Effects of Land Use and Human Population on Plant Productivity of the Indonesian Archipelago

Shunji OHTA 1 and Zenbei UCHIJIMA 2

1 Dept. of Basic Human Sciences, Sch. of Human Scis., Waseda University (Tokorozawa, Saitama 359, Japan) and 2 Sch. of Humanities, Miyazaki Municipal University (Funatsuka, Miyazaki 880, Japan)

Abstract

Dramatic changes have occurred in tropical forest areas and the net primary production (NPP) in South and Southeast Asia because of the influence of human activity during the past two hundred years. Recent research reveals that human population density has a significant impact on forest areas. Using this relation and the Chikugo model, we estimated the deforested area, and calculated the biomass degradation of the Indonesian archipelago. The potential total net production (TNP₀), defined as the area summation of NPP ignoring the impacts of human population, is evaluated to be about 74.9 x 10⁸ tonnes dry matter per year. The actual total net production (TNPₐ) calculated by considering human land use is estimated to be approximately 65.4 x 10⁸ tonnes dry matter per year, and to be 87% of TNP₀ of natural vegetation over the whole terrestrial area of Indonesia. However, there is a considerable difference between the islands with a high population density and with a low population density. The percentage of forest area of Java Island is less than 10%, and therefore the TNPₐ of Java to Timor Islands is only 38% of the potential. On the other hand, the forest areas of Irian Jaya and Papua New Guinea are more than 80% of the total land area of this island. TNPₐ in these islands with higher forest cover reaches at 90% of these TNP₀.

Key words: actual production, biomass degradation, human population, Indonesian archipelago, land use

1. Introduction

The tropical rain forests of the Indonesian archipelago are a centre of the rapid population growth and intensive industrialization. It is therefore expected that the massive deforestation of the tropical forests affects the regional environment and the plant production of this district. Human population growth in developing nations plays clearly an important role in land-use change (Richards and Flint, 1994). However, the relationship between population growth and change in the area of forests and/or cultivated land is related closely to climatic, environmental, economic, and social factors that vary with space and time. The influence of population growth on land-use change has thus been studied at contrasting spatial scales at different points in time (Richards and Flint, 1994). Recently, Matsuoka et al. (1994) have proposed an empirical relationship between human population density and the forest area of South East Asia.

On the other hand, the Chikugo model has been used successfully to study the present NPP distribution on a geographical scale (Seino and Uchijima, 1992) and to assess probable effects of climatic changes on plant production (Uchijima and Seino, 1988; Ohta et al., 1993; Uchijima and Ohta, 1996). However, these calculated NPP values are for the climatic potential under the present and future climates. Therefore, the detailed land use data of East Asia are needed to assess adverse effects of humans on the total net production of terrestrial vegetation in these areas (Ohta et al., 1993).

The objective of this study was to estimate the reduction of plant productivity due to human activity using the Chikugo model and human population data.
2. Models and Data Sets

The following Chikugo model (Uchijima and Seino, 1985; Ohta et al., 1993) was used to calculate the net primary productivity:

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

(1)

where NPP is the net primary productivity (tonne dry matter ha\(^{-1}\) year\(^{-1}\)), RDI (=Rn / lr) is the annual radiative dryness index (>0), Rn is the annual net radiation (kcal cm\(^{-2}\)), r is the annual precipitation (cm), l is the latent heat of water evaporation (kcal g\(^{-1}\)). The total net production (TNP, tonne dry matter year\(^{-1}\); t yr\(^{-1}\)) was simply calculated from:

\[ \text{TNP}_0 = \sum_{i=1}^{n} A_i \overline{\text{NPP}}_i, \]  

(2)

\[ \text{TNP}_a = \sum_{i=1}^{n} \sum_{j=1}^{m} E_{ij} A_{ji} \overline{\text{NPP}}_i, \]  

(3)

where TNP\(_0\) and TNP\(_a\) are the potential and the actual total net production, respectively. \(A_i\) and \(\overline{\text{NPP}}_i\) are the land area (ha) and mean NPP of the \(i\)-th land unit, respectively, and \(E_{ij}\) and \(A_{ji}\) denote, respectively, the production efficiency (0.0-1.0) for the \(j\)-th land use and the land area for \(j\)-th land use in the \(i\)-th land unit. Details of the model and data processing are shown in Ohta et al. (1993).

The climatic data of the Indonesian archipelago were converted into digital form on uniform 1\(^\circ\) latitude by 1\(^\circ\) longitude meshes. The current climate and population data were collected and compiled from: (1) Agroclimatological Data for Asia (FAO, 1987); (2) Climatic Table for the World (JMA, 1994); (3) The Gridded Population of the World (NCGIA, 1995).

Matsuoka et al. (1994) have proposed an empirical relationship between population density (P) and the ratio of forest area (W) of South East Asia:

\[ W = \frac{A_f}{A_0} = \frac{W_0}{P_0} \exp \left( -\left( \frac{P}{P_0} \right)^a \right), \]  

(4)

where \(A_f\) and \(A_0\) denote, respectively, the forest area and total land area. \(W_0\) and \(P_0\) are the ratio of forest area and population density at time 0, respectively, and a is the regression coefficient. Details of this model are shown in Matsuoka et al. (1994).

The main cause of deforestation in the Indonesian archipelago is thought to be the expansion of arable land (\(A_a\)) and residential area (\(A_h\)) in response to an increasing human population. Using this working assumption, we can assume the following relations:

\[ A_0 = A_f + A_a + A_h, \]  

(5)

\[ A_a + A_h = A_0 (1 - W), \]  

(6)

According to Norse et al. (1992) urban and industrial area \(A_h\) can be expressed as follows:

\[ A_h = \alpha P, \]  

(7)

where \(\alpha\) is the area per capita required for urban and industrial development. We assumed that \(\alpha\) was 0.1 ha (Norse et al., 1994). The ratio of forest area (\(A_f / A_0\)), cultivation area (\(A_a / A_0\)), and industrial area (\(A_h / A_0\)) to whole land area can be calculated from Eqs. (4), (5), (6), (7) and population data.
3. Effects of human population on land-use changes

To quantify effects of population density on the rapid deforestation and land-use changes, Eqs.(4) to (7), and human population data were used to calculate the area of the respective land-use categories. The results obtained for the major islands of the Indonesian archipelago are summarized in Table 1. The ratio of the forest area to the whole land area vary from less than 0.25 in Java to Timor islands, through 0.50-0.65 in Sumatra and Sulawesi islands, to above 0.8 in east Kalimantan island, Papua New Guinea and Irian Jaya. The ratio of the arable land to total land area varies from less than 0.1 in Irian Jaya, to above 0.3 in Sumatra and Sulawesi islands. In Java to Timor islands, the ratio of urban and industrialized area is more than 0.5.

Table 1 Potential and actual net production of the major islands of the Indonesian archipelago.

<table>
<thead>
<tr>
<th>Area</th>
<th>Land Area ($\times 10^5$ km$^2$)</th>
<th>Land Use Categories</th>
<th>Net Production ($\times 10^6$ t yr$^{-1}$)</th>
<th>TNP$_0$</th>
<th>TNP$_a$ / TNP$_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sumatra I.</td>
<td>4,424</td>
<td>$A_f / A_e$ 0.545  $A_e / A_e$ 0.374 $A_s / A_e$ 0.081</td>
<td>123 104 0.845</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kalimantan I.</td>
<td>7,341</td>
<td>0.792 0.190 0.019</td>
<td>213 201 0.943</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulawesi I.</td>
<td>1,867</td>
<td>0.626 0.305 0.070</td>
<td>5.5 4.7 0.868</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Java I. – Timor I.</td>
<td>1,880</td>
<td>0.224 0.212 0.564</td>
<td>4.5 1.7 0.361</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maluku Is.</td>
<td>603</td>
<td>0.730 0.241 0.029</td>
<td>1.8 1.7 0.923</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irian Jaya</td>
<td>4,026</td>
<td>0.918 0.078 0.005</td>
<td>11.2 11.0 0.979</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Papua New Guinea</td>
<td>3,998</td>
<td>0.843 0.147 0.009</td>
<td>10.2 9.8 0.961</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mindarao I. – Palawan I.</td>
<td>1,067</td>
<td>0.358 0.432 0.210</td>
<td>2.5 1.8 0.708</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malay Pen.</td>
<td>1,851</td>
<td>0.444 0.423 0.132</td>
<td>5.1 4.0 0.784</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other small islands</td>
<td>177</td>
<td>0.191 0.343 0.466</td>
<td>0.5 0.2 0.481</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>27,287</td>
<td>0.682 0.233 0.085</td>
<td>74.9 65.4 0.874</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. Reduction of relative plant production of the Indonesian archipelago with population density.
4. Effects of land-use changes on plant production

The potential total net production (TNP0) was calculated from Eq. (2), assuming that this region is completely covered in tropical rain forests with higher productivity. The TNP0-value of this region with land area of about 1.96% of the world (14.9 x 10^9 ha) was estimated to be 74.9 x 10^8 t yr^-1, which is about 5.5% of the world terrestrial TNP0 (=1367 x 10^8 t yr^-1) as reported by Seino and Uchijima (1992). This also indicates that this region is one of the most productive areas in the world.

The TNP0 is defined as the area summation of NPP without impacts of human land use. Wider tropical rain forests over the Indonesian archipelago are being deforested and converted into arable lands and/or urban areas. This massive deforestation would cause adverse effects on the plant production, mainly because of the decrease in closed tropical rain forests with higher productivity and the shift of the forest into other vegetation types such as secondary forests. The speed of deforestation of the tropical rain forests over the Indonesian Republic is as high as about 1.3% per year, reflecting rapid industrialization and urbanization (Richards and Flint, 1994). To quantify the effects of the rapid deforestation on the total net production of this country, first the land area type (j) of each i-th land unit was divided into the following three classes,

\[ j = f \ (\text{forest}), \ E = 1.0; \ j = a \ (\text{crop fields}), \ E = 0.8; \ j = h \ (\text{urban and industrialized area}), \ E = 0.0 \]

and Eq.(3) was used to calculate the respective actual net production. The results so obtained indicated that the TNPa would be 65.4 x 10^8 t yr^-1 equivalent to about 87% of the potential one (Table 1). An important conclusion to be drawn from these results is that at present the adverse effects of human land use on plant production would not be very significant unexpectedly in these regions. However, there is a considerable difference between the islands with high population density and with low population density. The percentage of forest area of Java Island is less than 10%, and therefore TNPa of Java to Timor Islands is only 38% of the potential. On the other hand, the forest area of Irian Jaya and Papua New Guinea are more than 80% of the total land area. TNPa in the islands with greater forest cover reaches at 90% of the TNP0. Figure 1 shows the dependence of population density on biomass reduction. The actual plant production decreases drastically with population density above 10^2 capita km^-2.

Acknowledgements

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References