Probable Effects of CO₂ - induced Climatic Changes on the Net Primary Productivity of Terrestrial Natural Vegetation in Monsoon East Asia

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Abstract

Three climatic scenarios of doubled CO₂ (GISS, GFDL, and UKMO) were used to simulate changes in the net primary productivity (NPP) of the natural vegetation of monsoon East Asia due to CO₂-doubling. These three scenarios and baseline climate data were treated to provide gridded data consisting of data nets of 1° × 1° meshes. The gridded data thus obtained were utilized together with the Chikugo model to assess NPP with baseline and CO₂-doubling climates. The potential total net production (TNP₀) of East Asia was climatically evaluated as 154×10^8 t dry matter yr⁻¹. The climatic changes induced by doubled CO₂ concentrations could lead to an increase in TNP₀ by 9 % to 15 %, depending on the climatic scenarios used. The estimated increase in TNP₀ would be limited by the gap between the shift speed of climatic zones and the migration speed of vegetation formations.

Key words: climatic change; terrestrial vegetation; net primary productivity; vegetation range; East Asia

1. Introduction

The net primary productivity (NPP) which is the net creation of organic matter by photosynthetic plants is the basis for determining the dimensions, activity, and biodiversity of terrestrial ecosystems. As is well known, CO₂ concentrations in the atmosphere continue to rise constantly at a rate of 1.0–1.5 ppm a year (Boden *et al.*, 1990). Climatic changes induced by such CO₂-increases would have a significant influence upon the biomass production of global terrestrial vegetation (Emanuel *et al.*, 1985; Pittock and Nix, 1986; Uchijima and Seino, 1988). However, little work has been done on the probable effects of CO₂-induced climatic changes on the NPP of terrestrial vegetation in East Asia with abundant vegetation formations and higher biomass production. Although favorable climatic conditions in this area bring about such high biomass production, resulting in a higher carrying capacity for all living things, conservation of natural ecosystems in this area is becoming more urgent problem due to the over use of land and large human population. Therefore, this study focuses on NPP-distribution and the magnitude of TNP₀ in terrestrial vegetation of monsoon East Asia under the present climate and projected doubled CO₂ climates.

2. Calculation of NPP from Climatic Data

The climatic data (air temperature, precipitation, global solar radiation, cloud amount and vapor pressure) for East Asia (70° E to 150° E and 10° N to 50° N; 16.67×10^8 ha) were treated to provide gridded climatic data to be available in digital form on uniform 1° latitude by 1° longitude meshes (1642 grid points). These meteorological data correspond to the normal climatic conditions for the period between the 1950s and the 1970s. We used equilibrium climatic scenarios obtained from three simulation experiments by the Goddard Institute for Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), and the United Kingdom Meteorological Office (UKMO) for $2 \times$ CO₂ levels (600 ppmv).

The Chikugo model (Uchijima and Seino, 1985) is based on two parameters, net radiation and the radiative dryness index, which, in a sense, combine the most important effects of temperature, precipitation, solar radiation and so on, not separate quantities, but rather as they simultaneously affect plants. This model is expressed as follows:

$$\text{NPP} = 0.29 [\exp(-0.216 \text{ RDI}^2)] R_n,$$

where NPP is net primary productivity ($\text{t dry matter ha}^{-1} \text{ yr}^{-1}$), RDI is the radiative dryness index ($= R_n / l r$; l is latent heat of evaporation ($\text{kcal g H}_2\text{O}^{-1}$), and r is precipitation ($\text{g H}_2\text{O cm}^{-2}$), and R_n is net radiation ($\text{kcal cm}^{-2} \text{ yr}^{-1}$). Net radiation is a measure of energy characterizing the intensity of biophysical processes on the Earth surface. The radiative dryness index is a ratio of annual net radiation to the energy necessary for evaporating annual precipitation, and is an index for characterizing the dryness of the climatic environment. We estimated the NPP of terrestrial vegetation using normal and three $2 \times \text{CO}_2$ climate data, and this Chikugo model.

3. Results and Discussion

To test the validity of our procedure, the NPP map of this area constructed using gridded NPP-data was superimposed onto vegetation maps. The NPP-values of gridded points in the spatial distribution areas of major vegetation formations were averaged to determine the respective mean NPPs of major kinds of vegetation. Each mean NPP thus obtained was thoroughly compared with field observation results (Whittaker and Likens, 1975), confirming that the procedure was valid and could be applied to predict NPP from weather data.

Current plant productivity defined as NPP under the baseline climate varied from below $1 \text{ t dry matter ha}^{-1} \text{ yr}^{-1}$ of inner desert districts (Taklimakan, Gobi and Tibetan

Fig. 1. Geographical distribution of net primary productivity ($\text{t dry matter ha}^{-1} \text{ yr}^{-1}$) of terrestrial vegetation under baseline climate conditions.

plateau), through 5 – 10 t dry matter ha⁻¹ yr⁻¹ of the deciduous broad-leaved forest zone of the Far Eastern part of this region and 10 – 20 t dry matter ha⁻¹ yr⁻¹ of the evergreen broad-leaved forest zone, to above 25 t dry matter ha⁻¹ yr⁻¹ of the sub-tropical and tropical humid forest zones of the mainland and islands of the Southeast Asia, and of the south coastal district of the Indian sub-continent (Fig. 1). The general pattern of NPP-distribution in this area agreed well with that obtained by other researchers (Lieth and Box, 1972; Lieth, 1975; Efimova, 1977; Warrick *et al.*, 1986; Seino and Uchijima, 1992). The potential of total net production (TNP₀) defined as the area summation of NPP under the baseline climate was evaluated to be about 154 × 10⁸ t dry matter yr⁻¹ and to be about 11 % of the global potential (1360 × 10⁸ t dry matter yr⁻¹; Seino and Uchijima, 1992).

Fig. 2. Distribution curves of percentage area with different NPP values for specified 2 × CO₂ climatic scenarios. Broken and solid lines represents the distribution curves for baseline and 2 × CO₂ climates, respectively. RTNP is the relative total net production, a measure of the ratio of TNP₀ over monsoon East Asia in scenario climates to that in the baseline climate.

the plants in these areas should be more sensitive or vulnerable to climatic changes, particularly 2 × CO₂ climatic warming.

Land areas which will become climatically unsuitable for each type of vegetation formation due to 2 × CO₂ climate warming was estimated by summing up the number of grid

Using three gridded 2 × CO₂ climatic data obtained from GISS-, GFDL-, and UKMO-scenarios, estimates were made with our procedure to evaluate the impacts of changes in climate on NPP-distribution and TNP₀ in monsoon East Asia. The NPP-distribution patterns obtained using these 2 × CO₂ scenarios were quite similar to that for the baseline climate, with several minor differences. Climatic warming due to a doubling of atmospheric CO₂ caused latitudinal and altitudinal shifts of NPP-isopleths in the whole area, resulting in the increment in TNP₀. Provided that plants could adapt to climatic changes through rapid migration (Pittock and Nix, 1986; Uchijima and Seino, 1988), increases in TNP₀ were about 9.5 % for GISS, 12.9% for GFDL, and 14.4% for UKMO, respectively (Fig. 2).

To make clear the mutual relationships among climatic variables, the productivity and distribution of major vegetation formations, a three dimensional graphic model (Fig. 3) was made using gridded baseline climatic data, gridded NPP values, and vegetation distribution maps. Using this graphic model, it was found that the respective ranges of major vegetation formations overlapped each other. These overlapped areas were thought to correspond to an ecotone, in which plants of respective vegetation formations are competing with each other for land and climatic resources. Therefore,

Fig. 3. Graphic model of the relation between climatic variables (RDI and R_n), NPP, and vegetation formations. The abscissa is the mean annual RDI and the ordinate is annual R_n ($\text{kcal cm}^{-2} \text{yr}^{-1}$). The family of curves denotes NPP calculated from the Chikugo model. Each ring in this figure indicates the spatial range of each vegetation formation on the RDI – R_n plane. The dotted lines (a and b) indicate the upper and lower limits of annual R_n in each climatic zone. TR: sub-tropical or tropical rain forest, MF: monsoon forest, S: savanna, EB: evergreen broad-leaved forest, DB: deciduous broad-leaved forest, DB+CF: mixed deciduous broad-leaved and conifer forest, CF: conifer forest, G₁: warm-temperate grassland, G₂: cool-temperate grassland, T: tundra, D: semi-desert or desert.

points pushed out of each ring (see Fig. 3) showing the distribution area of respective vegetation formations under the baseline climate. The results show that the percentage of land area climatically unsuitable for these vegetation formations to the entire land area varied from 15.1 % (GISS), 22.4 % (GFDL), to 30.7 % (UKMO), depending on the climatic scenarios used. The appearance of these climatically unsuitable land areas should lead to a reduction of the projected increment in NPP and TNP₀ in monsoon East Asia.

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