

Spatial Patterns of Anthropogenic Carbon Emission and Terrestrial Net Productivity

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This paper describes the current spatial patterns of the net primary productivity (NPP) of the terrestrial vegetation and carbon emission (C) in the world due to the burning of fossil fuels in order to clarify the amount of expansion of human activity. The C/NPP value varies spatially from almost zero to several tens of thousand times the local NPP. C/NPP is higher under the condition of extensive human activities due to a high human population density or when the local NPP is extremely low in severe climatic zones. In contrast, the low C/NPP areas are distributed mainly in sparsely populated districts, leading to a low impact of human activity. Although the area where C/NPP is less than 10% accounts for about 70% of the entire land area, one-third of these areas cannot contribute to carbon absorption because of low NPP with a shortage of climatic resources. Since more than half of the areas of the remaining areas are agricultural land and forest ecosystems with high NPP, the possible afforestation area was evaluated to be maximum of 30×10^6 km²; here only sequester carbons that correspond to 2% of the global total NPP are present. These analyses revealed that presently most of the areas where the NPP is high are those exclusively used by humans and that it is difficult for large-scale forest plantations to absorb a substantial amount of the carbon emitted annually by humans.

Key Words: Burning of fossil fuels, Net primary productivity, Human activity, Carbon sequestration

1. Introduction

Net primary productivity (NPP) is the amount of energy available for all consumer organisms, including human beings; it provides the basis for the maintenance and growth of an ecosystem. Therefore, it is essential to understand the global pattern of the potential NPPs of the land areas of the world ¹⁾.

On the other hand, the concentration of carbon dioxide in the atmosphere continues to increase at an annual rate of approximately 1.0 ppmv. This increase is mainly caused by the burning of fossil fuels and massive deforestation. In 2003, the annual carbon emissions from fossil fuels exceeded about 7×10^9 tonnes (t; 1t=10⁶g) C across the world ²⁾. Such human activities tremendously affect the climate system of the Earth. The Kyoto Protocol has established legally binding requirements for the emission limits in in-

dustrialized countries. The protocol also includes three flexibility mechanisms - emissions trading, joint implementation, and the clean development mechanism (CDM) - that help the industrialized countries to cost-effectively reach the emission reduction commitments. Thus, plant growth is very important because the CDM primarily relies on the amount of photosynthesis, which is fixed for atmospheric carbon dioxide.

Saugier *et al.* ³⁾ and Ohta ¹⁾ estimated the total net production of the world potential as about 62.6×10^9 tC year⁻¹ and 53.2×10^9 tC year⁻¹, respectively. However, the actual NPP decreases considerably from the potential value because of the food production for human and livestock. Vitousek *et al.* ⁴⁾ pointed out that nearly 40% of the potential terrestrial NPP was used directly because of human activities. In a more recent study ⁵⁾, the global value of the fraction of the human appropriation of terrestrial NPP was about 32%; however, the reported value had high uncertainty ⁶⁾.

Another measure of the human impact is the percentage of the primary production in the world and the total carbon emitted by the burning of fossil fuels

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(C/NPP). Although the global values of the human appropriation of terrestrial NPP, with relation to the total annual human consumption have been elucidated as mentioned above, little is known about the geographical distribution of the percent of C/NPP. In this paper, we first attempt to describe the spatial distributions of the carbon emission and C/NPP using the Chikugo model⁷⁾ and various data. Second, the specified C/NPP value in each major regional area and the latitudinal gradient of C/NPP were estimated for a discussion on the relationship between the major biome distributions in the world and the possibilities of carbon sequestration.

2. Materials and Methods

2.1. Data used for calculation and data processing

All the 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. Carbon released from a 0.5° grid was estimated by the gridded human population data of the world in 2000²⁾. The national fossil fuels emission data for 2000 was derived primarily from the energy statistics published by the United Nations⁸⁾. The gridded data of the carbon emission were interpolated as a fraction of the human population of each grid for an entire country, using the total national data of the fossil fuel consumption.

The global 0.5° land area data were also obtained from the CIESIN²⁾. The total terrestrial area excluding Antarctica and most of Greenland was 129.1×10^6 km². The seasonal surface albedo in each 1° latitude \times 1° longitude resolution⁹⁾ were interpolated from the seasonal to monthly data and converted to a 0.5° longitude \times 0.5° latitude resolution. 10 minute altitude data compiled by the U.S. Navy Fleet Numerical Oceanography Center was obtained from GRID-Geneva. Climatic data such as the mean of air temperature, global solar radiation, precipitation, cloud cover, and vapor pressure obtained from the IPCC Data Distribution Centre yield the monthly mean climatology from 1961 to 1990 and have 0.5° latitude \times 0.5° longitude spatial resolutions¹⁰⁾.

2.2. Calculation of NPP and C/NPP

Net radiation is the sum of the downward shortwave and the longwave radiation absorbed by the Earth's surface and the upward longwave radiation

emitted by it; thus it is the net energy available at the Earth's surface. The monthly net radiation was calculated by using the energy balance equations^{11),1)}. The potential net primary productivity of the terrestrial biomes was estimated using the Chikugo model⁷⁾ with the climatic data of the thermal and water resources.

Biomass is expressed in units of carbon, assuming that the plant biomass is 45% carbon. In this study, soil respiration is not considered, and it is assumed that the soil organic carbon would be under a steady-state condition. The C/NPP percent is calculated using the values of carbon dioxide from the fossil fuel consumption and the aboveground NPP data.

3. Results and Discussion

3.1. Relationship between fossil fuel combustion and plant production

According to Fig. 1a, the geographical patterns of annual carbon emissions by the consumption of fossil fuels showed very low values in sparsely populated areas such as those in high latitudes, high altitudes and arid regions. Conversely, the anthropogenic emissions of carbon in densely populated regions have significantly increased over the world. The amount of carbon emission in North America and Europe is 2 to 5 tC per capita, and is very high when compared with that of the other regions (Table 1). Carbon emission per capita in Central and Western Asia is reaching the same levels as that of North America and Europe. As shown in Table 1, although East Asia, where the population is concentrated, occupies only by 9% of the whole land area, its total amount of emission accounts for about 20% of the worldwide emission at 1255×10^6 tC.

The potential total net production (TNP) was obtained by multiplying the NPP by the land area. The C/NPP value of Africa, South America and South East Asia is extremely low when compared with that of the other regions (Table 1) because the TNP is high due to the abundant tropical rain forests.

To distinctly indicate the latitudinal changes in carbon emission, human population, and TNP, these gridded values were summed in the longitudinal direction and averaged by considering the land area for every 0.5 degree (Fig. 2). The top part of Fig. 2 shows the latitudinal gradients in the terrestrial area and the hu-

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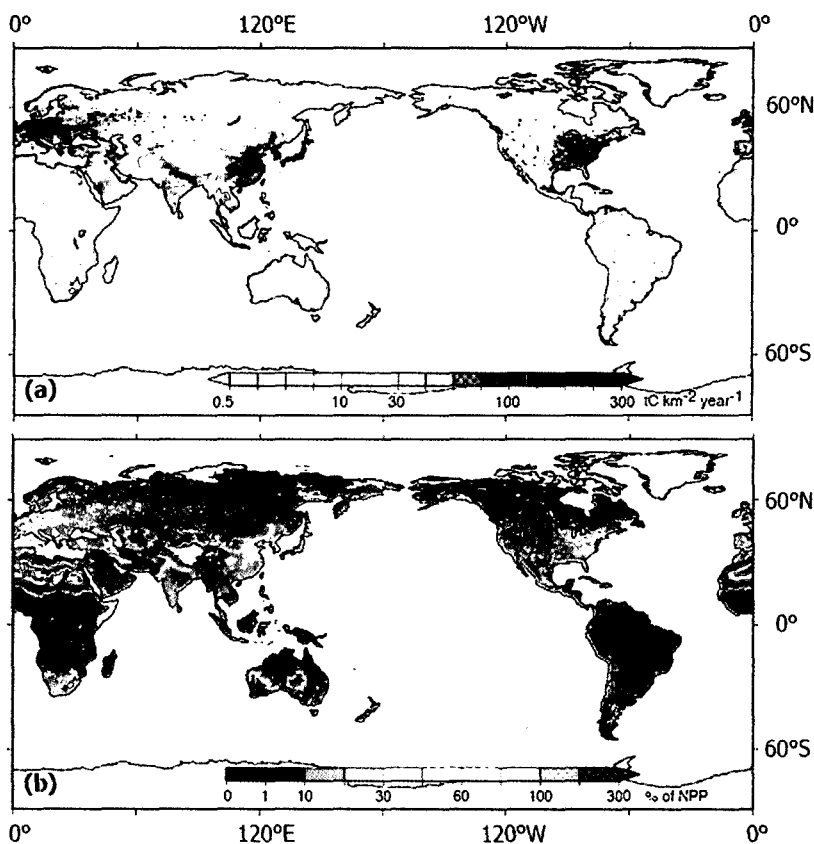


Fig. 1. Global distribution of (a) the annual carbon emission from the burning of fossil fuels and (b) the index into which the amount of carbon emission is divided by the net primary productivity. The analysis excludes most oceanic islands and national boundaries are not authoritative.

man population. The land area is concentrated on the mid- and high latitudes of the northern hemisphere. The human population curve has a clear peak in the 20° to 40°N region. Furthermore, the curve of the carbon emission from fossil fuels has a clearer peak at about 40°N. This trend implies that the developed nations and some developing countries with a high human population (the bottom part of Fig. 2) are intensively distributed in the zone. The latitudinal changes in the TNP (Fig. 2c) are completely opposite in phase with of the latitudinal changes in the human population (Fig. 2b) and carbon emissions (Fig. 2d). From the right side of Fig. 2, it is evident that the human activities in the equatorial zone are considerably smaller than that in the middle latitudes, although the tropical rain forests absorb carbons more efficiently than the seasonal forests and the temperate broad-leaved forests in the middle latitudes of both

the hemispheres.

3.2. Human impact index of the world

Figure 1b depicts the geographical distribution of the percentage of C/NPP. The C/NPP value can be considered as an index that expresses the magnitude of human influence. It is also found from Fig. 1b that the C/NPP value varies spatially from almost zero to several tens of thousand times the local NPP. The geographical distribution pattern of the C/NPP value obtained using the present procedure for the gridding data agreed well with the human footprint map reported by Sanderson *et al.* (2002).

The C/NPP value exceeded 100% under the condition of extensive human activities due to the high density of human population. The areas that are shown in red color in Fig. 1b have already emitted more carbon into the atmosphere than the local NPP; they are about 12% of the total land. The high

Table 1. Summary of the plant production and the human influence index by region

Region*	Land Area (10^6 km 2)	Population (10^6 capita)	TNP (10^9 tC)	Carbon Emission		C/NPP (%)
				(10^6 tC)	(tC/capita)	
Western Europe	2.49	365	0.95	775	2.12	81.31
Eastern Europe	18.99	320	3.45	696	2.18	20.16
North Europe	1.26	24	0.24	54	2.25	22.61
Baltic States	0.18	7	0.06	9	1.29	16.29
Africa	29.64	776	10.09	223	0.29	2.21
North America	19.60	316	4.92	1648	5.22	33.51
Central America	2.64	161	1.42	140	0.87	9.86
South America	16.98	328	11.76	177	0.54	1.51
East Asia	11.76	1481	3.24	1255	0.85	38.79
South East Asia	4.48	516	4.12	209	0.41	5.06
South Asia	4.49	1342	2.28	333	0.25	14.57
Central Asia	4.00	56	0.49	77	1.38	15.88
Western Asia	7.05	271	0.52	367	1.35	70.97
Oceania	8.55	30	2.00	104	3.47	5.22

* Definitions of regions were taken from the FAO-stat category.

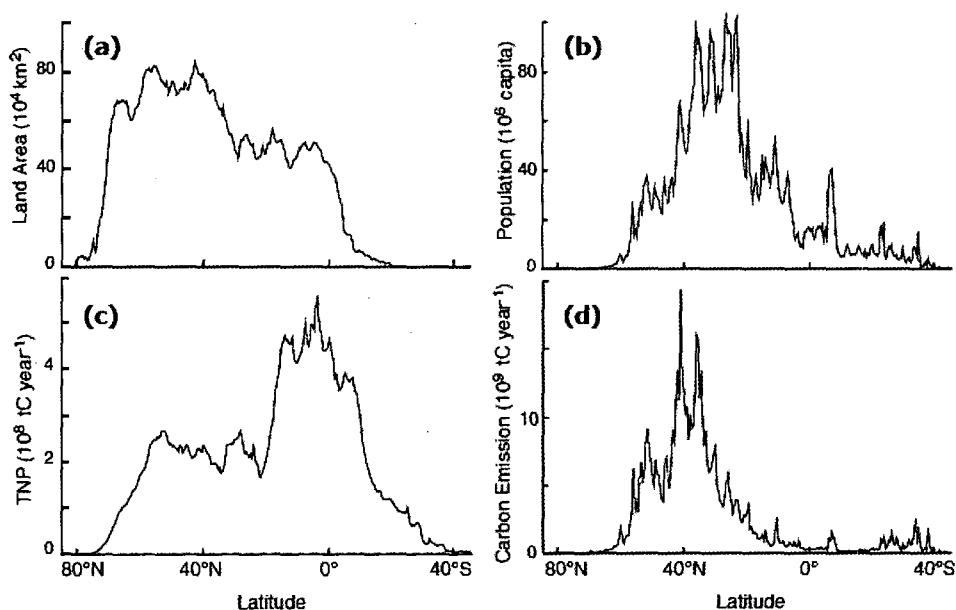


Fig. 2. Latitudinal changes in the (a) terrestrial land area, (b) human population, (c) annual total net production, and (d) annual carbon emissions from humans. All data have a spatial resolution of 0.5° latitude \times 0.5° longitude.

C/NPP area consists chiefly of land in many developed countries, for instance, the countries in Europe, East Asia, and the east coast of North America (Fig.

1b). The C/NPP value might also be high for areas with extremely low local NPP in severe climatic zones even if the anthropogenic carbon emission is

small.

In contrast, the low C/NPP areas are distributed mainly in areas with a low population density and consequently the human impact is less. Although the area where C/NPP is less than 10% accounts for about 70% of the whole land area, one-third of these areas cannot contribute to the carbon sequestration that we expected because of the low NPP with a shortage of climatic resources. More than half of the remaining areas are agricultural land and forest ecosystems with high NPP; however, these areas could not be converted to forest plantations because they were necessary for food supply. Consequently, the possible afforestation area was estimated to be a maximum of 30×10^6 km² (that is, less than 20% of the total land area). Assuming that the annual NPP of the area is 2.5 - 4.0 tC ha⁻¹ on an average, the annual carbon absorption in the area is estimated to be a maximum of 1.0×10^9 tC, which corresponds to about 2% of the global total NPP. Therefore, it is difficult for a large-scale plantation to absorb a substantial amount of the carbon emitted annually by humans.

The anthropogenic carbon emissions into the atmosphere in the whole continental area were estimated to be approximately 13% of the annual global NPP. In addition, by taking into account the human appropriation for food production^{4),5),6)}, it is considered that presently, half of the annual TNP is exclusively used by humans. Since the NPP indicates the carrying capacity for all living things as described previously, it is necessary to precisely evaluate the C/NPP value in consideration of the consumption of the other species.

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