An Agroclimatic Method of Estimating Net Primary Productivity of Natural Vegetation

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Introduction

A part of solar energy is fixed by plants into organic matters which support the life of all components of the biosphere. Therefore, the net primary productivity, that is, the net creation of organic matter by photosynthetic plants is the basis determining the functions of the life of all components and natural ecosystems on the earth. Furthermore the vegetation on the earth is an important partner for the changes in the atmospheric gas composition, particularly in CO_2 concentration. The converting efficiency of solar energy into organic matter is influenced not only by biological characteristics of plants but also by ambient environmental conditions. Of them solar energy impinging on plants and soil moisture in the root zone exert the determinate influence on the net primary productivity (NPP, t dry matter/(ha · yr)) of plants.

Therefore, the primary productivity of natural vegetation systems of various types has been the subject of research among plant ecologists in the world. In that research, many researchers have concentrated their attention on the method of estimating NPP of natural and crop vegetations. The methods presented by researchers can be divided into three groups, such as 1) plant ecological method based on the measurement of dry matter production of plants, 2) allometry method based on definite allometric correlations between dimensions of different parts of a tree, and 3) climatic method based on the use of relationships between dry matter production and climatic factors. In this paper, the data of NPP of various types of natural vegetation in individual climatic zones obtained through the International Biological Program (IBP, 1964–1974) were analyzed to build a model that estimates NPP-values from climatic parameters, which have been measured in a dense network over the world. This model was published as the Chikugo model in a previous paper[19]. The validity of this model was tested by comparing NPP-data for the individual prefectures in Japan estimated from this model and Iwaki's model[16]. It was found from the comparison that the Chikugo model could be applied to estimate NPP-values of natural vegetation with an acceptable error. This model was used to make clear the geographical distribution of NPP and the energy efficiency of dry matter production in Japan and world[18-20].

Theoretical basis of the Chikugo model

By applying physical approaches to the gas exchange between fully grown vegetations and the surface air layer[1,2] we can write the water use efficiency (WUE), that is, the ratio of net creation of dry matter (NPP) to transpiration loss of water (E_T), as follows:

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$$\mathrm{WUE}=\frac{\mathrm{NPP}}{E_T} \qquad \cdots\cdots(1)$$

Under the conditions that vegetation fully covers the ground surface and can absorb the most of incoming global solar radiation, the following relation is obtained as the first approximation:

$$E_T \simeq E_\Sigma=\frac{R_n}{l(1+\beta)} \qquad \cdots\cdots(2)$$

where E_Σ is the evapotranspiration from vegetation (t H_2O/ha or mm),
R_n is the net radiation (kcal/ha),
β is the Bowen ratio characterizing partition of the net radiation,
l is the latent heat of evaporation of water (kcal/g H_2O).

Combination of Eqs. (1) and (2) yielded

$$\mathrm{NPP}=\frac{A_0 R_n}{d(1+\beta)} \qquad \cdots\cdots(3)$$

where A_0 is an experimental constant relating to physical and physiological processes of gas exchange between vegetation and the surface air layer,
d is the water vapor deficit (mm Hg or mb).

Eq. (3) can be simplified as follows:

$$\mathrm{NPP}=\alpha \cdot R_n \qquad \cdots\cdots(3')$$

where $\alpha=A_0/d(1+\beta)$.

Eq. (3) expresses clearly that NPP is proportional to the magnitudes of R_n measured or estimated on natural vegetation and that the proportionality constant decreases with the product of d and $(1+\beta)$ characterizing the dryness of climate. Eq. (3) is the theoretical basis of the Chikugo model for estimating NPP-values of natural vegetation from the weather data.

The Chikugo model for estimating NPP

Eq. (3) requires the quantative knowledge on the relationship of A_0, d, and β to plant and climatic factors. However, the quantitative data of relationship have been restricted. Our modeling of NPP was based on the selected productivity data paired with the climatic data. The productivity data were derived from a recent publication: World Forest Biomass and Primary Production Data[4]. The climatic data were taken from the Selected Climatic Data for a Global Set of Standard Stations for Vegetation Science[14], World Atlas of Agroclimatological Resources[6] and Climatic Tables of Japan (Japan Meteorological Agency, 1982).

First, we classified the production data into 12 groups according to different levels of radiative dryness index which was graded by every 0.2 unit of the index. The radiative dryness index (RDI) $=R_n/l_r$, where r is annual

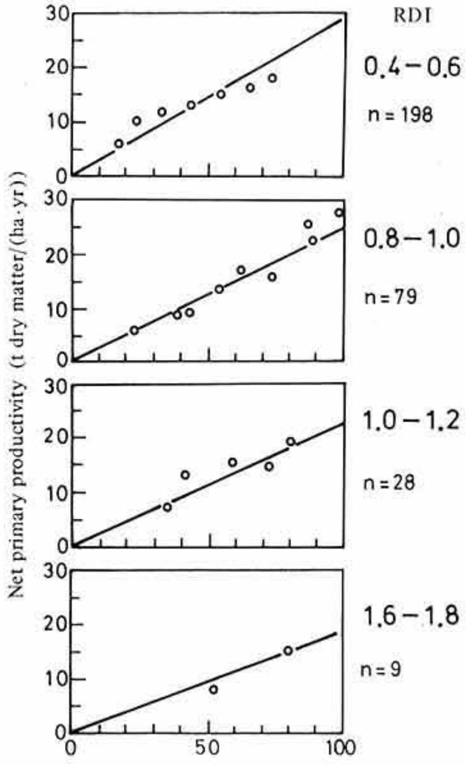

Fig. 1. Net primary productivity (NPP) as a function of annual net radiation (R_n) and radiation dryness index (RDI)
n: the number of the sample.

precipitation. Second, the NPP-data in each of the individual RDI-bands were grouped according to different R_n bands graded by every 5 kcal/cm² and averaged. About 700 pairs of data (NPP vs weather data) were available for the study. The relationship between annual net radiation (R_n) and net primary productivity as influenced by the dryness of climate (RDI) was studied using those averaged data. An example of the results obtained is presented in Fig. 1. It shows that the NPP-values increased linearly with the annual net radiation, and the proportionality constant (α) decreased with the increase in the dryness of climate, as expected from Eqs. (3) and (3′).

Fig. 2 shows the proportionality constant (α) as influenced by the radiative dryness index (RDI). The magnitude of α decreased monotonically with RDI. This relationship was well approximated by

$$\alpha = 0.29 \exp[-0.216\,\mathrm{RDI}^2] \quad \cdots\cdots(4)$$

By inserting Eq. (4) into Eq. (3′) we obtained

$$\mathrm{NPP} = 0.29\,[\exp(-0.216\,\mathrm{DRI}^2)]R_n \cdots\cdots(5)$$

This is the Chikugo model that estimates the net primary productivity of natural vegetation from weather parameters such as global solar radiation outside atmosphere, percent possible sunshine duration, albedo, temperature and humidity of air, and precipitation.

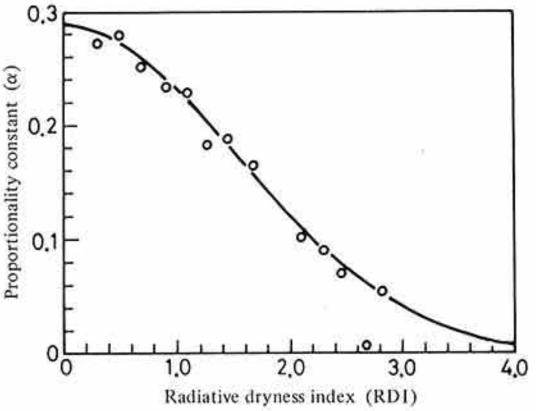

Fig. 2. Proportionality constant (α) of NPP vs R_n, as influenced by radiative dryness index (RDI)

Verification of the Chikugo model

The total net production (TNP, t dry matter/yr) of individual prefectures of Japan calculated on the basis of Eq. (6) was compared with results estimated by Iwaki[8)] using the data of the National Census of Green-Resources in Japan made by the Environment Agency of Japan. The TNP-values of the individual prefectures were estimated using the following equation:

$$\mathrm{TNP}_i = \sum_{j=1}^{4} A_{ij}\mathrm{NPP}_i E_j \qquad \cdots\cdots(6)$$

where TNP_i is the total net production of the i-th prefecture,
NPP_i is the average of NPP over the i-th prefecture,
A_{ij} is the acreage of the j-th land class in the i-th prefecture,
E_j is the production efficiency of the j-th land class.

Referring to Iwaki's report, the followings were used as the value of production efficiency for the individual land classes:

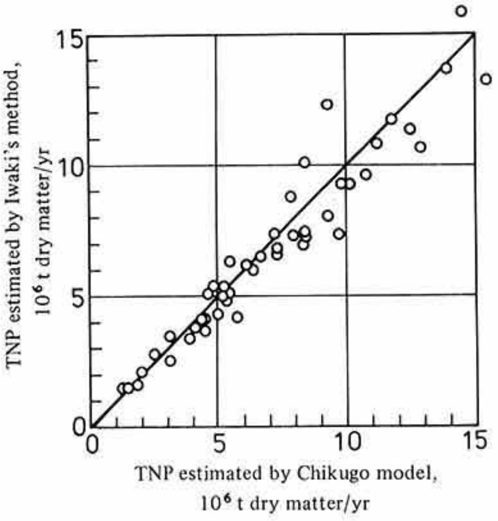

Fig. 3. Comparison of TNP values estimated using the Chikugo model and the values obtained (1981) with the Iwaki's method

j=1 (forest lands) $E_1=1.0$
j=2 (fruit tree land) $E_2=0.8$
j=3 (crop lands) $E_3=0.81$
j=4 (grass land) $E_4=0.625$

Fig. 3 shows the comparison of annual total net production estimated by the Chikugo model in the manner as described above and that estimated by Iwaki's method. Apparently, there is a good agreement between TNP-values estimated with the two independent methods, showing that the Chikugo model can be applied to estimate the NPP-value of natural vegetation.

Geographical distribution of net primary productivity and solar energy efficiency

The normal weather data (1951–1980) for about 150 stations and the weather data from the Automated Meteorological Data Acquisition System (AMeDAS) were treated with climatological methods to estimate annual net radiation and the radiation dryness index necessary for estimating NPP-values at individual meteorological points in Japan. The values of NPP estimated from Eq. (5) using the data of R_n and RDI are presented in Fig. 4–(1).

The NPP-value of natural vegetation in the central mountainous area of Hokkaido is lower than 8 t dry matter/(ha·yr). However, it increases in the south mainly because of increased thermal resources. The isopleth of 14 t dry matter/(ha·yr) extends southwards from Miyako city on the Pacific side of Tohoku district, along the foot of mountain areas in the south half of Tohoku, Kanto, and Chubu region, and then exactly to the north of the northeastern coast of the Lake Biwa, and then turned northwards to reach finally near Sakata city on the Japan Sea side of Tohoku

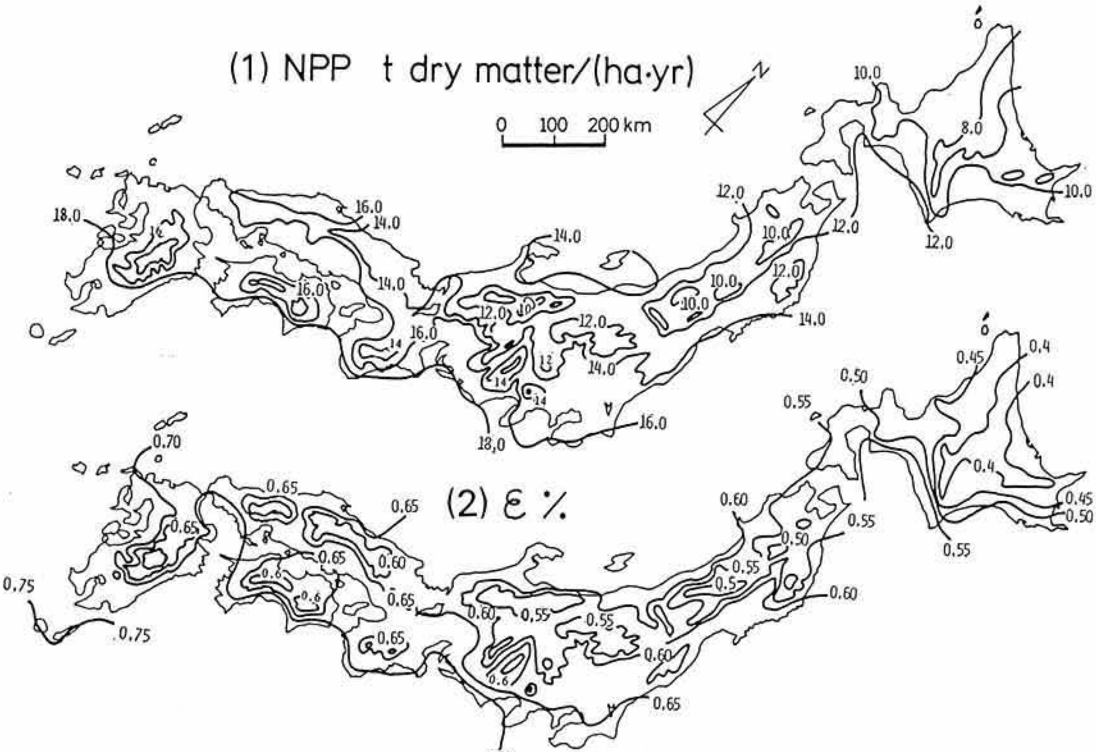

Fig. 4. Geographical distribution of NPP and of solar energy efficiency (ε) of natural vegetation in Japan

district. It was found that this isopleth runs near the boundary between deciduous broad leaf forests and evergreen broad leaf forests. The Pacific coastal region of the Kii-Peninsula, and two southwestern islands (Shikoku, and Kyushu) are the most productive in Japan, showing the net primary productivity higher than 18 t dry matter/(ha · yr). The NPP in the southmost Ryukyu Islands, in which thermal resources and global solar radiation are more favorable to plant growth, was to some extent higher than 20 t dry matter/(ha · yr).

Using the geographical distribution of NPP over Japan presented in Fig. 4 and the statistical data of land use in individual prefectures, the potential total net production of Japan was estimated at 379.5×10^6 t dry matter per year. This value of TNP of Japan agreed well with results reported by several other researchers[7,8,13,15].

The solar energy efficiency (ε%) of natural vegetation was calculated from

$$\varepsilon = \frac{\lambda \cdot \mathrm{NPP}}{S_t} \cdot 100\% \qquad \cdots\cdots(7)$$

where λ (=4.7 kcal/g dry matter) is the heat production of forest dry matter,

S_t is the annual global solar radiation (kcal/ha).

The geographical distribution of solar energy efficiency of natural vegetation calculated from Eq. (7) is given in Fig. 4–(2). The value of the energy efficiency increased along the southward direction, starting from 0.4% at the mountainous area of Hokkaido to 0.75% in the southern part of Kyushu with the national average of about 0.6%. However, this difference in the efficiency between Hokkaido and Kyushu was not due to the difference in photosynthetic activity of different vegetation types between these two districts, but due to the difference in the use of annual global solar radiation as given in Eq. (7). When the global solar radiation accumulated only for the plant-growing period with daily air temperature above 10°C was taken up, it yielded the solar energy efficiency from 0.7 to 0.9% independently of districts. This has the implication that the vegetation fixes annually into dry matter about one percent of global solar radiation which reached over Japan during the plant-growing period (9.03×10^{11} GJ).

A graphic model expressing the relationship between NPP and climate

Climatic conditions over the earth have the determinative influence on the growth of plants. Therefore, the difference in climatic conditions among individual regions of the earth causes the differentiation of plant types, and consequently that of net primary productivity of vegetation among districts. Graphic models of relationships between vegetation formation classes or net production and climatic factors have been demonstrated by several researchers[2,5,12].

The family of NPP vs R_n and RDI curve obtained from the Chikugo model was superimposed on a graph showing the relationships between major vegetation types and climatic conditions[3]. The result obtained is presented in Fig. 5. In the tundra climate with RDI lower than 0.3, the net primary productivity of vegetation is significantly limited by the shortage of radiation resources. The vegetation type in the forest climate with the RDI-range between 0.3 and 1.0 changes from tropical rain forest to boreal forest depending on the radiation resources. This graphic model shows that tropical rain forests of the tropical rain zone are the most productive (20–30 t dry matter/(ha · yr)), wet savanna and temperate broad-leaf forests (10–20 t dry matter/(ha · yr)) come next, followed by coniferous forests of the cool temperate zone (5–10 t dry matter/(ha · yr)). Boreal forests of the climatic zone with radiation resources lower than about 20 kcal/cm² are the lowest in productivity (lower than 5 t dry matter/(ha · yr)). Savanna and steppe vegetations of the steppe climate are significantly less productive than vegetations of the forest climate under the same radiation conditions. This is

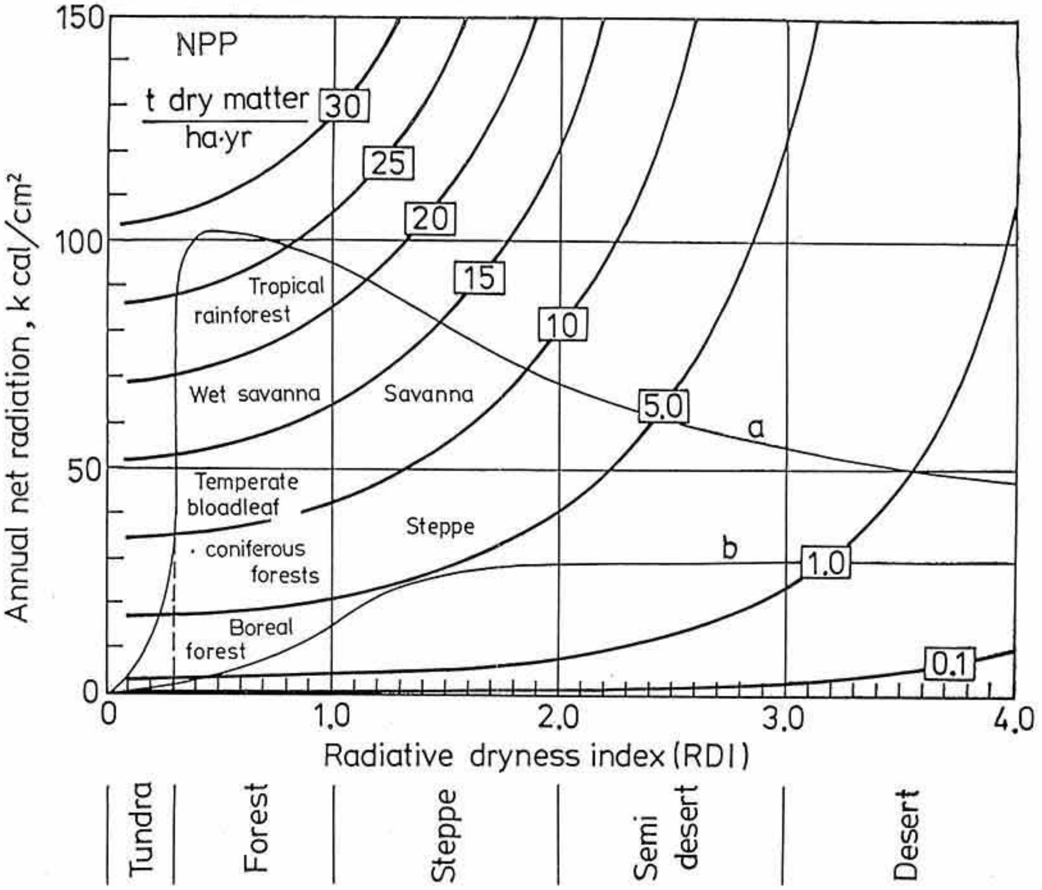

Fig. 5. Net primary productivity of natural vegetation as influenced by net radiation and radiative dryness index
Curves a and b denote upper and lower limits of annual net radiation in each climatic zone, respectively.

attributable to the bad combination of higher radiation and lower precipitation in that area. The situation of water shortage is more serious in the desert climate zone, which shows the net primary productivity of vegetation reduced to a level below around 1–2 t dry matter/(ha·yr).

Conclusion

This paper presents the usefulness of the Chikugo model in estimating the net primary productivity (NPP) of natural vegetation by using environmental parameters, which have been measured in a dense meteorological network over the world. Net radiation and radiative dryness index were taken up at first among environmental parameters. The net production of individual prefectures in Japan estimated using the Chikugo model was compared with the results already obtained by the Iwaki's method with good agreement. This agreement showed that the Chikugo model can be applied to estimate net primary productivity of natural vegetation, which underpins various research subjects such as a potential amount of agricultural production, biomass energy flow, and the balance of carbon-dioxide in the atmosphere.

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