

## **Modeling Carbon Dynamics of Terrestrial Ecosystems in Monsoon Asia**

Takehisa OIKAWA and Akihiko ITO

*Institute of Biological Sciences, University of Tsukuba, Japan*

**Abstract**—The Asiatic-Australian area is governed by the monsoon circulation, which is the most constant large wind system. In this great monsoon circulation, winds blow outward from Asia and inward onto Australia during the winter of the Northern Hemisphere, with a reversal of the circulation during the summer. Such a seasonal change in the wind direction regularly produces dry and wet seasons and then determines the biome types and dynamics of terrestrial ecosystems in Monsoon Asia.

In Monsoon Asia, land use and cover change is the most intensive because the human population density is highest in the world and is growing at a high rate. Ongoing global warming will accelerate land use and cover change, which positively affects global warming.

Based on this background information, a modeling approach which clarifies the carbon dynamics of terrestrial ecosystems will be introduced; this is a regional-scale ecosystem model (termed Sim-CYCLE) which covers the total area of Monsoon Asia (total land 20.6 million km<sup>2</sup>; a spacial resolution of 0.5 degree longitude-latitude). This mechanistic ecosystem model, which was based on the production theory established by Monsi and Saeki (1953) can provide a reliable estimate of carbon stock, gross primary productivity (GPP), net primary productivity (NPP), and net ecosystem productivity (NEP) under the present climatic conditions.

Moreover, we will show the predicted transient carbon balance change in Monsoon Asia based on the assumption that the atmospheric CO<sub>2</sub> concentration increases at an annual rate of 1% (doubling after 70 years) and that the resultant increasing CO<sub>2</sub> induces a climatic perturbation projected by three representative GCMs (GISS, GFDL, and MRI).

### INTRODUCTION

Southeast to East Asia, that is, Monsoon Asia, spreads from the equator facing the Indian Ocean through the Himalayan range and the Plateau of Tibet in the center of the mid-latitude zone to arid regions such as the Takla Makan and the Gobi desert. The enormous expanse of Monsoon Asia and its abundance of mountain barriers and inland depressions have resulted in significant differences among regions under the existing conditions of solar radiation, atmospheric circulation, and climate as a whole. A continental climate, associated with large land masses and characterized by an extreme annual range of temperature, produces the

marked dry and wet periods, where the prevailing winds reverse direction approximately every six months from the continent to the ocean in the winter and from the ocean to the continent in the summer.

In Monsoon Asia, where intense growth of human population and resultant environmental aggravation are expected, it is especially important to estimate the current and future state of terrestrial ecosystems. Since the increasing atmospheric CO<sub>2</sub> concentration and induced climatic change will affect plant and soil physiology, critical changes in ecosystem productivity and carbon storage have been expected.

Thus, we analyzed the carbon budget of the terrestrial ecosystems in Monsoon Asia including both the natural and managed ecosystems using a global-scale terrestrial carbon cycle model, Sim-CYCLE (Simulation model of Carbon cYCLE in Land Ecosystems), under the current and changing environmental conditions in the near future.

## DESCRIPTION OF SIM-CYCLE

### *Spatial configuration*

In this study, Monsoon Asia is defined as the region between latitude 40°N and 10°S, and longitude 60°E and 180°E (total land = 20.6 million km<sup>2</sup>; that is, 15% of the total global land area). Because Monsoon Asia occupies the vast region of the continent and it is the most diverse region on Earth reflecting climatic and topographic diversities, it is composed of a variety of biome types. For this study, we used the biome map shown in Fig. 1, which was modified from the original world map by Olson *et al.* (1983). It has a rather high spatial resolution of 0.5 degree longitude-latitude (total of 7,763 cells in Monsoon Asia). As summarized in Table 1, this region contains as many as 26 out of the 33 biome types in the world ranging from forests, grasslands, tundras, and deserts to croplands. Among them, the five largest biomes are as follows; warm grasslands (biome type (bt) 19), warm croplands (bt 31), tropical rain forests (bt 1), paddy fields (bt 29), and tundras (bt 21), as influenced by the typical monsoon climate.

These five major biome types in Monsoon Asia are described in Fig. 2. First, the warm grasslands cover about 16% of Monsoon Asia and mainly distributed in the subtropical to warm temperate region dominated by C<sub>4</sub> plants in the Gramineae family, where the vast grassy steppes of Central Asia are utilized for grazing animals feeding on the native grasses. Sustained heavy grazing of these natural grasslands can quickly lead to degradation of the vegetation and erosion of the soil, finally resulting in desertification.

Second, warm croplands, which have been frequently converted from natural grasslands, spread from the Middle East through Central Asia to the East Asia including North China and North Korea. They serve as rich sources of grain, where wheat is the dominant edible grain crop, and maize, barley, soybeans, sorghum and millet are also grown.

Third, the tropical rain forests are mainly distributed in the wettest parts of a string of archipelagos of Indonesia and the Philippines and most of the Malay

Table 1. Classification, cell number, and area of 26 biome types in Monsoon Asia of Sim-CYCLE simulation.

No.	Biome type	C <sub>3</sub> C <sub>4</sub>	Grid-cell	
			frequency	Area
			Total	(10 <sup>6</sup> km <sup>2</sup> )
1	Tropical and subtropical evergreen forest	○	792	2.4
2	Tropical montane forest	○	136	0.4
3	Tropical and subtropical seasonal forest	○	189	0.6
4	Mid latitude mixed woods	○	465	1.2
5	Mid latitude broad-leaved forest	○	136	0.3
6	Semiarid wood or low forest	○	3	0.0
7	Coniferous forest	○	114	0.3
8	Southern taiga	-	-	-
9	Main boreal taiga (evergreen)	○	2	0.0
10	Main boreal taiga (deciduous)	-	-	-
11	Northern taiga (evergreen)	-	-	-
12	Northern taiga (deciduous)	-	-	-
	total forests		1837	5.2
13	Second growth woods	○	366	1.0
14	Second growth fields	○ ○	245	0.7
15	Succulent and thorn woods	○ ○	47	0.1
16	Tropical savanna, woodland	○ ○	14	0.0
17	Mediterranean-type dry woods	○ ○	55	0.1
18	Heath and Moorland	- -	-	-
19	Warm or hot shrub and grassland	○ ○	1283	3.3
	total grasslands		2010	5.3
20	Tibetan meadow, Siberian highland	○	199	0.5
21	Tundra	○	723	1.8
22	Wooded tundra	○	52	0.1
23	Warm or hot wetlands	○	147	0.4
24	Cool bog and mire	-	-	-
25	Shore and hinterlands	○	42	0.1
	total tundras		1163	3.0
26	Cool semi-desert scrub	○	62	0.1
27	Non-polar desert	○ ○	523	1.3
28	Non-polar sand desert	○ ○	342	0.8
	total deserts		927	2.2
29	Paddy fields	○	684	1.9
30	Cool croplands	○	51	0.1
31	Warm croplands	○	1033	2.7
32	Irrigated	○	159	0.4
	total croplands		1927	5.1
33	Ice sheets	-	-	-
	total lands		7864	20.9

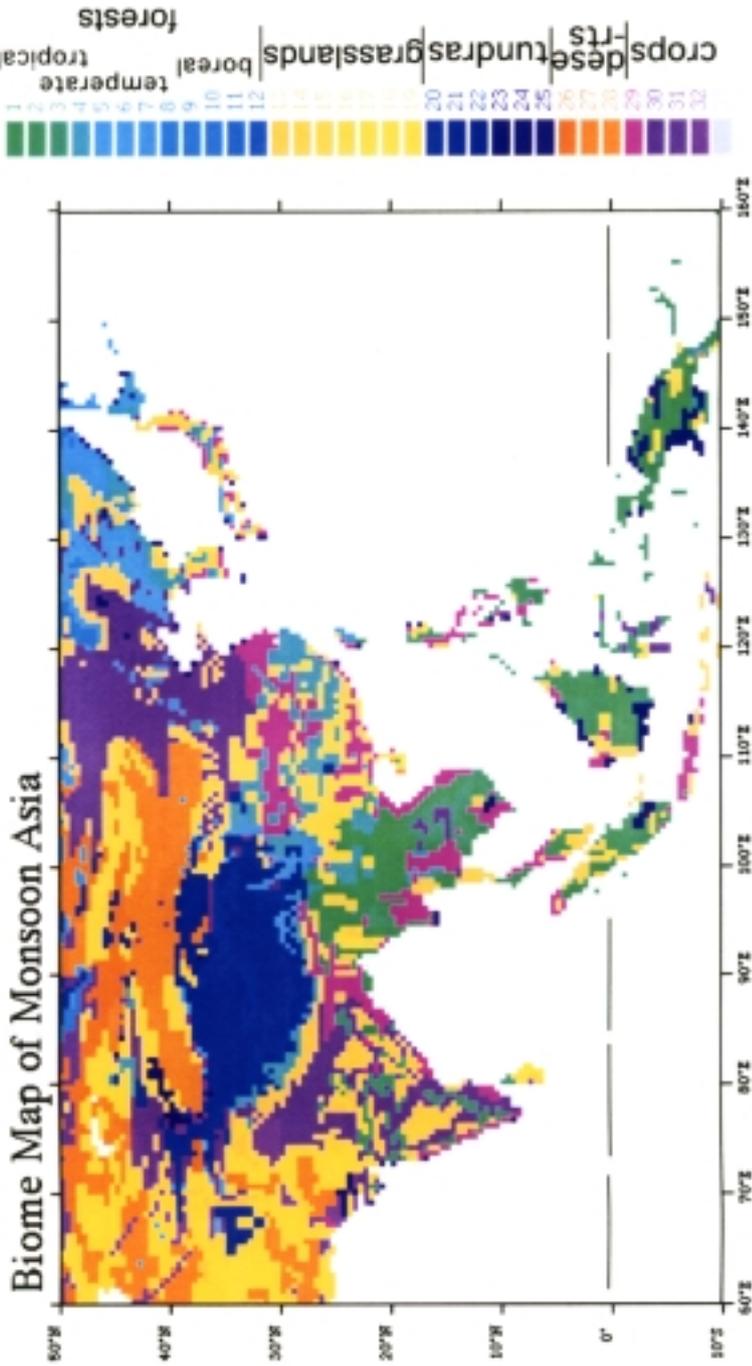


Fig. 1. The biome map in Monsoon Asia, Modified from the original world biome map by Olson *et al.* (1983).

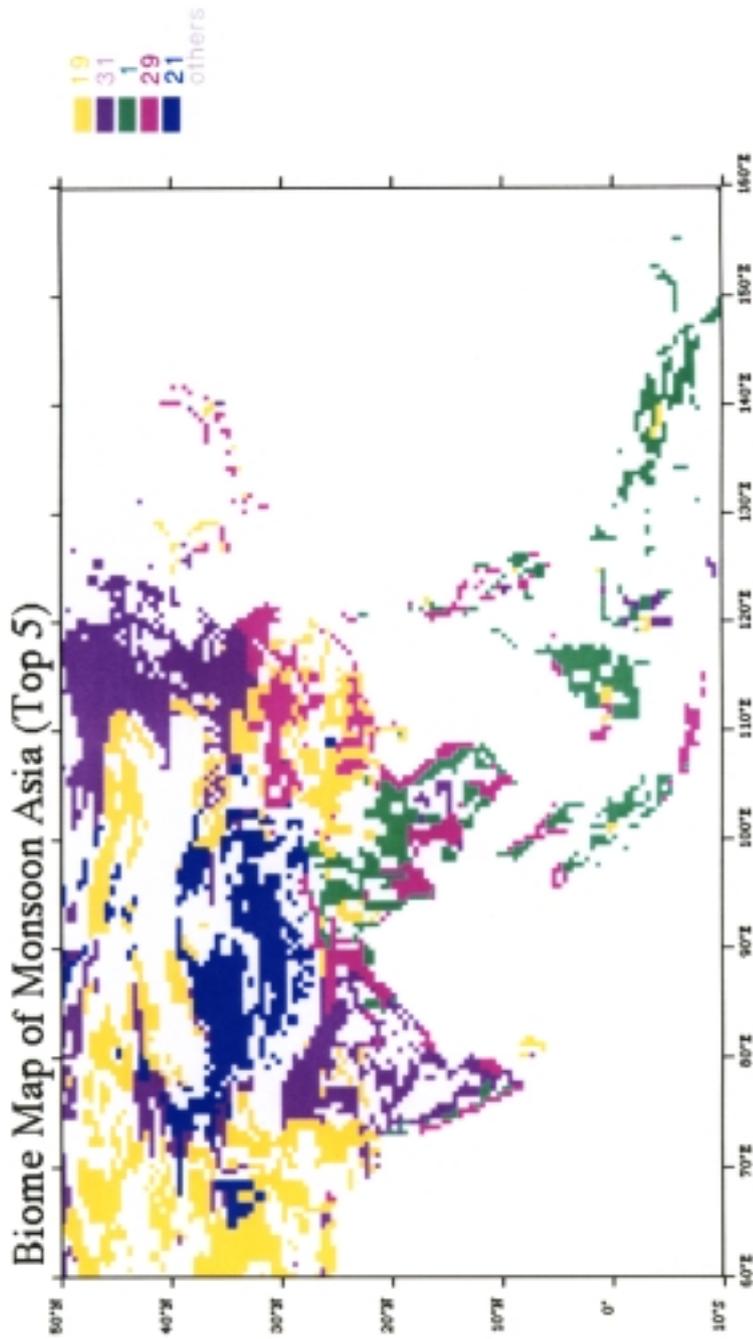


Fig. 2. The five major biome types in Monsoon Asia; warm grasslands (biome type (bt) 19), warm croplands (bt 31), tropical rain forests (bt 1), paddy fields (bt 29), and tundras (bt 21).

Peninsula. They have magnificent moist-evergreen forests noted for their tremendous richness of plant life exceeding as many as 500 woody species, of which major species belong to the Dipterocarpaceae family. They develop on lateritic infertile soils characterized by the leaching process due to excessive showery rainfall. In spite of the luxuriant appearance of these forests, most of the available plant nutrients rapidly circulate between the plants and the superficial layers of the soil; thus there is a heavy loss of fertility when the forests are felled and the trees burned.

Fourth, paddy fields are mainly distributed in the valleys from the tropical to warm temperate region, where alluvial soils predominate; they have been developed by thousands of years of cultivation and irrigation of the rice fields by virtue of plentiful rainfall brought about by the summer monsoon.

Fifth, tundras are characterized by bare ground and rock or by such vegetation as mosses, lichens, small herbs, and low shrubs. This type of biomes mainly distributed in the Plateau of Tibet reaching an elevation of 4,600 m, being often referred to as “the roof of the world”, because the western and southern border is formed by the Himalayan high mountain ranges extending more than 2,400 km from east to west in the central Asia.

The five biome types occupy some 60% of Monsoon Asia. Almost all these areas have been intensively used or directly or indirectly disrupted by human beings.

Our simulation using Sim-CYCLE was executed on the basis of the biomes in this map. The geographical distribution pattern of the biome types was assumed not to change with the passage of the simulation time. The climate and soil conditions are provided by several established global datasets (Leemans and Cramer, 1991; Bouwman, 1990; Webb *et al.*, 1991).

### *Ecosystem carbon cycle*

The basic structure of Sim-CYCLE is after Oikawa (1985), and the details are described by Ito (2000). In our carbon cycle model, carbon storage in a terrestrial ecosystem can be simplified into five compartments (Fig. 3): three of vegetation (foliage, stem, and root) and two of soil (litter and mineral soil). The  $C_4$  plants, dominating in the hot and warm grasslands, have different compartments than those of the  $C_3$  plants, because of the large difference in their physiological properties. Carbon fluxes, such as gross primary productivity (GPP), plant respiration (RP), net primary productivity ( $NPP = GPP - RP$ ), litterfall (LF), soil respiration (RS), and net ecosystem productivity ( $NEP = NPP - RS$ ), are repetitiously calculated by mechanistic formulas of carbon fluxes established by Monsi and Saeki (1953), in a monthly time-step for woody plants or daily time-step for herbal plants. These formulas include the proper dependence on environmental conditions (i.e.,  $CO_2$ , temperature, moisture), so that the model is able to evaluate the effect of global environmental changes. The model takes the planting and harvesting cycle in agricultural ecosystems into consideration, but does not consider the semi-annual crop in paddy fields and the shifting cultivation in tropical forest regions.

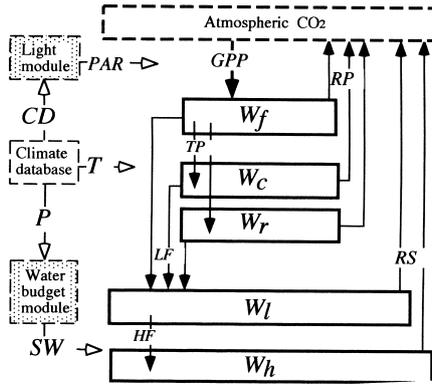


Fig. 3. Schematic diagram of Sim-CYCLE which was composed of five compartments: three of vegetation (foliage, stem, and root) and two of soil (litter and mineral soil).

CURRENT STATE OF CARBON CYCLE

Figure 4 exemplifies monthly changes in the four typical biomes in Monsoon Asia, where the GPP, NPP and NEP were calculated using such climatic conditions as air temperature, PPFD, net radiation, and precipitation illustrated in the upper panels of Fig. 4, where these are based on the NCEP/NCAR-Reanalysis Dataset). As shown in Fig. 4A, the climatic conditions in a tropical rain forest are characterized by higher temperatures, abundant precipitation and weak wind velocity throughout the year. Reflecting these favorite and monotonous climatic conditions, the GPP and NPP were always higher and did not show very significant seasonal changes. The annual values of the GPP and NPP were 25.1 and 11.5 Mg C ha<sup>-1</sup>year<sup>-1</sup>, respectively.

Although a tropical seasonal forest has similar climatic conditions as those of a tropical rain forest, they are characterized by a winter dry season lasting a few months (cf. Fig. 4B). This dry season suppressed the monthly GPP and NPP, leading to a seasonality of NEP; that is, this forest ecosystem acts as a source in the dry season and a sink in the wet season for atmospheric CO<sub>2</sub>. The annual GPP and NPP values were comparable with those of the tropical rain forest shown in Fig. 4A.

Figure 4C shows an example of paddy fields, where the annual GPP and NPP values were 9.2 and 4.1 Mg C ha<sup>-1</sup>year<sup>-1</sup>, respectively. One should note that in addition to a large amount of rice production, methane is heavily evolved from the paddy fields due to their side-effects.

In contrast to the humid biomes demonstrated in Figs. 4A to C, Monsoon Asia has a vast arid area such as the Takla Makan and the Gobi desert in the central continent. Figure 4D shows a desert where the annual GPP and NPP values were as low as 1.8 and 0.8 Mg C ha<sup>-1</sup>year<sup>-1</sup>, respectively, because the extremely limited

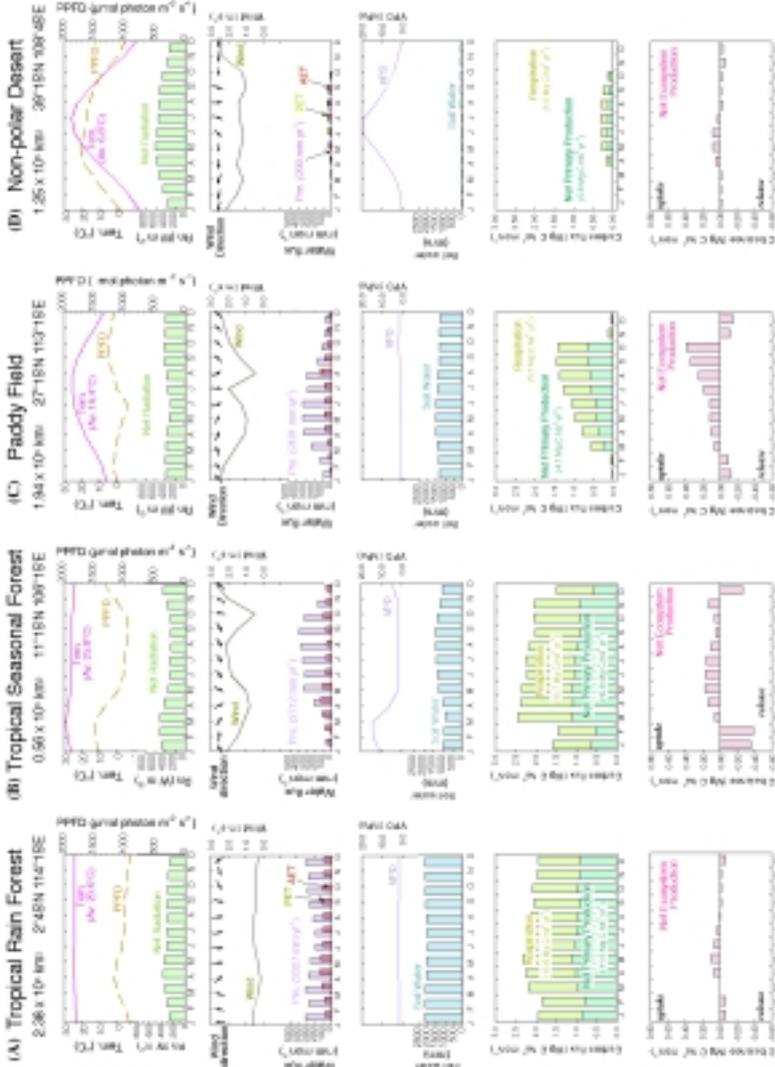


Fig. 4. Monthly changes in the four typical biomes of Monsoon Asia, where the GPP, NPP and NEP were calculated using such climatic conditions as air temperature, PPFD, net radiation, and precipitation. (A) Tropical Rain Forest; (B) Tropical Seasonal Forest; (C) Paddy Field and (D) Non-polar Desert.

precipitation was not able to satisfy the demand for potential evapo-transpiration estimated by the Penman-Monteith equation, and thus induced stomatal closure, remarkably reduced primary productivity and resultant biomass accumulation.

Figure 5 is the distribution of annual NPP (top), plant carbon (middle) and soil organic carbon (bottom) in Monsoon Asia, estimated from the steady state simulation under long-term mean climate conditions. Areas having NPP values higher than  $10 \text{ Mg C ha}^{-1}\text{year}^{-1}$  are found around the equator, which is mainly occupied by the tropical and seasonal rain forests. On the other hand, such extremely unproductive areas as the Gobi and the Takla Makan deserts widely spread in the middle latitudinal zone of the inner continent. Summing up all values, we determined that the regional values of the NPP, plant biomass and soil organic carbon were  $8.7 \text{ Pg C/year}$ ,  $84.8$  and  $208.4 \text{ Pg C}$ , respectively. From a global point of view, each of them is about 16%, which is proportional to its area. The  $\text{C}_4$  plants mainly distributed in the arid grasslands are estimated to produce  $0.71 \text{ Pg C/year}$  in NPP, which corresponds to about 8% in regional NPP, although their biomass occupies only a tiny portion. Currently, the agricultural ecosystems including the paddy fields may produce a significantly high fraction of NPP such as 24%, which is more than two times compared with the global mean fraction. This is one of the most important characteristics in the Monsoon Asia region, and this fraction will inevitably increase more and more in the next century at the expense of the tropical rain forests due to the high pressure of ever-increasing human population in this area. Such land use change will induce one of the most serious impacts on human beings in the next century.

These results have already been validated on a global scale, by comparison with several estimations of the NPP (Lieth, 1975; Box *et al.*, 1989) and LAI (Sellers *et al.*, 1996), based on empirical model and remote sensing (Ito, 2000).

#### SIMULATION OF GLOBAL ENVIRONMENTAL CHANGE

To simulate the carbon dynamics under future global environmental changes, we input an atmospheric  $\text{CO}_2$  increase rate of 1%/year and induced climate perturbations estimated by three representative GCMs (GFDL, Manabe *et al.*, 1991; GISS, Russel *et al.*, 1995; MRI, Japan Meteorological Agency, 1996). The simulation is initialized by the equilibrium state described in the former section, and continued until the atmospheric  $\text{CO}_2$  doubled (70 years later) under the assumption of no biome type change.

The transitions in the primary productivity for 70 years are shown in Fig. 6 where the GPP and NPP increased due to the  $\text{CO}_2$  fertilization effect and temperature rise independent of the three GCM scenarios. For instance, the predicted increases of the NPP after 70 years ranged from 0.4 in GFDL to 0.7  $\text{Pg C/year}$  in MRI, being mainly attributable to those of the moist biomes.

Although plant biomass was predicted to increase in a similar manner with the NPP, the ecosystem total carbon storage including plant and soil organic matter will not increase very much or even decrease, because of the enhancement in soil respiration caused by the temperature increase. As a consequence, the 70-

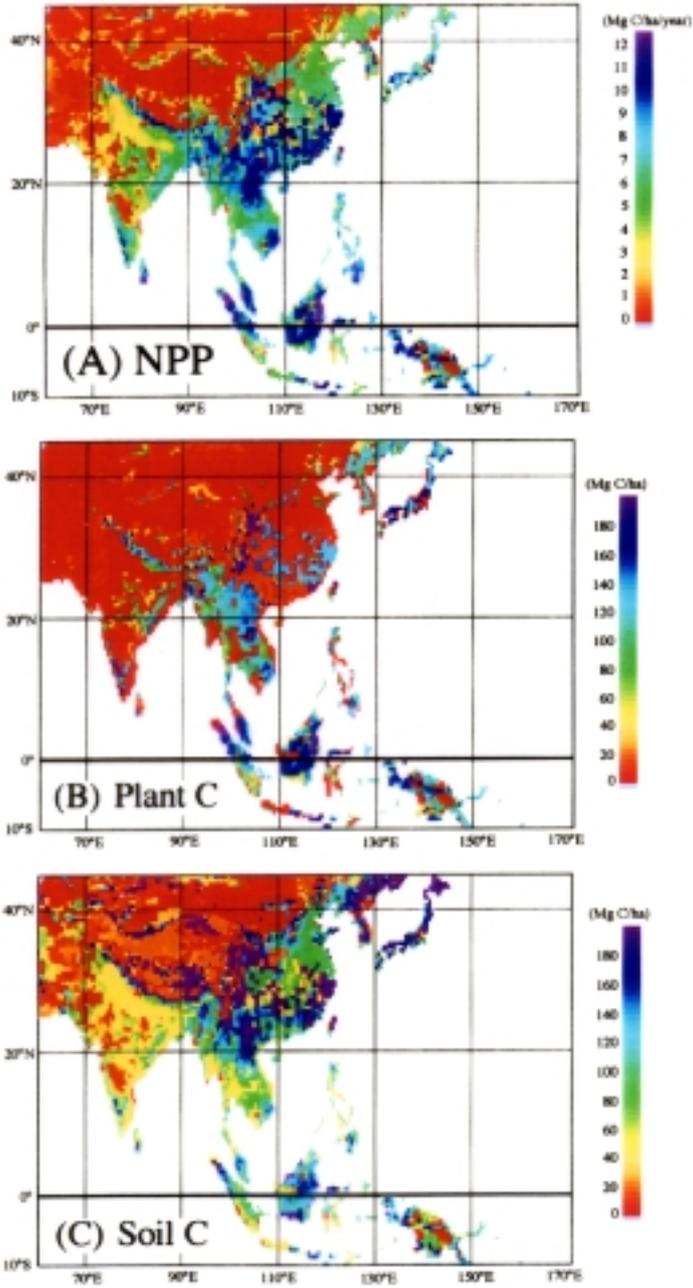


Fig. 5. Regional distribution of (A) NPP, (B) plant carbon, and (C) soil carbon, in Monsoon Asia, estimated by the equilibrium run.

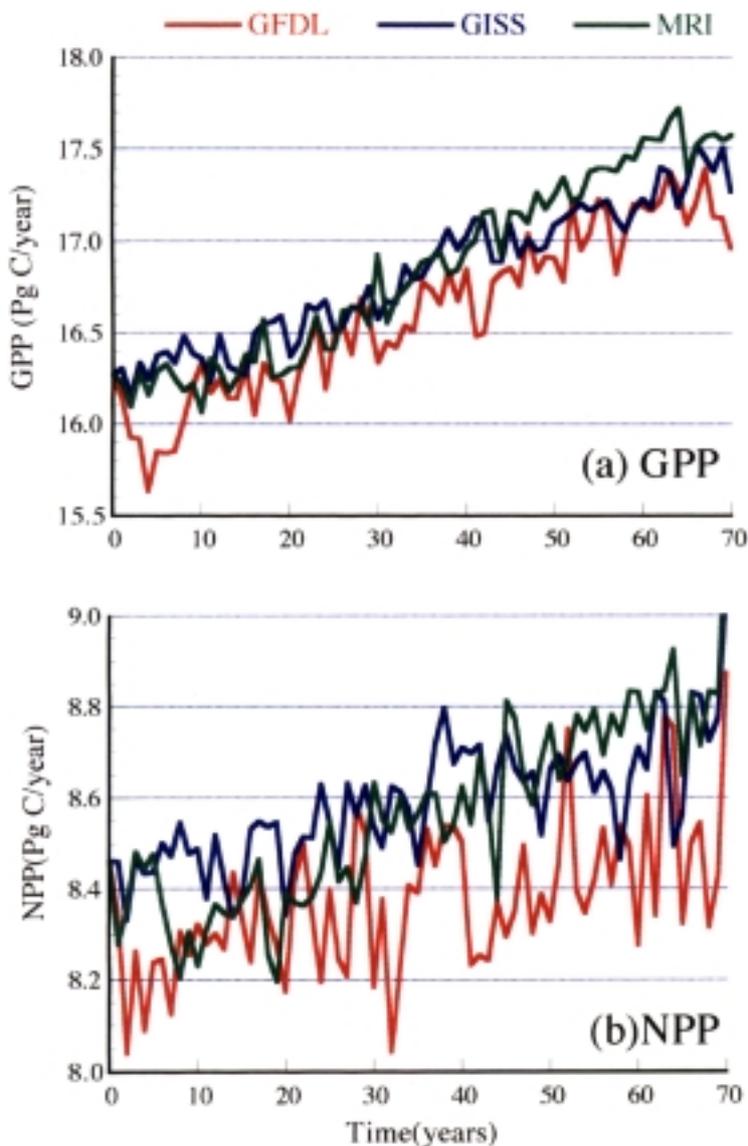


Fig. 6. Projected time trends of GPP (top) and NPP (bottom) in Monsoon Asia, using the three GCM scenarios based on doubling of  $\text{CO}_2$  concentration during a 70-years period.

year average NEP values ranged from  $-0.22$  to  $+0.03$  Pg C/year, depending on the adopted GCM scenarios. This suggests that Monsoon Asia may not be as a large sink for future doubling of the  $\text{CO}_2$  climate, even when unless considering the human exploitation.

## CONCLUSION

The mechanistic ecosystem model Sim-CYCLE successfully reproduced the carbon dynamics of terrestrial ecosystems in Monsoon Asia. Our present simulation study shows that the global environmental change may inevitably affect the carbon budget of Monsoon Asia, where the density of the human population is the highest in the world and is still growing at a high rate.

Finally, I would like to mention that further research for Sim-CYCLE validation is mentioned. Both examinations and applications are anticipated for the Sim-CYCLE. Testing validity of the model should span various scales.

(1) Local-scale tests, e.g. a comparison with observed CO<sub>2</sub> exchange with aerodynamic methods represented by the eddy correlation technique, are plausible to confirm the structure of the carbon cycle description in a terrestrial ecosystem. Worldwide Fluxnetwork is a very promising means to validate the CO<sub>2</sub> exchange estimated by Sim-CYCLE.

(2) Regional-scale tests are to be done to investigate the significance of heterogeneity within a grid-cell. Recent advances in remote sensing techniques is expected to bring a breakthrough in this area (Field *et al.*, 1995; Sellers *et al.*, 1995; Lüdeke *et al.*, 1996).

(3) Biosphere-scale tests are not easy, but feasible by analyzing the observed atmospheric CO<sub>2</sub> concentrations and stable carbon isotope ratios. The three-dimensional atmospheric transport models, based on the surface CO<sub>2</sub> exchange data, have made it possible to reproduce the spatial and temporal distribution of atmospheric CO<sub>2</sub> (Keeling *et al.*, 1989; Hunt *et al.*, 1996). Sim-CYCLE is designed to provide a simulation of the changing global environment in the future, and we have already obtained promising results from simulations on continental and global scales as presented here. Therefore, Sim-CYCLE will become a more potent and useful tool for rationally predicting the fate of terrestrial ecosystems in the world under the changing climate induced by increasing atmospheric CO<sub>2</sub>.

*Acknowledgments*—Many of the global datasets were supplied via UNEP/GRID-Tsukuba. Outputs from the GCMs employed here were supplied by the Geophysical Fluid Dynamics Laboratory, Goddard Institute of Space Studies, and Meteorological Research Institute.

## REFERENCES

- Bouwman, A. F., 1990. Global emission on nitrous oxide from natural soils, NASA/GISS National Institute of Public-Health and Environmental Protection.
- Box, E. O., B. N. Holden and V. Kalb, 1989. Accuracy of the AVHRR vegetation index as a predictor of biomass, primary productivity and net CO<sub>2</sub> flux. *Vegetatio*, **80**: 71–89.
- Field, C. B., J. T. Randerson and C. M. Malmstrom, 1995. Global netprimary production: combining ecology and remote sensing. *Remote Sensing of Environment*, **18**, 1214–1225.
- Japan Meteorological Agency, 1996. Global warming project with MRI-CGCM, Vol. 1.
- Hunt, E. R., S. C. Piper, R. Nemani, C. D. Keeling, R. D. Otto and S. W. Running, 1996. Global net carbon exchange and intra-annual atmospheric CO<sub>2</sub> concentrations predicted by an ecosystem process model and three-dimensional atmospheric transport model. *Global Biogeochemical Cycles*, **10**, 431–456.

- Ito, A., 2000. The relationship between atmospheric change and carbon dynamics in terrestrial ecosystems: A global study using a mechanistic model, Sim-CYCLE. Doctor Thesis of Univ. Tsukuba.
- Keeling, C. D., R. B. Bacastow, A. F. Carter, S. C. Piper, T. P. Whorf, M. Heimann, W. G. Mook and H. Roeloffzen, 1989. A three-dimensional model of atmospheric CO<sub>2</sub> transport based on observed winds: 1. Analysis of observational data. *Geophysical Monograph*, **55**, 165–236.
- Leemans, R. and W. P. Cramer, 1991. The IIASA database for mean monthly values of temperature, precipitation and cloudiness of a global terrestrial grid. RR-91-18, IIASA.
- Lieth, H., 1975. Modeling the primary production of the world. In: *Primary Production of the Biosphere*, H. Lieth and R. H. Whittaker (editors), Springer-Verlag, pp. 237–263.
- Lüdeke, M. K. B., P. H. Ramage and G. H. Kohlmaier, 1996. The use of satellite NADV data for the validation of global vegetation phenology models: application to the Frankfurt Biosphere Model. *Ecological Modelling*, **91**, 255–270.
- Manabe, S., R. J. Stouffer, M. J. Spelman and K. Bryan, 1991. Transient response of a coupled ocean-atmosphere model to gradual changes of atmospheric CO<sub>2</sub>. Part I. annual mean response. *J. Climate*, **4**: 785–818.
- Monsi, M. and T. Saeki, 1953. Über den Lichtfaktor in den Pflanzengesellschaften und seine Bedeutung für die Stoffproduktion. *Jap. J. Bot.*, **14**: 22–52.
- Oikawa, T., 1985. Simulation of forest carbon dynamics based on dry-matter production model: 1. Fundamental model structure of a tropical rainforest ecosystem. *Botanical Magazine*, **98**: 225–238.
- Olson, J. S., J. A. Watts and L. J. Allison, 1983. Carbon in live vegetation of major world ecosystems. ORNL-5862, Oak Ridge National Laboratory.
- Russel, G. L., J. R. Miller and D. Rind, 1995. A coupled atmosphere-ocean model for transient climate change studies. *Atmosphere-Ocean*, **33**(4): 683–730.
- Sellers, P. J., S. O. Los, C. J. Tucker, C. O. Justice, D. A. Dazlich, G. J. Collatz and D. A. Randall, 1996. A revised land surface parameterization (SiB2) for atmospheric GCMs. part II: the generalization of global fields of terrestrial biophysical parameters from satellite data. *J. Climate*, **9**: 706–737.
- Webb, R. S., C. E. Rosenzweig and E. R. Levine, 1991. A global data set of soil particle size properties, NASA.

---

T. Oikawa (e-mail: oikawa@oak.biol.tsukuba.ac.jp) and A. Ito