

The amount of CO_2 emitted by energy consumption is given by the following equation:

$$CO_2 \text{ emission by energy consumption (Gg C/a)} = \sum (C_i \times F_i \times E_i),$$

where C_i (TOE/a) is the annual consumption of the ith fuel type, F_i (Gg C/TOE) is the emission factor of the ith fuel type , and E_i is the combustion efficiency of the ith fuel type. Data of annual consumption of fuel types, an emission factor and combustion efficiency of each fuel type were compiled from refs. [5—7], respectively.

1.2 Solvent/other product use

Naphtha and asphalt are included in this solvent/other product use sector unlike the IPCC guideline since those are not regarded as energy sources in Korea. In addition, solvent and asphalt are not considered in this study because solvent is used less than 1% of that of naphtha[6] and the fraction of carbon stored in asphalt is completely conservative[5]. The following equation is employed to estimate the CO_2 emission from naphtha:

$$CO_2 \text{ emission by naphtha (Gg C/a)} = A \times (1 - S) \times F,$$

where A, S, and F are domestic consumption of naphtha (TOE/a), the fraction of carbon remaining in products, and emission factor (Gg C/TOE), respectively. Data of each term are collected in the Yearbook of Energy Statistics[8] reported by the Ministry of Commerce. The fraction of carbon stored in naphtha and CO_2 emission factor are adopted from ref. [5].

1.3 Industrial process

Contribution of mineral and metal production to CO_2 fluxes may also be included in industrial processes[5], while the fuel combustion of industrial sector is included in energy consumption sector. In the present paper, release of CO_2 from industrial sector is estimated only by limestone consumption because the consumption of dolomite is negligible.

$$CO_2 \text{ emission by limestone consumption (Gg C/a)} = 0.12 \times A \times P,$$

where A (Gg $CaCO_3$/a) and P are mean amount of limestone consumed and degree of purity(85%), respectively. The ratio of C to $CaCO_3$ molecular weight is 0.12. Amounts of limestone consumed from 1990 to 1997 are collected from ref. [6].

1.4 Waste combustion

The combustion of anthropogenic materials, such as plastics, papers and food wastes, releases additional CO_2 into the atmosphere. Carbon dioxide emission by waste combustion is estimated according to the IPCC guideline. When waste incineration is concerned, a recommended approach is to divide carbon of the incinerated wastes into biomass and fossil fuel based fractions[5]. In this paper, only plastic materials are considered as the contribution and others to CO_2 emission are negligibly low.

$$CO_2 \text{ emission from wastes (plastic materials only) (Gg C/a)} = A \times F,$$

where A and F are the amount of plastic waste combustion (TOE/a) and CO_2 emission factor (Gg C/TOE) of plastic materials, respectively. Relevant data are acquired from ref. [9] reported by the Ministry of Environment in Korea.

1.5 Land-use change and forestry

According to the revised 1996 IPCC guideline for national greenhouse gas inventories, major changes in carbon stocks in land-use change and forestry section occurred by (i) changes in forest and other woody biomass stocks, (ii) emission from forest and grassland conversion, (iii) abandonment of managed land, and (iv) fluxes caused by land-use change and management. The third component is not considered, because the area of abandoned land in over-populated Korea (472 capita/km^2) is negligible.

1.5.1 Changes in forest and other woody biomass stocks. To estimate the changes in forest and other woody biomass stocks, we extracted growing stock data for each forest type in the Statistical Yearbook of Forestry[4]. Annual change of biomass stock is given by the stock of a year minus that of the following year:

Net carbon removal of forest growth from the atmosphere (Gg C/a)
= Annual net biomass increment × C fraction of dry matter,
Annual net biomass increment (Gg dry matter/a)
= Net increment of stem biomass (Gg dry matter/a) × Ratio of aboveground biomass to stem biomass × Ratio of total biomass to aboveground biomass.

Emission of CO_2 by commercial harvesting and fuel wood production is estimated as follows:
Carbon emission (Gg C/a) = Total biomass consumption × C fraction of dry matter,
Total biomass consumption (Gg dry matter/a)
= Aboveground biomass consumption × Ratio of total biomass to aboveground biomass,
Aboveground biomass consumption (Gg dry matter/a)
= Fuel wood consumption + Aboveground biomass removed by commercial harvest,
Aboveground biomass removed by commercial harvest (Gg dry matter/a)
= Volume of commercial harvest (1000 m^3) × Conversion factor of log to stem volume (1/0.85) × Oven dried specific gravity × Ratio of aboveground biomass to stem biomass.

The ratio of aboveground biomass to stem biomass is 1.29 for conifers and 1.22 for broad-leaved trees and the ratio of total biomass to aboveground biomass is 1.28 for conifers and 1.41 for broad-leaved trees[10].

Net increment of stem biomass (Gg dry matter) is equal to the product of net increment of stem volume and oven-dried specific gravity (t/m^3 dry matter). Oven-dried specific gravity (t/m^3, dry matter) is 0.47 for conifers and 0.80 for broad-leaved trees[11]. Carbon fraction of dry biomass is assumed to be 0.5 for both aboveground and belowground biomass[12].

1.5.2 Loss of forest and grassland biomass by the burning and decay of aboveground biomass. In Korea, on-site burning is prohibited by law. When forest areas are converted for other land use, woods are used for commercial timber and fuel, and woody debris remains decayed on site. In this section, we consider carbon dioxide emission by the decay of aboveground biomass only, and carbon dioxide release from soil is calculated in other sections. We assume that the woody debris decay occurred over a 10 a period and the fraction left to decay is 0.6. The data of forest conversion are acquired from unpublished documents of Korea Forest Service (Lee Chag Jae, personal communication).

Emission by biomass decay (Gg C)
= Average area damaged during the past 10 a (×1000 ha)
×Net change in biomass density (tons dry matter/ha, difference in average biomass between forest and other converted land types)
×Fraction left to decay (0.6)×C fraction of dry matter (0.5).

1.5.3 Emission and uptake from soil by land-use change and management. Carbon flux from soil occurs through three processes: (i) changes in carbon pool stored in soil and litter of mineral soils, (ii) emissions from organic soils converted to agriculture or plantations, and (iii) emissions from liming of agricultural soils. The second fraction is not included in the estimation because the amount is negligibly small and there is no reliable data in Korea. The third one is already considered in industrial sources of CO_2.

Carbon stored in soil and litter of mineral soils by land-use change is assumed to be respired from only the top 30 cm layer of soil. Because carbon emission or uptake by soil after land-use change occurs slowly, we assume that it continues for 20 a[5].

Change in carbon (Gg C/a) = Carbon content of each soil type by land-use (Gg C/ha, 60.5 for paddy field, 45.9 for cropland, 69.7 for forest, 11.5 for other lands including roads, urban area and so on)×Average annual changes in land area by land-use for the past 20 a (million ha).

2 Results and discussion

2.1 CO_2 emission by energy consumption

Consumptions of fuel oil and other energy sources increased by 87% and more than 100% from 1990 to 1997, respectively (table 1). While consumption of anthracite in 1997 fell to one-fifth of the amount in 1990, that of LNG increased five-fold. Overall, a large amount of CO_2 was emitted by energy use at the rate of 63.6 Tg C/a and 112.9 Tg in 1990 and 1997, respectively. Consumption of fuel oil accounted for, on average, 55% of total CO_2 efflux in 1990. The contribution of energy consumption to total CO_2 efflux increased up to 60% during the period of 1992—1995 and decreased to 56% in 1997 when an economic crisis occurred.

Table 1 Effluxes of CO_2 by energy consumption in South Korea from 1990 to 1997

Year	1990	1991	1992	1993	1994	1995	1996	1997
Fuel oil	32.5	37.6	42.9	46.9	51.4	56.6	60.1	60.9
Bituminous coal	15.0	17.0	18.0	21.6	24.0	26.1	30.8	34.1
Anthracite	10.7	8.8	6.8	5.5	3.8	3.2	2.8	2.1
LNG	1.9	2.2	2.9	3.6	4.8	5.8	7.6	9.3
LPG	2.6	3.1	3.9	4.2	4.5	4.7	4.9	5.1
Charcoal and others	0.9	0.7	0.8	0.8	1.0	1.2	1.3	1.5
CO_2 emission	63.6	69.3	75.2	82.6	89.6	97.5	107.5	112.9

Unit: Tg C/a.

2.2 CO_2 emission by solvent/other product use

The amount of naphtha consumed domestically each year was 7556200 m^3/a in 1990 and 30972500 m^3/a in 1997, quadrupling CO_2 emission of 1.25—5.19 Tg C/a. The results indicate that the fraction of total CO_2 emission attributable to naphtha consumption was approximately 2% in 1990 and 3.5% in 1997 (table 2).

Table 2 Changes of non-fuel domestic consumption and limestone production in South Korea from 1990 to 1997 (National Statistical Office)

Year	1990	1991	1992	1993	1994	1995	1996	1997
Naphtha	47553	65671	97158	108577	123276	131474	141273	194918
Solvent	458	362	349	410	680	733	664	785
Asphalt	5113	7015	9972	9453	9416	9524	10726	11958
Limestone production /Gg • a^{-1}	48463	59054	65333	76738	82669	87199	88108	92283

Unit: 1000 m^3.

2.3 CO_2 emission by limestone use in industrial processes

Limestone is used for cement, iron, chemical and other industrial purposes. Because dolomite is consumed at an insignificant rate, less than 3% of that of limestone, it is not taken into consideration in this calculation. Limestone consumption was 48463 Gg/a in 1990 and 92283 Gg/a in 1997, evolving gaseous CO_2 at the rate of 4.9 and 9.4 Tg C/a, respectively. The fractions of total CO_2 emission attributable to limestone use were 7%—9% during the period of time, making limestone the second largest source of CO_2 emission.

2.4 CO_2 emission by waste combustion

In the waste sector, CO_2 emission was mostly attributed to plastics combusted in 1996 and 1997, and estimated from the data on the ratio of consumption to production in plastics from 1990 to 1995 when no data are available. The amount of plastics combusted was substantially reduced in 1994 and 1995 due to a change in the Korean classification system of wastes. Waste combustion increased CO_2 emission by 523% from 80 Gg C/a in 1990 to 503 Gg C/a in 1997 but was responsible for only 0.13%—0.42% of total CO_2 emission.

2.5 Changes in CO_2 fluxes by land-use change and forestry

Forested area occupied about 67% of Korea's total land surface until the mid-1970s, followed by continuous decrease to 65% in 1995 (table 3). Total forest area was approximately 64780 km^2 in 1990 and 62530 km^2 in 1997. However, conversion rate decreased thereafter, and the current conversion rate is less than 100 km^2 per year, which is about 0.08% of total forest area per year. Most of the forest has been converted to meet urban development. Recently, forested areas are seldom converted for the purpose of agriculture, because the market values of agricultural products are degrading. Moreover, marginal croplands on and near a mountainous area have been abandoned due to the lack of labor and low economic return. Parts of abandoned croplands are even converted to forest by secondary succession.

Table 3 Changes in areas of land-use types in South Korea from 1990 to 1997 (National Statistical Office)

Year	1990	1991	1992	1993	1994	1995	1996	1997
Rice paddy	13453	13352	13147	12983	12671	12059	11761	11629
Dry field	7635	7557	7552	7565	7656	7794	7693	7607
Forest land	64760	64677	64638	64598	64556	64519	64479	64413
Others	13425	13714	13977	14245	14511	14897	15379	15725
Total	99273	99300	99314	99391	99394	99269	99312	99374

Unit: km^2.

Although forested area declined, biomass stock has accumulated continuously. Total growing stock was 145.7×10^6 m^3 in 1980, 248.4×10^6 m^3 in 1990 and 340.8×10^6 m^3 in 1997 (fig. 1). The fractions of growing stocks of coniferous, broad-leaved, and mixed forests in 1997 were 44.2%, 27.8% and 28.0%, respectively.

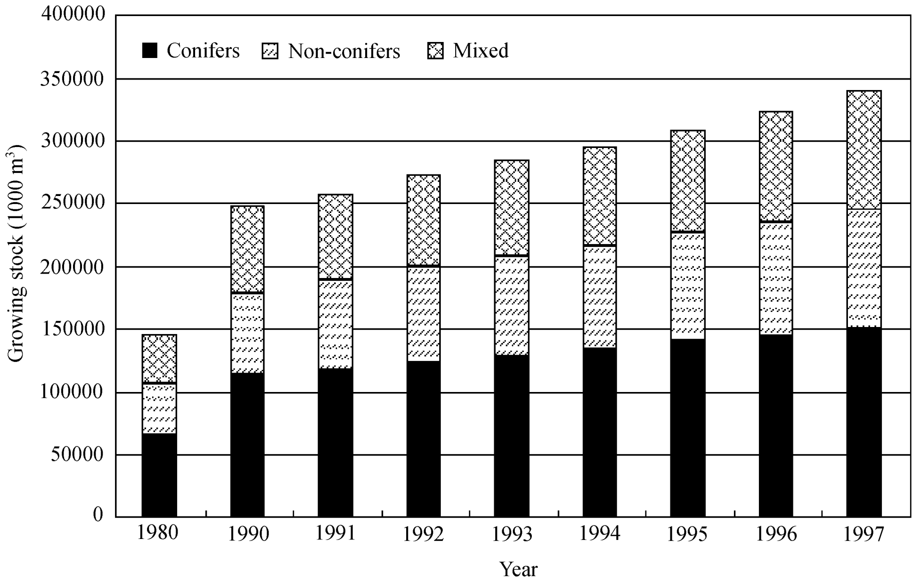

Fig. 1. Growing stock of each forest type in South Korea from 1980 to 1997.

The carbon storage in forest biomass was 125.6 Tg C in 1990 and increased up to 175.9 Tg C in 1997 (fig. 2). We assumed that a mixed forest was composed of conifers and non-conifers evenly. The fraction of carbon storage in conifer trees and non-conifer trees was 44% and 56% in 1997, respectively. The ratio of carbon storage in non-conifer trees is relatively high when the ratio of growing stocks is considered. This is why the specific gravity of broad leaves is higher than that of conifers even though land area of non-conifer trees (16840 km^2) is smaller than that of conifer trees (27820 km^2).

Net carbon sequestration by the stock changes in forest and other woody biomass gradually increased from 7.96 Tg C in 1990 to 10.19 Tg C in 1997 (table 4). Carbon dioxide emission by harvesting was only a small portion of this category. This implies that Korean forests are relatively young and about 10% of forest growth is harvested. However, carbon dioxide emission by the conversion of forest and grassland for other land-use increased from 46 Gg C in 1990 to 79 Gg C in 1997.

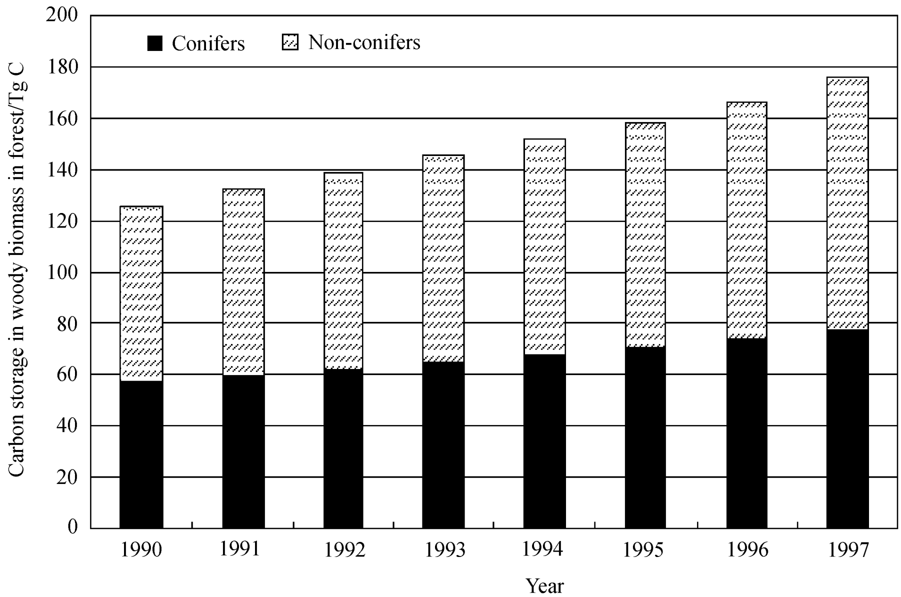

Fig. 2. Carbon storage in woody biomass in South Korea from 1990 to 1997.

Table 4 Annual uptake and emission of CO_2 by changes in land-use change and forestry. Negative values indicate net uptake

Year	1990	1991	1992	1993	1994	1995	1996	1997
Growth	–7.96	–7.77	–7.12	–7.32	–6.77	–7.49	–8.52	–10.19
Harvest	0.80	0.85	0.73	0.72	0.70	0.63	0.68	0.62
Forest/grassland conversion	0.05	0.05	0.06	0.06	0.07	0.07	0.08	0.08
CO_2 emission from soil	0.61	0.62	0.58	0.76	0.84	0.98	1.02	1.03
Total	–6.50	–6.25	–5.74	–5.76	–5.16	–5.82	–6.74	–8.46

Unit: Tg C/a.

Carbon stock in soil including forests, cultivated lands, and other areas was estimated to be 377.18 Tg C in 1990[13]. In the same year, carbon stored in wood products was estimated to be 34.31 Tg C and in woody biomass 125.59 Tg C, indicating that the fractions of carbon stocks in soils, wood productions and woody biomass were 70.2%, 6.4% and 23.4%, respectively. Soil component is the biggest carbon pool in land-use change and forestry sector, but CO_2 uptake and emission rates are much greater in biomass than those in soils. Carbon dioxide emission by limestone consumption for agriculture can be one of the sources from soils. But it is already included in the industrial sources.

Net uptake of CO_2 in land-use change and forestry sector from 1990 to 1997 was 6.50 Tg C in 1990 and 8.46 Tg C in 1997.

3 Conclusions and recommendations

Net CO_2 emission was 63.4 and 119.6 Tg C/a in 1990 and 1997, respectively. More than 90%

of total CO_2 emission was derived from energy consumption (fig. 3). The second largest source of CO_2 is limestone used in industrial processes, followed by the use of solvent/other products use. Emission from wastes combustion contributed less than 0.5% to the total CO_2 budget. The effects of land-use change on CO_2 evolution were relatively small. As a carbon sink, forests absorbed 10.2% of the total amount of CO_2 released in the atmosphere in 1990 and 7.5% in 1997 (fig. 4).

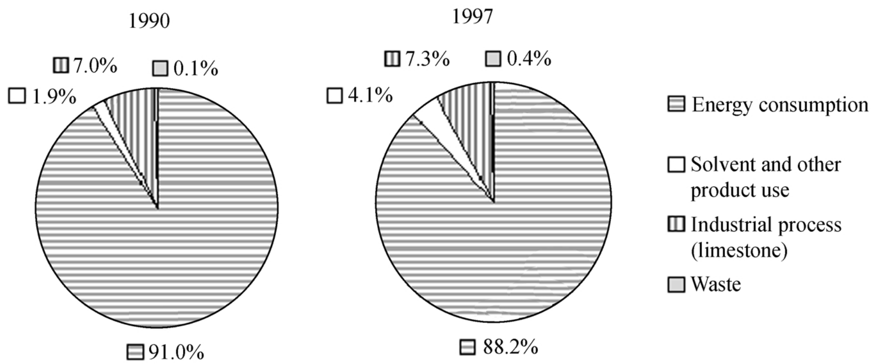

Fig. 3. Fractions of total CO_2 efflux attributable to major sources.

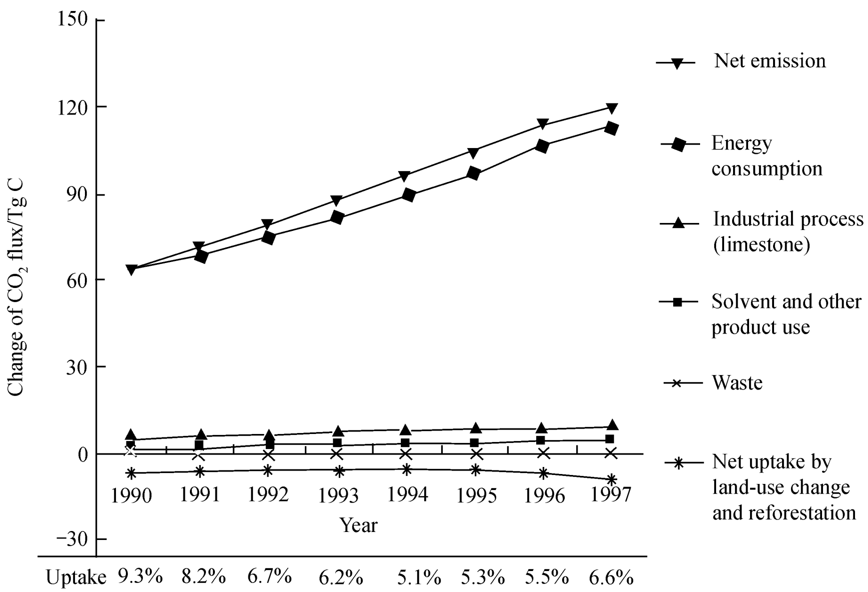

Fig. 4. Changes in annual CO_2 fluxes from major sources and to sink from 1990 to 1997. Numbers on the bottom indicate the ratios of uptake of sink to total effluxes of sources.

Although our slightly modified IPCC method requires less data and results in a larger estimate of CO_2 released by industrial processes, the estimates of net CO_2 emission are similar in the two methods. Net CO_2 emission is intimately related to GDP as Korean economy has heavily relied on energy consumption and industrial activities, which are major sources of CO_2.

Although forest biomass has increasingly stored carbon, it is overwhelmed by the release of CO_2 from extensive energy consumption, suggesting that energy-saving strategies will be more effective than any management practices of forest for the reduction of CO_2 emission. However, the results should be cautiously interpreted because plant uptake of CO_2 could have been underestimated. In the present study, carbon contained in belowground living biomass, decomposing detritus and soil organic matter are not fully considered[14]. Accordingly, carbon sequestration by forests will warrant further attention in the future studies.

Carbon sequestration by soil and detritus during the study period is estimated roughly by using annual mortality and decomposition rate of deadwoods. The detailed estimation relies on further available information on longevity and decomposition rate of leaf and fine root of major species. Due to recent development of remote sensing techniques[15], regional and global-scale phenology data are available. Combined with remote sensing techniques, a process-oriented vegetation growth model can be applied to reliable estimation of carbon fluxes through the atmosphere-vegetation-soil continuum on regional and global scales.

Acknowledgements We are grateful to Leandro Buendia, Chuluun Togtohy, and Pep Canadell for giving many constructive comments on an early draft of this paper. This work was supported by “Eco-technopia 21 Project”, Ministry of Environment, Republic of Korea.

References

1. Houghton, R. A., Woodwell, G. M., Global climatic change, Scientific American, 1989, 260(4): 36—44.
2. Korea Energy Economics Institute, The Second-year Study of Planning National Actions for the United Nations Framework Convention on Climate Change (in Korean), 1998.
3. Cebrian, J., Duarte, C. M., Plant growth-rate dependence of detrital carbon storage in ecosystems, Science, 1995, 268: 1606—1608.
4. Korea Forest Service, Statistical Yearbook of Forestry (in Korean), 1990—1997.
5. IPCC, Revised 1996 IPCC Guideline for National Greenhouse Gas Inventories, IPCC/OECD/IEA, 1996.
6. Ministry of Commerce, Industry and Energy, Yearbook of Mineral Statistics (in Korean), Kyungi: Ministry of Commerce, 1999, 140—142.
7. You, D. H., Shin, J. S., The Studies about Greenhouse Gases Emission Inventory and Its Management (in Korean), Kyungi: Korea Energy Economics Institute, 1999, 83—85.
8. Ministry of Commerce, Industry and Energy, Yearbook of Energy Statistics (in Korean), Kyungi: Ministry of Commerce, 1981—1998.
9. Ministry of Environment, Republic of Korea, Environmental Statistic Yearbook (in Korean), 1987—1998.
10. Kim, K. D., Kim, C. M., Research trends on forest biomass production in Korea, J. Kor. For. Energy, 1988, 13(1): 94—107.
11. Korea Forest Research Institute, Wood properties and uses of the major tree species growing in Korea, Research Notes of KFRI, Vol. 95 (in Korean), 1994.
12. Gower, S. T., Krankina, O., Olson, R. J. et al., Net primary production and carbon allocation patterns of boreal forest ecosystems, Ecological Applications, 2001, 11: 1395—1411.
13. Kim, K. H., Kim, S. K., Kim, S. Y. et al., Korean forest and greenhouse gases, Research Notes of KFRI (in Korean), 1996, 126: 270.
14. Hall, G. M., Mitigating an organization’s future net carbon emissions by native forest restoration, Ecological Applications, 2001, 11: 1622—1633.
15. Landsberg, J. J., Gower, S. T., Applications of Physiological Ecology to Forest Management, San Diego: Academic Press, 1997.