Global Patterns of Energy Efficiency of Terrestrial Productivity

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Abstract

This paper describes current patterns of net primary productivity (NPP) and radiation use efficiency (RUE) of terrestrial vegetation of the world. Geographical patterns of NPP showed little productivity in areas with a shortage of climate resources, mainly in high latitudes, high altitudes and arid areas. Potential total net production (TNP) was evaluated to be about 53.2×10^9 tC year⁻¹ with a total land area of 129.1×10^8 ha excluding Antarctica. Annual shortwave radiation absorbed at the whole terrestrial area has reached 7.2×10^{14} GJ. Using this value and the potential TNP in the whole continental area, the world mean of annual RUE in the total for land surface was estimated to be 0.24%. The latitudinal gradient in RUE during the growing period revealed that higher efficiency was in low and high latitudes, which were dominated by tropical rain forests and conifer forests. In contrast, deciduous broad-leaved forests and temperate or tropical grasslands in the mid-latitudes were of efficiency at lower converting the useable solar radiation into biomass, owing mainly to decreased precipitation and the resulting decrease in available water.

Key words: Radiation use efficiency, Net primary productivity, Geographical distribution, Terrestrial biome

1. Introduction

Plant production is the fixation of solar energy by autotrophs in an ecosystem. Net primary productivity (NPP) is the amount of energy left over after autotrophs have met their own energy needs of respiratory heat. NPP is thus the amount of energy available to all consumer organisms, including humans, and is the beginning of energy flow along the pathways in an ecosystem. Therefore, it is essential to find a global pattern of terrestrial plant energetics that would provide a basis for calculating the productive potential of land areas of the world. Jordan (1971) pointed out that efficiency of wood production increases as amounts of available solar energy decrease, while efficiency of litter production appears to change very little, from analyzing field observation data of 27 communities.

The NPP and the radiation use efficiency (RUE) of primary production, which is defined as a ratio of the energy yield of NPP and the radiation absorbed per unit area of ground in the same time, has long been the subject of research among plant ecologists (Kira, 1976; Uchijima & Seino, 1987). Golley (1972) has estimated that total net production was about 40.0×10^9 tC year⁻¹, and the world RUE of terrestrial vegetation in relationship to annual global solar radiation to be 0.20 %. Lieth (1975) has reported that the world mean value of RUE for the land is 0.30%, based on the total NPP value of about 54.9×10^9 tC year⁻¹.

Although the global values of the efficiency of NPP in relationship to total annual solar radiation have been

elucidated as mentioned above, little is known about the global distribution of RUE except for some preliminary reports (Uchijima & Seino, 1987). In this paper, the author attempts to describe the spatial distributions and the latitudinal changes in NPP and RUE using the Chikugo model (Uchijima & Seino, 1985), climate and vegetation data. The specified RUE value in each major biome and the latitudinal gradient of RUE were estimated for discussion of the relationship between the world biome distributions and the energy use efficiency of net production.

2. Materials and Methods

2.1 Data used for calculation

All data have a resolution of 0.5° latitude $\times$ 0.5° longitude, interpolated or extrapolated climatologically or geologically if necessary, and they cover all terrestrial land areas excluding Antarctica.

The global climatic data such as mean air temperature, global solar radiation, precipitation, cloud cover, vapor pressure obtained from the IPCC Data Distribution Centre are mean monthly climatology from 1961 to 1990 and have 0.5° latitude $\times$ 0.5° longitude spatial resolutions (New *et al.*, 1999). These data sets cover all terrestrial land excluding Antarctica.

Global $0.5^\circ \times 0.5^\circ$ land area data was obtained from the CIESIN. The total terrestrial area excluding Antarctica and most of Greenland was 129.1×10^8 ha. The $1^\circ \times 1^\circ$ resolution seasonal surface albedo data (Matthews, 1983) were interpolated from seasonal to monthly and from 1° longitude $\times$ 1° latitude to 0.5°

longitude $\times$ 0.5° latitude resolution. 10 minute global altitude data compiled by the U. S. Navy Fleet Numerical Oceanography Center was obtained from GRID-Geneva. The 0.5° $\times$ 0.5° resolution vegetation data set was obtained from the IRL/LDEO Climate Data Library, compiled by Olson *et al.* (1983). This data set represents the world's Major Ecosystem Complexes ranked by the amounts of carbon in live vegetation and has 44 land ecosystem classes. In this study, the classes were categorized into 12 major biome units (Table 1) to be able to compare easily with previous studies.

2.2 Calculation of net radiation

Net radiation, which is the sum of downward short and longwave radiation absorbed by the Earth's surface and upward longwave radiation emitted by the Earth's surface, is the net energy available at the surface. Monthly net radiation (R_n , kcal cm⁻²) was calculated using energy balance equation (Ohta *et al.*, 1993).

$$R_n = (1 - \alpha)S_i - \sigma T^4 (0.39 - 0.058\sqrt{e}) \times (1 - cn^2) \quad (1)$$

where α is monthly surface albedo (range 0.0-1.0), S_i is monthly global solar radiation (kcal cm⁻²), σ is the Stefan-Boltzman constant, T is monthly mean air temperature (K), e is monthly vapor pressure (mmHg), c is proportionality constant, n is cloud amount (range 0.0-1.0). Since albedo data (Mathews, 1983) represents snow free conditions excluding Antarctica and Greenland, α was assumed to equal 0.70 in case T was lower than 0°C. c depends on latitude and range between 0.50 at the equator and 0.89 at 90° North and South (Budyko, 1956). Since downward longwave radiation decreases sharply with an increase in altitude, net radiation at high altitudes (mean altitude over 1500m) was calculated using correction coefficient (F_{df}), which reflects the influence of altitude on downward longwave radiation.

$$R_n = (1 - \alpha)S_i - \{\sigma T_s^4 - \sigma T^4 (0.61 + 0.058\sqrt{e} \times F_{df})\} (1 - cn^2) \quad (2)$$

where T_s is surface temperature (K). T_s was assumed to equal $T - 2$ (K). According to Ohta *et al.* (1993), correction coefficient (F_{df}) was evaluated by

$$F_{df} = -0.1742 + 0.00116P \quad (3)$$

where P is atmospheric pressure (hPa). P is expressed by the following equation:

$$P = P_0 ((T_0 - \Gamma z) / T_0)^{(g/R\Gamma)} \quad (4)$$

where P_0 is atmospheric pressure at the sea level (1013.25 hPa), T_0 is air temperature at 0m ($T + \Gamma z$), Γ is lapse rate (0.006 K m⁻¹), z is altitude (m), g is the acceleration of gravity (9.81 m s⁻²) and R is the gas constant (287 J K⁻¹ kg⁻¹).

2.3 Calculation of NPP and RUE

Potential net primary productivity of terrestrial biomes (NPP, t ha⁻¹ year⁻¹) was estimated using the

Chikugo model (Uchijima & Seino, 1985) with annual net radiation (kcal cm⁻²) as described in the previous section.

$$NPP = 0.29(\exp(-0.216RDI^2))R_n \quad (5)$$

where RDI is radiative dryness index ($= R_n / I_r$). I_r is latent heat of evaporation (kcal gH₂O⁻¹) and r is precipitation (cm). Biomass is expressed in units of carbon, assuming that plant biomass is 50% carbon.

Energy use efficiency, which is called the Lindeman radio, is a ratio of chemical energy created by photosynthesis to absorbed solar energy. Radiation use efficiency (RUE_{st}, %) based on the NPP and global solar radiation is as follows:

$$RUE_{st} = (\lambda \times NPP) / S_i \times 100 \quad (6)$$

where λ is energy content of organic dry matter as seen in Table 1 (kcal g⁻¹, Jordan, 1971; Lieth, 1975), S_i is annual global solar radiation (kcal cm⁻²).

3. Results and Discussion

3.1 Geographical distribution of NPP

Geographical patterns of NPP showed little productivity in areas with a shortage of climate resources, mainly in high latitudes, high altitudes and arid areas (Fig. 1a). The hyper-arid regions with extremely low NPP of less than 0.5 tC ha⁻¹ year⁻¹ lie beneath the subtropical high that is near 20 to 30 degrees in both hemispheres such as the Sahara, Namib Desert and Simpson Desert in Australia. Low NPP areas were also found in high latitudes such as Greenland, the northeast of the Eurasian Continent, northernmost North America, and Ice-cap climates in high altitudes such as the Rocky Mountains, Andes and the Himalayas. The middle latitude belt with relatively plentiful precipitation of Europe, East Asia, and the East coastal regions of North America are covered with temperate forest with NPP-values between 5 to 8 tC ha⁻¹ year⁻¹. More than 10 tC ha⁻¹ year⁻¹ were found at the equatorial zone with higher temperature and abundant precipitation throughout the year, allowing the growth of evergreen and deciduous broad-leaved forests.

3.2 Total net production and RUE of the world

Potential total net production (TNP) was obtained by multiplication of NPP by land area. NPP was evaluated in all terrestrial land excluding Antarctica. The total land area used in calculation of TNP was 129.1 $\times$ 10⁹ ha. The potential global net production of terrestrial vegetation was 53.2 $\times$ 10⁹ tC year⁻¹ (Table 1). This result agreed well with previous studies (e.g., Lieth, 1975; Saugier *et al.*, 2001) in an acceptable error. Annual global solar radiation absorbed at the whole terrestrial area has reached 7.2 $\times$ 10¹⁴ GJ. Using this value and the potential TNP in the whole continental area, the world mean of annual RUE_{st} in the total for land surface was estimated to be 0.24%, as

Fig.1 Geographical distribution of net primary productivity (a), and the efficiency of net primary productivity in relationship to total annual global solar radiation (b) of terrestrial vegetation.

global solar radiation (a- dotted line), net radiation (a- solid line), annual mean of NPP (b), RUE_{St} (c- dotted line), and $\text{RUE}_{Rn>0}$ (c- solid line) of terrestrial area.

Table 1 Net primary productivity and radiation use efficiency of primary production for each biome.

Biome	Land area (10^8 ha)	Mean combustion value (kcal g^{-1})	Mean NPP ($\text{t C ha}^{-1} \text{ yr}^{-1}$)	TNP (10^9 t C yr^{-1})	RUE_{St} (%)	$\text{RUE}_{Rn>0}$ (%)
Tropical rain forest	11.33	4.1	10.25	11.61	0.76	1.20
Tropical seasonal forest	4.66	4.2	7.46	3.48	0.46	0.83
Temperate evergreen broad-leaved forest	3.48	4.5	7.39	2.57	0.49	0.94
Temperate deciduous broad-leaved forest	4.19	4.6	5.27	2.21	0.39	0.85
Boreal forest	16.34	4.8	2.47	4.04	0.22	0.57
Tundra or alpine tundra	12.29	4.5	1.03	1.27	0.08	0.21
Temperate grassland	21.95	4.0	3.39	7.45	0.22	0.47
Scrub or shrub	3.88	4.6	6.11	2.37	0.40	0.76
Savanna	14.05	4.0	4.83	6.78	0.30	0.54
Desert or semi-desert	17.90	4.5	0.33	0.58	0.02	0.07
Crop land	15.12	4.1	5.59	8.44	0.37	0.74
Others	2.75	4.4	6.25	1.72	0.40	0.76
Global	129.1	—	—	53.2	0.24	0.56

continental area, the world mean of annual RUE_{St} in the total for land surface was estimated to be 0.24%, as shown in Table 1. The results coincided very well with estimation values of TNP and RUE_{St} based on the International Biological Programme (Lieth, 1975).

Figure 1b gives the spatial distribution of RUE_{St} , calculated based on Eq.6. Only a small proportion of annual global solar energy is converted by photosynthesis into plant biomass. Even the most

efficient tropical forests can only fix less than 1% of annual global solar radiation. RUE_{St} in arid zones has the lowest efficiency, and is less than 0.1% of annual shortwave radiation.

3.3 Biome differences in NPP and RUE

To evaluate the average NPP and RUE for major vegetation formations, the NPP map (Fig.1a) was superimposed onto a vegetation map proposed by Olson *et al.* (1983). As seen in Table 1, tropical

forests occupy about 11% of land area and about 28% of global terrestrial TNP, respectively. All forests account for about half of terrestrial TNP, occupying approximately one third of total land. Savannas and temperate grasslands, in contrast, occupy an equivalent area to all forests, and only about 25% of terrestrial TNP.

RUE_{S_r} ranged from 0.02% in desert/semi-desert, through 0.39% in deciduous broad-leaved forests, to 0.76% in tropical rain forests. To study the RUE in relationship to solar radiation during the growing season ($RUE_{Rn>0}$), the energy efficiency of net production was calculated using monthly net radiation data instead of S_r in Eq.6. However, $RUE_{Rn>0}$ was summed up if only monthly net radiation was a positive value. $RUE_{Rn>0}$ values in temperate or tropical grasslands were about 0.5%, and those in forests ranged from 0.57% in boreal forests, through 0.8 to 0.9% in scrub or shrub and deciduous broad-leaved forests, to 1.20% in tropical rain forests, and the world mean value was 0.56% (Table 1). The remarkable difference between RUE_{S_r} and $RUE_{Rn>0}$ is in areas with limited radiation but with sufficient water resources such as tundra and boreal forests. This means that plants at high latitudes and altitudes can intercept light intensively during the short growing period, and there is not so much difference of photosynthetic rate between plant types (Kira, 1976).

3.4 Latitudinal gradients in NPP and RUE

As described above, the energy use efficiency of net production changes latitudinally depending on NPP and climates of each latitudinal zone. To indicate distinctly the latitudinal changes in NPP and RUE, these gridded values were summed up in the longitudinal direction and averaged by considering the land area with every 0.5 degree (Fig. 2).

The top of Fig. 2 shows the latitudinal change in annual global solar radiation, and net radiation. Annual solar radiation generally decreases as latitude increases. A deep trough caused by plentiful rainfall in the equatorial zone divides the two peaks. The latitudinal changes in the NPP (the middle of Fig. 2) and RUE_{S_r} (the bottom of Fig. 2) are completely opposite in phase with those of solar radiations. NPP and RUE_{S_r} -curves have a clear peak in the equatorial zone. This trend means that the tropical rain forests in the equatorial zone can more efficiently use the solar energy than the seasonal forests and temperate broad-leaved forests in the middle latitudes of both hemispheres. In other words, although plants in mid-latitude high pressure zones (approximately 30° N and S) have abundant thermal resources, the net production is limited due to water shortages. It is also evident from the bottom of Fig.2 that the $RUE_{Rn>0}$ -curve is characterized by three distinct peaks which are divided by two deep troughs. In the peaks, boreal forests are dominated by gymnosperm trees such as spruce, fir, larch and pine, reflecting less available solar radiation and the greater advantage of gymnosperms over

angiosperms (Jordan, 1971). There are two reasons that explain why the efficiency of radiation use during the growing period in mid-latitudes is low. First, caloric concentrations of angiosperms are lower than those of gymnosperms. The second reason is that steppes and savannas, which have lower caloric concentrations than trees, occupy as much as three times the forest area in mid-latitudes due to mainly climatic aridity. It is very interesting that heavy deforestations and massive human activities have occurred in the mid-latitudes, which have the lower RUE during the growing season.

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