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Development of the Bio-Geographical and GeoChemical (BGGC) Model for Assessments of Climate Change Impacts on the Terrestrial Ecosystem in Japan

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Abstract

This study developed the Bio-Geographical and GeoChemical model (BGGC model) to assess the future impacts of global climate change, as prescribed by the IPCC-SRES, on the distribution and functioning of terrestrial ecosystems in Japan.

The BGGC model simulates the cycling of carbon, nitrogen, and water in vegetation, soil ecosystems and the atmosphere. Some modules in the model borrow most of their basic structures from the sub-model of CENTURY4 (Parton *et al.*, 1993) and the modified BIOME3 (Ishigami *et al.*, 2002). The BGGC model is broadly divided into two sub-models, the vegetation competition sub-model and the soil organic matter sub-model. The vegetation competition sub-model consists of the photosynthesis model and the canopy model. The photosynthesis model estimates the optimized net primary productivity (NPP) and leaf area index (LAI) to satisfy the soil nitrogen, and annual moisture. The canopy model considers the canopy structure for forest vegetation types. On the other hand, the soil organic matter sub-model, which is linked to the vegetation competition sub-model, simulates carbon, nitrogen, and water dynamics in the soil ecosystem. The distribution of potential natural vegetation types was determined by the estimated NPP and LAI.

In order to assess the impact of climate change on the terrestrial ecosystem, this study estimated the distribution of potential natural vegetation in Japan using NPP. The GCMs experimental data used were the CSIRO-Mk2 and ECHAM4/OPYC3 for each of A2 and B2 scenarios in the SRES. Comparison of the averages of simulated NPP under each scenario with the average NPP under current climate conditions showed that the average NPP could increase about 19 to 33 percent by the year 2050 and 25 to 53 percent by the year 2080.

Key words: BGGC model, Japan, NPP, Potential natural vegetation

1. Introduction

Vegetation in terrestrial ecosystems provides not only an important habitat for animals but most importantly it plays a significant role in the cycle of carbon and nutrients. IPCC reports indicated that the changes in global climate caused by the continual increase in greenhouse gases will affect the ecosystem in future. This study attempts to develop a model to evaluate the impact of climate change on ecosystems. For evaluation of the impact, there are several models to simulate vegetation distribution, carbon and nutrient cycle such as process-based models and semi-empirical models (Haxeltine and Prentice, 1996; Neilson *et al.*, 1998; Levy *et al.*, 2004 etc.).

The process-based model includes knowledge on the physiological responses of plants to environmental change. This is a suitable model for predicting the effect of climate change on the ecosystem because the plants physiological and ecological functions must be considered. This study deals with the development of the Bio-Geographical and GeoChemical model (BGGC model) to assess the future impacts of global change, as prescribed by the IPCC-SRES, on the distribution and functioning of terrestrial ecosystems in Japan.

2. Model Structure

The BGGC model consists of two types of process-based model. The one is the bio-geographical model, which puts emphasis on the determination of what kind of vegetation could live in a given location. The other is the bio-geochemical model, which simulates the carbon and nutrient cycles within ecosystems on the basis of given vegetation distribution.

Most of the basic structures of some modules in the model were borrowed from the sub-model of CENTURY4 (Parton *et al.*, 1993) and the modified BIOME3 (Ishigami *et al.*, 2002). The BGGC model is divided into two sub-models, the vegetation competition sub-model and the soil organic matter sub-model. The vegetation competition sub-model contains the photosynthesis model and the canopy

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model. The photosynthesis model estimates the optimized net primary productivity (NPP) and leaf area index (LAI) for each plant functional type (PFT) to satisfy annual moisture and the soil nitrogen. In order to consider the effect of CO_2 and nitrogen on photosynthesis, the model contains the Farquhar photosynthesis model as simplified by Collats et al (1991) and canopy photosynsynthesis model developed by Hikosaka (2003). The PFTs were determined by differences in phenological type (evergreen or deciduous), leaf type (broad-leaved or conifer) and the rooting depth. Competition among PFTs is simulated by using the estimated NPP of each PFT as an index of competitiveness. The PFT with the highest NPP is selected as the dominant type. The canopy model takes account of the effect of difference in the canopy structure of the forest vegetation on calculation of daily net photosynthesis. The distribution of potential natural vegetation types was determined by the selected PFT and the estimated NPP and LAI. On the other hand, the soil organic matter sub-model simulates carbon, nitrogen, and water dynamics in the soil ecosystem. The model includes three soil organic matter pools with different potential decomposition rates. The model is linked to the vegetation competition model that provides the soil nitrogen and receives the NPP in return. In other words, the two sub-models are linked by the exchange of soil nitrogen and NPP between the two sub-models.

Fig. 1 shows the schematic diagram of the BGGC model.

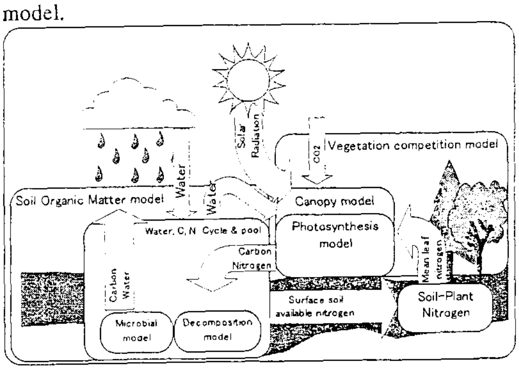

Fig. 1 Schematic diagram of BGGC model.

3. Data

3.1 Climate and soil data

In order to estimate the distribution of potential natural vegetation in Japan, with NPP under both current and future climatic conditions, monthly climate normals data (average for 30 years; 1971 to 2000) and GCMs experimental data prescribed by IPCC-SRES (The Intergovernmental Panel on Climate Change, Special Report on Emissions Scenarios) were used in this study. The GCMs experimental data were the CSIRO-Mk2 and ECHAM4/OPYC3 for each of A2 and B2 scenarios in the SRES. Since each scenario has different assumptions on global population, gross world product, and final energy, GHGs emission scenarios are different. All data were arranged in the form of a 10 x 10 sq. km grid system. Although high-spatial resolution GCMs are required to assess the regional climate impacts, grid resolutions of current GCMs are roughly 3° longitude x 3° latitude. Yokozawa *et al.* (2003) statistically interpolated the GCMs data (based on the IS92a emission scenario) to a 10 x 10 sq. km grid data. This study applied the same method to GCMs data based on SRES scenarios. The number of grids is 4,691. Soil texture data was obtained from Haxeltine and Prentice (1996).

Fig. 2 shows boxplots of changes in annual mean temperature between normals and GCMs experimental data (CSIRO-Mk2 and ECHAM4/OPYC3), while Fig. 3 represents boxplots of ratios of GCMs annual precipitation to normals.

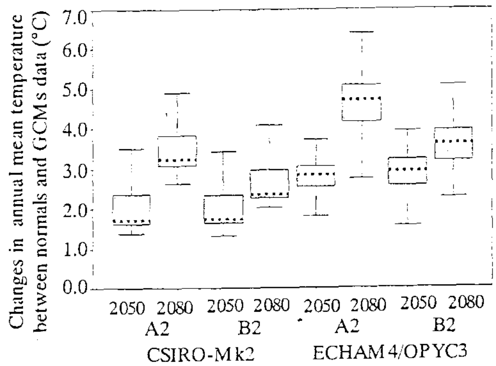

Fig. 2 Boxplots of changes in temperature between normals and GCMs data

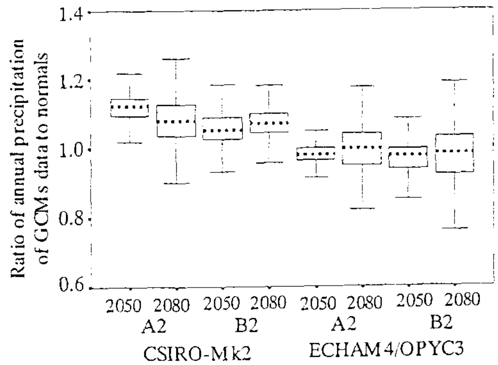

Fig. 3 Boxplots of ratio of annual precipitation of GCMs data to normals.

The bottom of each box is the 25th percentile, the top is the 75th percentile, and the dotted line in the box is the 50th percentile. In both GCMs data, projected temperatures under the A2 scenario are higher than under the B2. Annual precipitation and solar radiation projected by CSIRO-Mk2 increased over Japan.

3.2 CO_2 concentration data

CO_2 concentration data for A2 and B2 scenarios were obtained from the IPCC WG-1 report (IPCC, 2001). CO_2 concentrations in 2050 and 2080 for A2 scenario are 537 and 713 ppm respectively, Those for B2 scenarios are 476 and 570 ppm respectively.

4. Results and Discussion

Fig. 4 and 5 show the estimated NPP and the distribution of potential natural vegetation type under current climatic conditions (CO_2 concentration, 367 ppm), respectively.

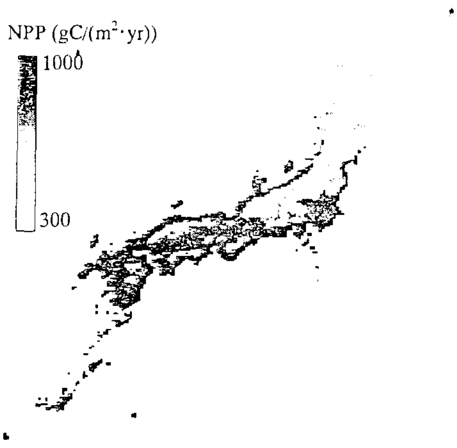

Fig. 4 Estimated NPP under current climatic conditions (CO_2 concentration 367 ppm)

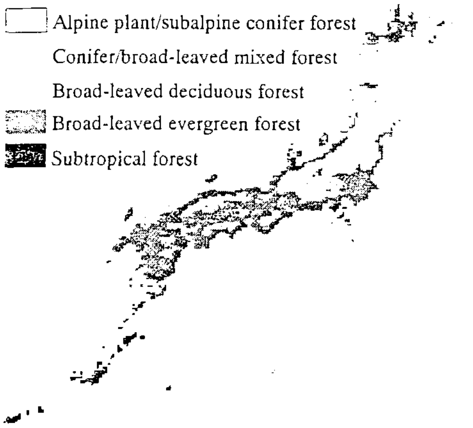

Fig. 5 Estimated distribution of potential natural vegetation type under current climatic conditions (CO_2 concentration 367 ppm)

Comparing with the NPP distribution estimated by the model previously developed by Ishigami *et al.* (2002), the model developed in this study could simulate it more successfully. The model has correctly estimated the vegetation distribution except for the broad-leaved evergreen forest in the Hokkaido region.

Fig. 6 shows the estimated NPP under CSIRO-Mk2 and ECHAM4/OPYC3 experimental data for each of A2 and B2 scenarios. Comparing the averages of simulated NPP for each scenario with the average NPP under current climatic conditions, an increase of 19 to 33 percent in the average NPP for year 2050 and about 25 to 53 percent for year 2080 can be observed.

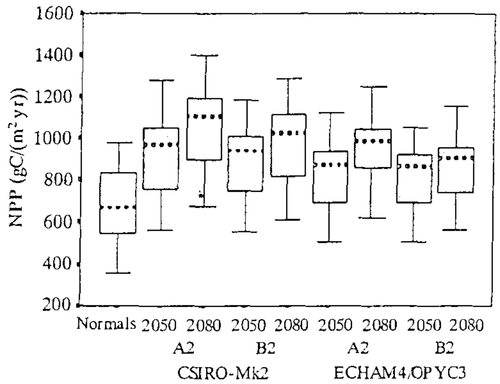

Fig. 6 Comparison of simulated NPP under each SRES scenario

To compare the influence of CO_2 concentration and climate conditions on changes in simulated NPP, the CO_2 concentration (367 and 713 ppm), current climatic conditions as well as the conditions for 2080s were set according to A2 scenario and CSIRO-Mk2 experimental data. Fig. 7 shows the boxplots of simulated NPP under the different conditions. In both

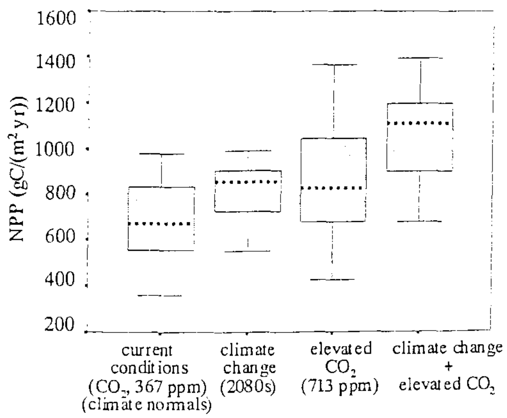

Fig. 7 Effects of elevated CO_2 and climate change on the predicted NPP

conditions an increase in NPP can be observed. Also, it can be observed that an elevated CO_2 has a larger influence on the calculation of NPP than climate conditions.

This study developed the BGGC model to assess the future impact of global climate change. This model has the characteristics of both a bio-geographical model and a bio-geochemical model which enable estimation of the potential distribution of natural vegetation using NPP under future climate conditions. The model included the processes of CO_2 effect on NPP, the responses of NPP to climate that specifically considered plant functional type, and competition among PFTs for light and water. The model is also capable of determining which vegetation type is most suited for given climatic conditions. In order to improve it as a bio-geochemical model, however, there is still a need to consider the dynamic processes involved in vegetation structure due to climate and CO_2 effects.

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