B-1.4 Quantitative Analysis of Carbon Budgets in Temperate Regional Ecosystem

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Abstract To clarify the carbon cycle in terrestrial ecosystems on a regional scale, we estimated the carbon budgets in the basin of Koise River, Ibaraki Prefecture (30 km x 30 km) using Landsat TM data. We calculated carbon budgets in four major ecosystems of the study area using compartment models which were designed to accept remote sensed carbon stocks in plants and soils. The mean annual carbon budgets in croplands, paddy fields, broad-leaved forests and coniferous forests were -151, 2.8, -60 and 543 gC m^{-2} yr^{-1}, respectively. Although the croplands and broad-leaved forests acted as a source of carbon dioxide (CO_2), the coniferous forests absorbed a larger amount of CO_2. Therefore, the study area as a whole was estimated to act as a sink of CO_2 (40 kt C yr^{-1}).

Key Words Carbon budget, Compartment model, Landsat TM data, Remote sensing

1. Introduction

Carbon dioxide (CO_2) is a major greenhouse gas (Intergovernmental Panel on Climate Change 1990). Atmospheric CO_2 has been increasing as a result of human activities, and this presents a threat of global warming. Therefore, scientific interests in the carbon cycle in terrestrial ecosystems have grown recently. Previous studies on the carbon cycle were based on land-use types and have neglected the spatial heterogeneity within an ecosystem (*e.g.* Houghton *et al.* 1983). To investigate regional variation of the carbon cycle, it is necessary to understand the global carbon budget. However, there are few quantitative analyses of the carbon cycle in a regional ecosystem.

A satellite remote sensing technique is very useful in studying the regional carbon cycle. Our objectives in this study are (1) to propose a method to estimate the carbon cycle in terrestrial ecosystems on a regional scale using Landsat TM data and (2) to identify how heterogeneous a distribution of carbon budgets is in a regional ecosystem.

2. Methods

Our study area was the basin of Koise River (30 km x 30 km), Ibaraki Prefecture, Japan. Mt. Tsukuba and the north edge of Lake Kasumigaura are located in this area. We used Landsat TM (Thematic Mapper) data. First, we carried out the land-cover classification using TM data and identified various types of ecosystem in the study area. Second, we estimated carbon stocks in the soil and in the aboveground plant biomass also using TM data. Third, we constructed compartment models of the carbon dynamics for each of the major ecosystems, which were designed to accept remote sensed data. Then we used the estimates of the carbon stocks from TM data as the parameters of this model, simulated the annual carbon fluxes in the major ecosystems. Finally, we estimated carbon budgets in the study area as a whole by summing up the budgets in all ecosystems.

3. Results and Discussion

Land-cover classification

We classified the land-cover of the study area into paddy field, cropland, grassland, broad-leaved forest, coniferous forest, bare soil, lake and city, by means of maximum likelihood classifier using TM data (bands 1, 3, 4 and 5) on 24 July 1987. Major ecosystems in the study area were cropland, paddy field, broad-leaved forests and coniferous forests (Table 1). Our ground-truth showed 88% reliability of this classification.

Carbon budget in croplands

Shingyoji *et al.* (1990) revealed that TM3 was sensitive to the topsoil organic matter in croplands (andosol) and developed the following equation to estimate the topsoil organic matter content (H; %) using TM data on 23 January 1985:

$$\log H\ (\%) = -0.0268(\mathrm{TM3}) + 1.71.$$

We assumed that the total carbon content (%) is 0.58 times H and the mean soil bulk density of 0-30 cm depth is 700 kg/m^3; then the carbon stock in the soil of 0-30 cm depth (C; gC m^{-2}) in croplands can be given by the following equation:

$$C = 1218\ H.$$

Normalized Differential Vegetation Index, NDVI=(TM4-TM3)/(TM4+TM3), is well-known as an indicator of plant biomass (*e.g.* Price 1987). We examined the relationship between the carbon contents in the aboveground parts of major crops in 1987 (Ibaraki Statistical Information Center 1988) and NDVI from TM data on 24 July 1987, and developed the equation to estimate the carbon stock in aboveground plant biomass (B; gC m^{-2}) in croplands as follows:

$$B^{1/2} = 110.4(\mathrm{NDVI}+1)^{1/2} - 120.4.$$

Since most of the carbon stock in phytomass will be removed by harvesting crops, this is not a real stock in croplands. Some residual of plant parts will be left in croplands as stubble. Thus, we examined the relationship between the carbon stocks in aboveground plant biomass (B; gC m^{-2}) and in stubble (S; gC m^{-2}) for the main crops in the study area, and found a linear relationship ($r=0.83$, $p<0.01$) as follows:

$$S = 0.56B - 0.17.$$

We calculated annual inputs of carbon (gC m^{-2} yr^{-1}) in the form of stubble into croplands using this equation.

Since cropland undergoes harvest and plowing, and becomes bare at least once a year, it is unnecessary to consider the carbon stock in plants. The soil is a major reservoir of carbon in cropland. There are two forms of carbon input from plants to soils: stubble (S;gC m^{-2}) and root exudation (E; gC m^{-2}), and the organic matter is decomposed by soil micro-organisms and CO_2 is released into the atmosphere (Fig. 1). We developed a two-compartment model of carbon dynamics in croplands (Fig. 1) and derived the differential equation of carbon stock in soils (C; gC m^{-2}) as follows:

$$dC/dt = 0.3S - 0.02C,$$

where t is time (yr). Here, we assumed that the organic matter of root exudation is one-tenth of net production (Barber and Martin 1976) and is decomposed within a year, and the annual decomposition rate of fresh stubble is 0.7 (Janssen 1984, Jenkinson 1990, Jenkinson *et al.* 1991). The decomposition rate (0.02) of hardly decomposable organic matter is derived from the soil respiration rate of single-cropping experimental fields in our institute (Bekku *et al.*, unpublished).

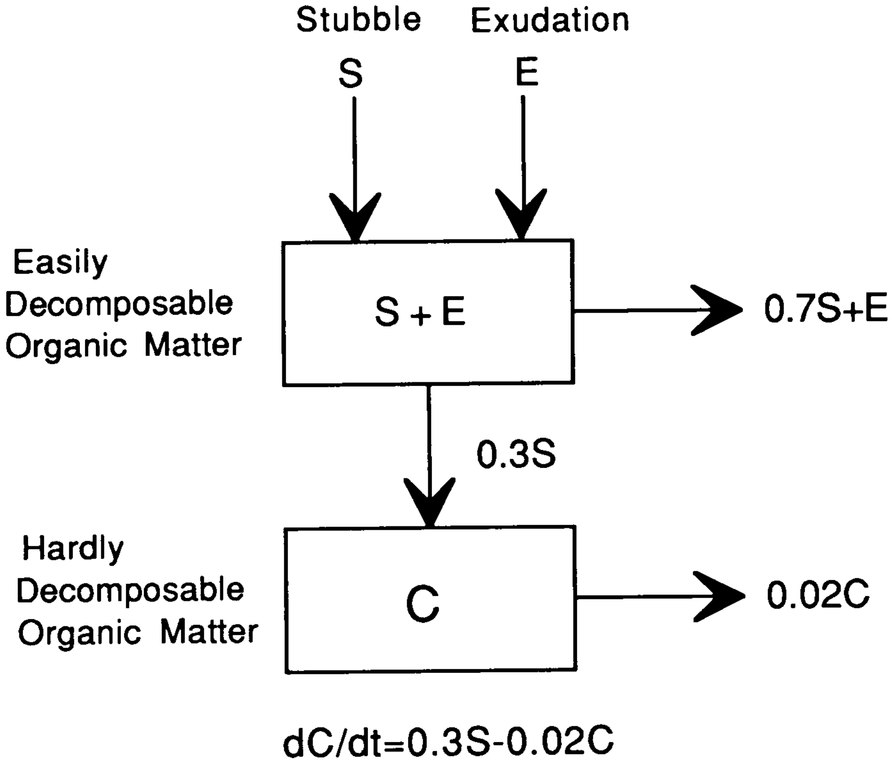

Fig. 1 Yearly dynamics of soil carbon (C) in croplands

Annual carbon budget in cropland is given by the difference in soil carbon stocks between the initial and the next year, using the differential equation. Since S and an initial value of C can be derived from TM data, we can estimate the carbon budget in the croplands from TM data. The annual carbon budgets varied markedly from -493 to +40 gC m^{-2} yr^{-1} with an average of -151 gC m^{-2} yr^{-1} (Fig. 2), suggesting that most croplands in the study area act as a source of CO_2. This confirms the previous studies conducted in Japan (Kumura 1977, Koizumi *et al.* 1993).

Carbon budget in paddy fields

Similar to the croplands, we used the equation of Shingyoji *et al.* (1990) to estimate the topsoil organic matter content (H; %) using TM data on 23 January 1985. We also assumed that the total carbon content (%) is 0.58 times H and the mean soil bulk density of 0-30 cm depth is 525 kg/m^3; then the carbon stock in the soil of 0-30 cm depth (C; gC m^{-2}) in paddy fields can be given by the following equation:

$$C = 913.5 H.$$

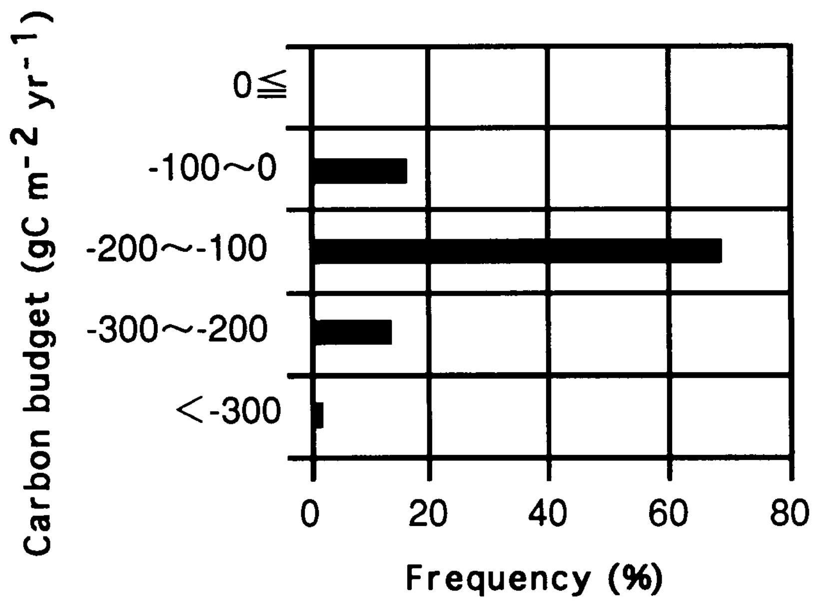

Fig. 2 Frequency distribution of the annual carbon budgets in croplands

We also examined the relationship between the carbon contents in the aboveground parts of rice in 1987 (Ibaraki Statistical Information Center 1988) and NDVI from TM data on 24 July 1987, and developed the equation to estimate the carbon stock in aboveground plant biomass (B; gC m^{-2}) in croplands as follows:

$$B = 739.8(\mathrm{NDVI}).$$

In the case of paddy fields, there are two types of stubble at a harvest time (Ss) and after the harvest (Sw) by the regrowth of rice. We assumed that the Ss and Sw consist of rice plant parts without unhulled rice and the whole parts, respectively. Then, the Ss and Sw can be given by the following equations:

$$Ss = 0.57\ B,$$
$$Sw = 1.04\ B.$$

We calculated annual inputs of carbon (gC m^{-2} yr^{-1}) in the form of stubble into paddy fields using this equation.

We also developed a two-compartment model of carbon dynamics in paddy fields (Fig. 3) and derived the differential equation of carbon stock in soils (C; gC m^{-2}) as follows:

$$dC/dt = 0.3(Ss+Sw) - 0.015C,$$

where t is time (yr). Here, we assumed that the organic matter of root exudation is 2% of net production (Bekku *et al.*, unpublished) and is decomposed within a year, and the annual decomposition rate of fresh stubble is 0.7, similar to the major crops. The decomposition rate (0.015) of hardly decomposable organic matter is derived from the soil respiration rate of single-cropping experimental fields in our institute (Koizumi *et al.*, unpublished).

The average carbon flux was 2.8 gC m^{-2} yr^{-1}, suggesting that the paddy fields in the study area act as neither a source nor a sink of CO_2.

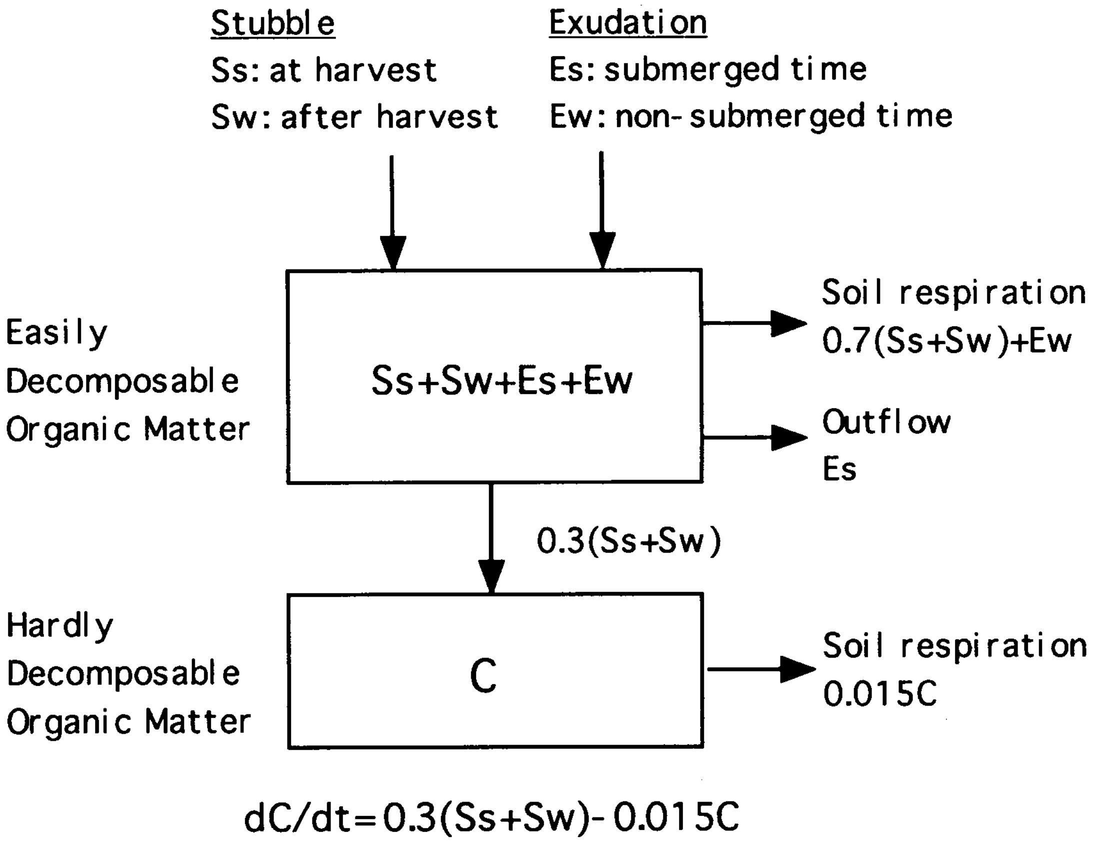

Fig. 3 Yearly dynamics of soil carbon (C) in paddy fields

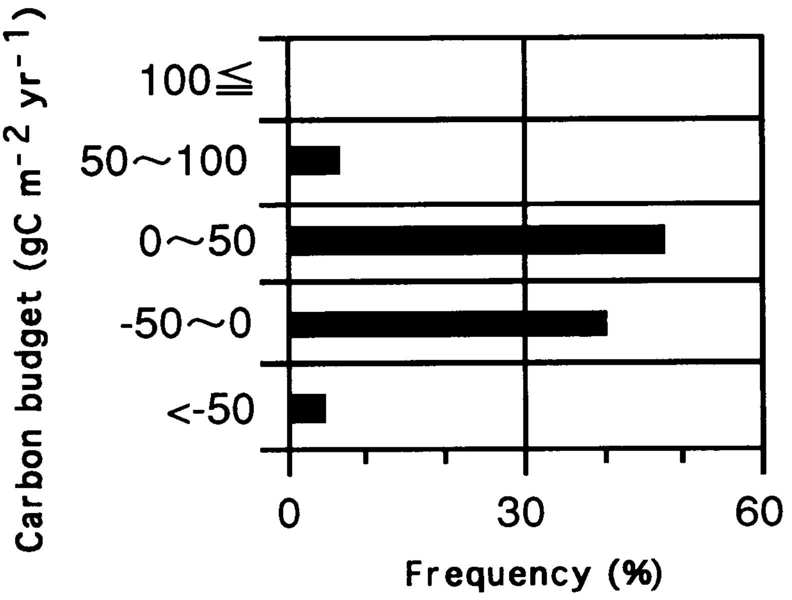

Fig. 4 Frequency distribution of the annual carbon budgets in paddy fields

Carbon budget in forests

At first, we surveyed the tree density, dbh and tree height using the point-centered quarter method, and estimated the aboveground biomass density in each forest using the previous allometric correlation equations. Then, we divided the forests into coniferous and broad-leaved forests as well as sunny and shady sides, and developed multiple regression equations of the aboveground biomass (kg d.w. m^{-2}) for coniferous (N) and broad-leaved (D) trees as follows:

Sunny sides; $N = 5207 - 136.1(TM1/TM2) - 6789(TM3/TM4) - 5183NDVI$ $(R^2 = 0.97)$
$D = 141.5 - 197.3(TM2/TM3) + 26.56(TM4/TM3)$ $(R^2 = 0.97)$
Shady sides; $N = -502.1 - 297.9(TM4/TM3) + 2856NDVI$ $(R^2 = 0.98)$
$D = -527.2 + 110.8(TM2/TM1) - 133.7(TM4/TM3) + 1733NDVI$ $(R^2 = 0.96)$

These equations showed high ratios of contribution, allowing us to estimate the aboveground biomass in forests with a small error.

Using these equations and assuming that the carbon content in tree biomass is 0.5, we calculated aboveground carbon stocks in forests in 6 August 1986 and 24 July 1987. Then we estimated the annual aboveground carbon budgets in the forests. The aboveground carbon budgets varied among forest types (Fig. 5); those of coniferous and broad-leaved forests were 893 and -115 gC m^{-2} yr^{-1} on the average, respectively. These results indicate that the broad-leaved forests in the study area acted as a source of CO_2 but the coniferous forests acted as a larger sink. Consequently, the annual aboveground carbon budgets of all forests as a whole was 320 gC m^{-2} yr^{-1}, acting as a sink of carbon.

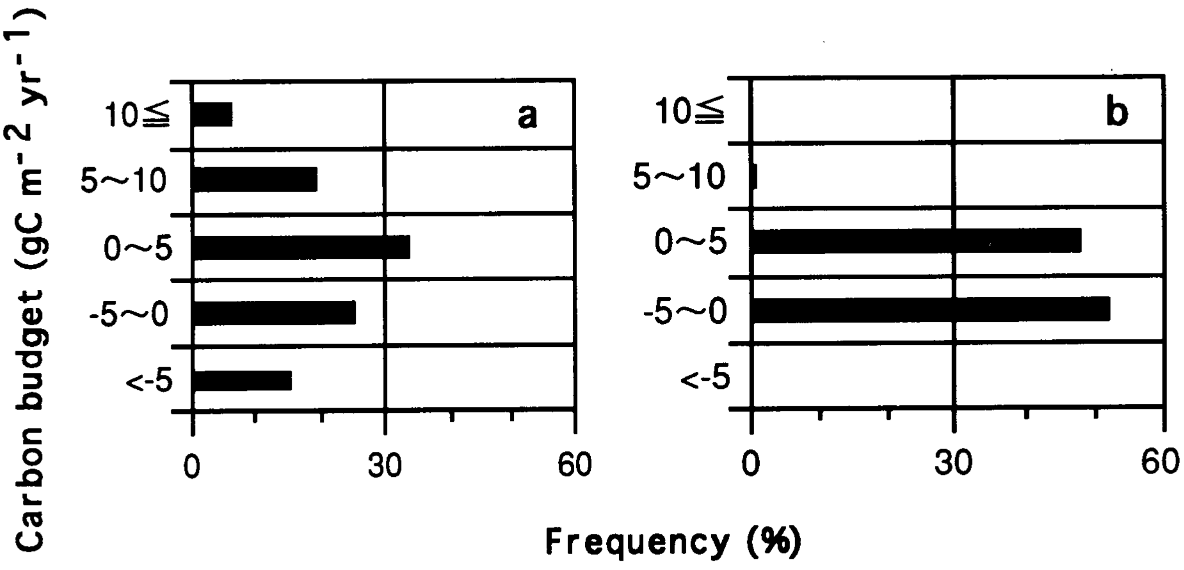

Fig. 5 Frequency distributions of the annual aboveground carbon budgets in coniferous (a) and broad-leaved (b) forests

Carbon budget in the whole ecosystem of the study area

We estimated the carbon budgets at a whole ecosystem level for croplands and paddy fields. However, it's so difficult to estimate a belowground carbon budget in forests using Landsat TM data that we estimated only the aboveground carbon budget in the forests. Therefore, according to Matsumoto *et al.* (unpublished data from B-1.3.3 of this project research) and Nakane *et al.* (1984), we assumed that the belowground carbon budgets in broad-leaved and coniferous forests are +55 and -350 gC m^{-2} yr^{-1}, respectively. Then we obtained the total carbon budgets in the whole ecosystem of the study area (Table 1).

Table 1 Areas and annual carbon budgets of the major ecosystems in the study area

Ecosystem	Area (km^2)	Mean carbon flux (gC m^{-2} yr^{-1})	Total carbon budget (10^3 tC yr^{-1})
Cropland	205	-151	-31.0
Broad-leaved forest	196	-60	-11.7
Coniferous forest	151	543	82.0
Paddy field	141	3	0.4
Other	207	-	-
Total	900		39.7

The total carbon budgets in the croplands and broad-leaved forests still showed minus values, acting as a source of carbon. However, the coniferous forests absorbed a larger amount of carbon and the total carbon budget in the whole ecosystems of the study area acted as a sink of carbon (40 kt C yr^{-1}).

4. Conclusions

The study area consists of various types of ecosystem and the carbon budgets varied obviously between the ecosystem types (Table 1). Moreover, these budgets also varied spatially within each of the ecosystems (Figs. 2, 4 and 5). This means that we have to take into account the heterogeneity on this spatial scale to estimate the regional carbon budgets. Therefore the method we proposed here, in which a mathematical model is combined with satellite data, is very useful for that purpose.

5. References

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