Changes in annual CO\textsubscript{2} fluxes estimated from inventory data in South Korea

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Abstract  Using a slightly modified IPCC method, we examined changes in annual fluxes of CO\textsubscript{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\textsubscript{2} released by industrial processes, comparing with the original IPCC guideline. However, net CO\textsubscript{2} emission is not substantially different from the estimates of IPCC and modified methods. Net CO\textsubscript{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\textsubscript{2}. Total efflux of CO\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{2} emission in Korea than any other practices. It is presumed that plant uptake of CO\textsubscript{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\textsubscript{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\textsubscript{2} is attributed to accelerated fossil fuel combustion and deforestation\textsuperscript{[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\textsuperscript{[2]} such that there must be a rapid increase of CO\textsubscript{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\textsubscript{2}.

A major sink of CO\textsubscript{2} is driven by forest regrowth because a fraction of carbon is absorbed and held by living biomass and detritus in terrestrial ecosystems\textsuperscript{[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\textsuperscript{[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\textsuperscript{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\textsuperscript{3}/ha in 2000\textsuperscript{[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\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{2} was estimated by a simplified IPCC method.

1 Methods

Major sources of CO\textsubscript{2} can be grouped into energy consumption, solvent/other product use, industrial processes, waste, land-use change, and forestry\textsuperscript{[5]}.

1.1 Energy consumption

The amount of CO\textsubscript{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 \( i \)th fuel type, \( F_i \) (Gg C/TOE) is the emission factor of the \( i \)th fuel type, and \( E_i \) is the combustion efficiency of the \( i \)th fuel type. Data of annual consumption of fuel types, an emission factor and combustion efficiency of each fuel type were
Supp. CHANGES IN ANNUAL CO\textsubscript{2} FLUXES IN SOUTH KOREA

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\textsuperscript{[6]} and the fraction of carbon stored in asphalt is completely conservative\textsuperscript{[5]}. The following equation is employed to estimate the CO\textsubscript{2} emission from naphtha:

\[
\text{CO}_2 \text{ emission by naphtha (Gg C/a)} = A \times (1 - S) \times F,
\]

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\textsuperscript{[8]} reported by the Ministry of Commerce. The fraction of carbon stored in naphtha and CO\textsubscript{2} emission factor are adopted from ref. [5].

1.3 Industrial process

Contribution of mineral and metal production to CO\textsubscript{2} fluxes may also be included in industrial processes\textsuperscript{[5]}, while the fuel combustion of industrial sector is included in energy consumption sector. In the present paper, release of CO\textsubscript{2} from industrial sector is estimated only by limestone consumption because the consumption of dolomite is negligible.

\[
\text{CO}_2 \text{ emission by limestone consumption (Gg C/a)} = 0.12 \times A \times P,
\]

where \(A\) (Gg CaCO\textsubscript{3}/a) and \(P\) are mean amount of limestone consumed and degree of purity(85%), respectively. The ratio of C to CaCO\textsubscript{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\textsubscript{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\textsuperscript{[5]}. In this paper, only plastic materials are considered as the contribution and others to CO\textsubscript{2} emission are negligibly low.

\[
\text{CO}_2 \text{ emission from wastes (plastic materials only) (Gg C/a)} = A \times F,
\]

where \(A\) and \(F\) are the amount of plastic waste combustion (TOE/a) and CO\textsubscript{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 for-
est 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/km²) 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 Sta-
tistical Yearbook of Forestry\[4\]. Annual change of biomass stock is given by the stock of a year
minus that of the following year:

\[
\text{Net carbon removal of forest growth from the atmosphere (Gg C/a)} = \text{Annual net biomass increment} \times \text{C fraction of dry matter},
\]

\[
\text{Annual net biomass increment (Gg dry matter/a)} = \text{Net increment of stem biomass (Gg dry matter/a)} \times \text{Ratio of aboveground biomass to stem biomass} \times \text{Ratio of total biomass to aboveground biomass}.
\]

Emission of CO₂ by commercial harvesting and fuel wood production is estimated as follows:

\[
\text{Carbon emission (Gg C/a)} = \text{Total biomass consumption} \times \text{C fraction of dry matter},
\]

\[
\text{Total biomass consumption (Gg dry matter/a)} = \text{Aboveground biomass consumption} \times \text{Ratio of total biomass to aboveground biomass},
\]

\[
\text{Aboveground biomass consumption (Gg dry matter/a)} = \text{Fuel wood consumption} + \text{Aboveground biomass removed by commercial harvest},
\]

\[
\text{Aboveground biomass removed by commercial harvest (Gg dry matter/a)} = \text{Volume of commercial harvest (1000 m}^3\text{) \times Conversion factor of log to stem volume (1/0.85) \times Oven dried specific gravity \times \text{Ratio of aboveground biomass to stem biomass}}.
\]

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/m³ dry matter). Oven-dried specific gravity (t/m³,
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 bio-
mass. 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)

\[
\text{Emission by biomass decay} = \text{Average area damaged during the past 10 a} \times 1000 \text{ ha} \times \text{Net change in biomass density} \times \text{Fraction left to decay} \times \text{C fraction of dry matter}
\]

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 CO2.

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) \times \text{Average annual changes in land area by land-use for the past 20 a (million ha)}.

2 Results and discussion

2.1 CO2 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 CO2 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 CO2 efflux in 1990. The contribution of energy consumption to total CO2 efflux increased up to 60% during the period of 1992—1995 and decreased to 56% in 1997 when an economic crisis occurred.

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</thead>
<tbody>
<tr>
<td>Fuel oil</td>
<td>32.5</td>
<td>37.6</td>
<td>42.9</td>
<td>46.9</td>
<td>51.4</td>
<td>56.6</td>
<td>60.1</td>
<td>60.9</td>
</tr>
<tr>
<td>Bituminous coal</td>
<td>15.0</td>
<td>17.0</td>
<td>18.0</td>
<td>21.6</td>
<td>24.0</td>
<td>26.1</td>
<td>30.8</td>
<td>34.1</td>
</tr>
<tr>
<td>Anthracite</td>
<td>10.7</td>
<td>8.8</td>
<td>6.8</td>
<td>5.5</td>
<td>3.8</td>
<td>3.2</td>
<td>2.8</td>
<td>2.1</td>
</tr>
<tr>
<td>LNG</td>
<td>1.9</td>
<td>2.2</td>
<td>2.9</td>
<td>3.6</td>
<td>4.8</td>
<td>5.8</td>
<td>7.6</td>
<td>9.3</td>
</tr>
<tr>
<td>LPG</td>
<td>2.6</td>
<td>3.1</td>
<td>3.9</td>
<td>4.2</td>
<td>4.5</td>
<td>4.7</td>
<td>4.9</td>
<td>5.1</td>
</tr>
<tr>
<td>Charcoal and others</td>
<td>0.9</td>
<td>0.7</td>
<td>0.8</td>
<td>0.8</td>
<td>1.0</td>
<td>1.2</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>CO2 emission</td>
<td>63.6</td>
<td>69.3</td>
<td>75.2</td>
<td>82.6</td>
<td>89.6</td>
<td>97.5</td>
<td>107.5</td>
<td>112.9</td>
</tr>
</tbody>
</table>

Unit: Tg C/a.
2.2 CO₂ emission by solvent/other product use

The amount of naphtha consumed domestically each year was 7556200 m³/a in 1990 and 30972500 m³/a in 1997, quadrupling CO₂ emission of 1.25—5.19 Tg C/a. The results indicate that the fraction of total CO₂ 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)

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<tbody>
<tr>
<td>Naphtha</td>
<td>47553</td>
<td>65671</td>
<td>97158</td>
<td>108577</td>
<td>123276</td>
<td>131474</td>
<td>141273</td>
<td>194918</td>
</tr>
<tr>
<td>Solvent</td>
<td>458</td>
<td>362</td>
<td>349</td>
<td>410</td>
<td>680</td>
<td>733</td>
<td>664</td>
<td>785</td>
</tr>
<tr>
<td>Asphalt</td>
<td>5113</td>
<td>7015</td>
<td>9972</td>
<td>9453</td>
<td>9416</td>
<td>9524</td>
<td>10726</td>
<td>11958</td>
</tr>
<tr>
<td>Limestone production</td>
<td>48463</td>
<td>59054</td>
<td>65333</td>
<td>76738</td>
<td>82669</td>
<td>87199</td>
<td>88108</td>
<td>92283</td>
</tr>
</tbody>
</table>

Unit: 1000 m³.

2.3 CO₂ 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 CO₂ at the rate of 4.9 and 9.4 Tg C/a, respectively. The fractions of total CO₂ emission attributable to limestone use were 7%—9% during the period of time, making limestone the second largest source of CO₂ emission.

2.4 CO₂ emission by waste combustion

In the waste sector, CO₂ 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 CO₂ 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 CO₂ emission.

2.5 Changes in CO₂ 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 km² in 1990 and 62530 km² in 1997. However, conversion rate decreased thereafter, and the current conversion rate is less than 100 km² 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)

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<tbody>
<tr>
<td>Rice paddy</td>
<td>13453</td>
<td>13352</td>
<td>13147</td>
<td>12983</td>
<td>12671</td>
<td>12059</td>
<td>11761</td>
<td>11629</td>
</tr>
<tr>
<td>Dry field</td>
<td>7635</td>
<td>7557</td>
<td>7552</td>
<td>7565</td>
<td>7656</td>
<td>7794</td>
<td>7693</td>
<td>7607</td>
</tr>
<tr>
<td>Forest land</td>
<td>64760</td>
<td>64677</td>
<td>64638</td>
<td>64598</td>
<td>64556</td>
<td>64519</td>
<td>64479</td>
<td>64413</td>
</tr>
<tr>
<td>Others</td>
<td>13425</td>
<td>13714</td>
<td>13977</td>
<td>14245</td>
<td>14511</td>
<td>14897</td>
<td>15379</td>
<td>15725</td>
</tr>
<tr>
<td>Total</td>
<td>99273</td>
<td>99300</td>
<td>99314</td>
<td>99391</td>
<td>99394</td>
<td>99269</td>
<td>99312</td>
<td>99374</td>
</tr>
</tbody>
</table>

Unit: km².

Although forested area declined, biomass stock has accumulated continuously. Total growing stock was $145.7 \times 10^6$ m³ in 1980, $248.4 \times 10^6$ m³ in 1990 and $340.8 \times 10^6$ m³ 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.](image-url)

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 km²) is smaller than that of conifer trees (27820 km²).

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.

![Carbon storage in woody biomass in South Korea from 1990 to 1997.](image)

**Table 4** Annual uptake and emission of CO₂ by changes in land-use change and forestry. Negative values indicate net uptake

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<tbody>
<tr>
<td>Growth</td>
<td>−7.96</td>
<td>−7.77</td>
<td>−7.12</td>
<td>−7.32</td>
<td>−6.77</td>
<td>−7.49</td>
<td>−8.52</td>
<td>−10.19</td>
</tr>
<tr>
<td>Harvest</td>
<td>0.80</td>
<td>0.85</td>
<td>0.73</td>
<td>0.72</td>
<td>0.70</td>
<td>0.63</td>
<td>0.68</td>
<td>0.62</td>
</tr>
<tr>
<td>Forest/grassland conversion</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
<td>0.06</td>
<td>0.07</td>
<td>0.07</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>CO₂ emission from soil</td>
<td>0.61</td>
<td>0.62</td>
<td>0.58</td>
<td>0.76</td>
<td>0.84</td>
<td>0.98</td>
<td>1.02</td>
<td>1.03</td>
</tr>
<tr>
<td>Total</td>
<td>−6.50</td>
<td>−6.25</td>
<td>−5.74</td>
<td>−5.76</td>
<td>−5.16</td>
<td>−5.82</td>
<td>−6.74</td>
<td>−8.46</td>
</tr>
</tbody>
</table>

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 CO₂ uptake and emission rates are much greater in biomass than those in soils. Carbon dioxide emission by lime-stone consumption for agriculture can be one of the sources from soils. But it is already included in the industrial sources.

Net uptake of CO₂ 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 CO₂ emission was 63.4 and 119.6 Tg C/a in 1990 and 1997, respectively. More than 90\%
of total CO₂ emission was derived from energy consumption (fig. 3). The second largest source of 
CO₂ 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 CO₂ budget. The effects 
of land-use change on CO₂ evolution were relatively small. As a carbon sink, forests absorbed 
10.2% of the total amount of CO₂ released in the atmosphere in 1990 and 7.5% in 1997 (fig. 4).

![Fig. 3. Fractions of total CO₂ efflux attributable to major sources.](image)

![Fig. 4. Changes in annual CO₂ 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.](image)

Although our slightly modified IPCC method requires less data and results in a larger esti-
mate of CO₂ released by industrial processes, the estimates of net CO₂ emission are similar in the 
two methods. Net CO₂ emission is intimately related to GDP as Korean economy has heavily re-
lied on energy consumption and industrial activities, which are major sources of CO₂.
Although forest biomass has increasingly stored carbon, it is overwhelmed by the release of CO₂ from extensive energy consumption, suggesting that energy-saving strategies will be more effective than any management practices of forest for the reduction of CO₂ emission. However, the results should be cautiously interpreted because plant uptake of CO₂ could have been underestimated. In the present study, carbon contained in belowground living biomass, decomposing detritus and soil organic matter are not fully considered. 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, 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.

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