Stand structure and dynamics of a tropical secondary forest – A rural forest in West Sumatra, Indonesia –

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ABSTRACT Human impacts on a tropical rain forest were observed through stand structure and dynamics of a rural forest in Sumatra. Species composition has been successively changing through continuous and biased impact by local people under nearly dynamic equilibrium conditions in tree density and basal area. Soft wood species (broad-leaved trees with low stem hardness) with fast growth-rates tended to increase their dominance under higher human impact. Because of the lower bulk density of their stem wood and lower tree height, the stem biomass in a rural forest stand could be estimated at only a half of that of a mature forest even under the same basal area conditions. Turnover times of basal area in these rural forests were about 15 years and 25 years for open forest stands and closed forest stands, respectively. When we examined the productivity of several rural forest stands in the study area, an optimum curve could be drawn for the relationship between biomass and productivity. We propose a new criterion for the management of secondary forests based on their economical and environmental functions.

Key words: biomass, logging, West Sumatra, productivity, secondary forest, species diversity, stem hardness

Although conservation of tropical forests is one of the most important issues for global and local environments, we do not have enough information about floristic and ecological traits of these forests (Brown and Lugo, 1990; Laumonier, 1997). We focus on an upstream rural forest producing not only various forest products but also fields that have been fruitful to local people for a long period. The conservative management could be characterized by the small-scale, continuous and species-selective activities of the local people (Yoneda, 2000). These forests have been largely being depleted in Indonesia since the end of the Soeharto regime.

Disturbance of secondary forests would be advantageous for short-lived, light-demanding, and fast-growing species as well as for most pioneer species at gap sites in mature forests (Brokaw, 1983). These growth traits affect largely the stand structure. Ogawa (1969) represented the differences of tree forms between a secondary forest and a mature forest in their stem diameter-height allometry. Yoneda et al. (1999) showed that a tropical secondary forest consisted of soft wood species (broad-leaved tree species with low stem hardness) with high stem growth rates and with productivity nearly equivalent to a neighboring mature forest. We should, however, evaluate the productivity of secondary forests by considering their regeneration stage (Kira & Shidei, 1967). These properties of a secondary forest will be affected by various factors such as management, climate, and soil.

This study aims to evaluate human impact on flora, biomass and productivity of a tropical rain forest through a rural forest under traditional and recent management by the Minangkabau people in West Sumatra, and to propose the idea of sustainable forest management based on biological productivity and environmental functions. We assessed the intensity of human impact

INTRODUCTION

Brown et al. (1989) estimated that disturbed, broad-leaved forest in the tropics was equivalent to 30 % in area and 20 % in stem biomass of the primary or old secondary forest. These forests, however, face deforestation owing to the increase of human impact (FAO, 2001).
on a rural forest by tree densities and distance from a village, though their activities such as logging, collection of non-woody products and clearing are very diverse. Species composition and biomass are major properties of stand structure in this study, and their recent dynamics could be assessed by continuous observation. We try to clarify human impact on a secondary forest through a comparison of these attributes in forest stands with different intensities of human disturbance including a mature forest. Adaptive growth traits of secondary species and sound management of secondary forests are major items to be discussed in this paper.

MATERIALS AND METHODS

Study site
This study was conducted in the rural forest of Sipisang Village (00° 34’ S, 100° 21’ E) located 50 km north from Padang City, West Sumatra (Yoneda, 2000). Annual rainfall was estimated to be an average of over 2000 mm, with no dry season. Five belt-transects 10 m wide were established in Sipisang territory in January 1995 (Fig. 1). They are designated ALT, BLT, CLT, DLT and ELT and range from 150 m to 325 m in altitude (Table 1). Base lines of these transects were measured, and the position of every target tree was coordinated with these base lines. Target trees were every tree over 15 cm in stem diameter at breast height, dbh, except a distant zone of ALT being over 20 cm dbh. A transect on a main ridge, ALT, was extended up to 1190 m in altitude during the two years of 2001 and 2002 for a census of big trees over 50 cm dbh. The total horizontal length of these transects was 6741 m. Two study plots were established on the main ridge in 1995 and 2001. They were named Kandis plot (KAN) and Angkang plot (ANK) after the local names of the sites. The areas were 0.75 ha and 1.0 ha, respectively.

Tree census
A tree census along these belt-transects was repeated six times at ALT and four times along the other four transects during 7.7 years ending in September 2002, and repeated twice at extended ALT. The dbh of every target tree was measured at each census, and new target trees were registered at each observation. A census at each of the two plots was conducted seven times at KAN during 7.1 years and twice at ANK during 0.9 year. Tree height was measured for all trees at KAN in 1995 and for 51 trees with various dbh at ANK in 2001. Stem hardness was assessed as the maximum power for pulling out a nail (JISA 5508, 65 mm length, 3.05 mm diameter) driven in 60 mm deep (Yoneda, 1997). The total number of trees observed for stem hardness was 422 trees over 10 cm dbh at KAN and 214 trees over 20 cm dbh at ANK.

Fig. 1. Map of study sites in Sipisang, Padang Pariaman District, West Sumatra. Thick lines show the observed belt-transects in a rural forest, and a thin line is an extended belt-transect for ALT up to 1190 m in altitude. Figures beside the thick lines show the five belt-transects of Table 1. The two closed circles show study plots KAN and ANK. Contour lines are indicated at 250 m intervals.
Table 1. General descriptions of the 5 belt-transects and 2 study plots.

<table>
<thead>
<tr>
<th>Abbreviation Transect or plot</th>
<th>Position in Fig. 1</th>
<th>Horizontal length (m)</th>
<th>Altitude (m)</th>
<th>Target trees (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALT</td>
<td>①</td>
<td>2013</td>
<td>150-325</td>
<td>D &gt; 15, D &gt; 20*</td>
</tr>
<tr>
<td>Extended ALT</td>
<td>①</td>
<td>3501</td>
<td>325-1190</td>
<td>D &gt; 50</td>
</tr>
<tr>
<td>BLT</td>
<td>②</td>
<td>386</td>
<td>162-234</td>
<td>D &gt; 15</td>
</tr>
<tr>
<td>CLT</td>
<td>③</td>
<td>348</td>
<td>184-263</td>
<td>D &gt; 15</td>
</tr>
<tr>
<td>DLT</td>
<td>④</td>
<td>172</td>
<td>160-230</td>
<td>D &gt; 15</td>
</tr>
<tr>
<td>ELT</td>
<td>⑤</td>
<td>321</td>
<td>160-267</td>
<td>D &gt; 15</td>
</tr>
<tr>
<td>KAN</td>
<td>KAN</td>
<td>0.75**</td>
<td>245-275</td>
<td>D &gt; 8</td>
</tr>
<tr>
<td>ANK</td>
<td>ANK</td>
<td>1.00**</td>
<td>600-650</td>
<td>D &gt; 8</td>
</tr>
</tbody>
</table>

*: trees in a zone over 1300 m in horizontal distance from the starting point of this study (cf. Fig. 2). **: area in ha. D: dbh in cm.

Definition of increment rates, death rates and productivity
Let’s define the stand biomass at time \( t \), as \( Y_t = B_t + D' \) and the biomass at a later time \( t' \), as \( Y_{t'} = B_{t'} + N' \), for which \( B_t \) and \( B_{t'} \) are the biomasses at \( t \) and \( t' \), respectively for all registered living trees throughout the period. \( D' \) and \( N' \) are the biomasses at \( t \) and \( t' \) for all died trees and all newcomers during the period, respectively. Then we can express the annual increment rates, death rates and productivity of a forest stand by the following equations. Death rate here is defined as a value caused by death of a tree individual excluding fine litter-fall rates.

\[
\text{Increment rate} \ (I) = \frac{(B_t - B_{t'})}{(t_{t'} - t_t)},
\]

\[
\text{Death rate} \ (D) = D_t\]

\[
\text{Productivity} \ (P) = \frac{(Y_t - Y_{t'})}{(t_{t'} - t_t)} + D - \frac{(B_{t'} + N')}{(t_{t'} - t_t)} - \frac{(B_t + D')}{(t_{t'} - t_t)} + D \\
= \frac{(B_t - B_{t'})}{(t_{t'} - t_t)} + \frac{N'}{(t_{t'} - t_t)} - D'/t_{t'} + D \\
= \frac{I + N'}{t_{t'}} + I + N',
\]

of which \( D \) and \( N \) are annual values of \( D' \) and \( N' \), respectively.

Tree species identification
The percentage of trees identified at genus level was 67 at five transects without extended ALT, 93 at KAN and 12 at ANK in tree number. Specimens are held in the Herbariums of Osaka Museum of Nature History, Andalas University and Kagoshima University.

RESULTS

Definition and stand structure of a rural forest
We try to examine logging impact on stand structure in this forest area. Figure 2-A shows the horizontal distribution pattern of tree density for big trees over 50 cm dbh along the ridge route, ALT. The tree density increased with increase in distance from the village. This resulted mainly from higher logging activities in a forest nearer to the village, although logged stumps could be observed throughout the whole range under 900 m in altitude. Reduction at around 4000 m was derived from local land-sliding. The average tree density at a zone over 3500 m, a mature forest zone, was ca. 50 ha⁻¹. The tree density largely changed within a zone between 1750 m and 3500 m. Based on this distribution pattern we defined the rural forest to be a neighboring forest within 1750 m in distance, 300 m in altitude, having suffered intensive logging by local people in this area. The remaining big tree density in this zone was less than 20 ha⁻¹.

Horizontal distribution patterns of tree density of smaller trees along ALT clearly showed two zones with different densities in the rural forest (Fig. 2-B). Namely the density within 500 m was apparently lower than a zone over 750 m in distance having nearly equivalent density to one in the mature forest zone. We could detect similar differences in the density of big trees over 50 cm dbh between these two zones (Fig. 2-A). Then, for convenience, we classified the rural forest into two types; an open forest type with lower density and a closed forest with higher density. We could observe small grass patches in the open forest zone at the beginning of this study in 1995, and the deforestation for fields tended to accelerate in this zone, particularly during the last several years. The closed forest has, on the whole, kept its forest conditions, though selective logging has been conducted for the remaining big trees.

Four other belt-transects could be classified by their tree densities into the above two types. Two transects of BLT and CLT were open forest types, and those of the DLT and ELT were closed forest types (Table 2). The tree density at KAN was nearly equivalent to the average value in the closed forest zone. At the beginning of this
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study the open forest showed an average tree density and basal area of trees over 20 cm dbh to be 71 ha⁻¹ and 8.3 m² ha⁻¹ respectively. These values were equivalent to 38 % and 46 % of the values of the closed forest (Table 2).

Table 3 shows family compositions of the open and closed forests. Fagaceae, Moraceae, Sapotaceae, Euphorbiaceae and Myristicaceae were dominant families in both forest types at the accuracy within the composition of identified species. These families consist of few genera. Most of species of these families except Fagaceae were typical of a secondary forest, and Euphorbiaceae and Moraceae, including many pioneer species, were highly dominant in tree numbers in the open forest. The high dominance of Fagaceae resulted
from its vigorous growth rate and lower logging impact because of its low timber quality. Family composition at KAN was nearly the same as that of the closed forest, though a few emergent trees of *Koompasia mallacensis* and *Shorea retinodes* remained in the plot.

Species composition at KAN was largely different from a plot at ANK in a mature forest zone of ALT, where species identification has not yet been completed. Let’s compare stem hardness of trees between these two plots since this is a growth trait parameter of each tree (Yoneda et al., 1999). The average stem hardness of trees over 20 cm *dbh* was 51 ± 16 kg f cm\(^{-1}\) (average ± SD, N = 118) at KAN. This value was only a half of 96 ± 29 kg f cm\(^{-1}\) at ANK. These results show that the rural forest shifted to a guild of soft wood trees in its species composition.

The relationships between *dbh* and tree height, *H*, can be approximated by the following extended allometry (Ogawa, 1969) for both the KAN and ANK plots.

\[
\frac{1}{H} = \frac{1}{a \cdot \text{dbh}^h} + \frac{1}{H^*}
\]

where *h* is an allometry coefficient. Two parameters, *a* and *H*\(^*\), were determined by the least square method under the conditions where *h* = 1 (P < 0.001). Ogawa (1980) proposed that these two parameters of *a* and *H*\(^*\) had positive correlation with the biomass concentration per space and the potential canopy height of a forest, respectively. The Kandis plot was higher in *a* and lower in *H*\(^*\) in comparison with the values at ANK (Fig. 3-A). The parameters of the two plots indicate small trees under 17 cm *dbh* at KAN to be higher than at ANK. This shows that the tree height at KAN tends to be higher at smaller sizes in *dbh* than at ANK. When we examined this *dbh*–*H* relationship for major families at KAN, families with many soft wood species tended to be higher in parameter *a* than the families with hard wood species (broad-leaved trees with high stem hardness) (Fig. 3-B). Figure 3 shows that one regressed curve can satisfy these reciprocal relationships between *a* and *H*\(^*\) not only for the total trees of each plot but also the major families in some secondary and primary forests in this area.

**Stand dynamics during the last seven years**

The basal area of the open forest stand showed little change during the whole observation period of 7.7 years, though the tree density increased by a factor 1.2 (Table 2). We could, however, observe high productivity and high death rates of trees in the basal area during the period. Logging caused eighty-three percent of the total death rate. Namely this dynamic equilibrium condition in the basal areas was produced by the balance between the high natural increment rates and the highly human-effected death rates in the open forest. The average turnover time as a ratio of average existing basal area to the average value of annual production and death rates was estimated at 15 years.

The closed forest stands increased both their basal

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**Fig. 3.** A: The relationships between *a* and *H*\(^*\) of Eq. (1) at secondary (\(\bigcirc\): KAN, SCF) and primary (\(\bigcirc\): ANK, PIN) forest stands in study this area. For abbreviations of SCF and PIN refer to Table 7. B: The relationships with parameters obtained from major families in these stands. Triangles, closed circles and crosses show parameters for soft and hard wood families at KAN, and for major families of PIN, respectively. Curves in a diagram show the relationships of *a*\(H^*\) = constant.
Changes of family composition in the open and closed forest stands in a rural forest during 7.7 years. Symbols are the same as those in Table 2. 500, 1750, BLT, CLT, DLT and ELT show zones of an observed belt-transect (see Text).

Table 4. Comparison of logging impact on tree density and basal area for major families in a rural forest. Impact of each family is evaluated as a ratio of the percentage of logged trees to total trees in the basal area. Table 1 shows that Fagaceae, Sapotaceae, Apocynaceae and Thymelaceae suffered above average impact, and

Table 3. Changes of family composition in the open and closed forest stands in a rural forest during 7.7 years. Symbols are the same as those in Table 2. 500, 1750, BLT, CLT, DLT and ELT show zones of an observed belt-transect (see Text).

Death rates were somewhat lower than the increment rates because of the lower impact of logging. This is the major reason for the differences between the open and closed forest stands. The turnover time of basal area was 25 years, when we could assume, as a first approximation, dynamic equilibrium conditions.

Changes of tree density and basal area during the period were different among families of each forest type (Table 3). In particular Fagaceae tended to decrease in basal area, while Moraceae and Euphorbiaceae both increased in tree density and basal area. These changes in each family could be examined with their growth traits and logging impact. Let’s try to assess the logging impact on the death rates of trees above 30 cm dbh in the rural forest. Died trees accounted for 28 % of the total number of monitored trees in 7.7 years, with the logged ones accounted for 61 % of the total number of died trees. Logged trees accounted for 17 % of the total tree number and for 22 % in total basal area (Table 4). We evaluated the logging impact on each family with a relative ratio of logged trees to total trees in the basal area. Table 4 shows that Fagaceae, Sapotaceae, Apocynaceae and Thymelaceae suffered above average impact, and

area and tree density by a factor 1.2 during the period.
Moraceae and Euphorbiaceae showed clearly lower impact. All Thymelaceae were *Aquilaria malaccensis* being logged for amber collection. These results show that the species composition of a rural forest changes successively through the continuous and biased impact of local people even under dynamic equilibrium conditions of tree density and basal area.

We examined the influences of stem hardness on the relative growth rates of dbh, RGRD, over 7.1 years using 379 trees over 10 cm dbh at KAN (Table 5). Stem hardness showed significant negative correlation with RGRD, particularly at smaller dbh sizes. When we calculate the average values of stem hardness and RGRD of each major family regardless of dbh sizes, a similar negative correlation ($R^2 = 0.210$, $N = 29$, $P = 0.025$) can be detected in their relationships. That is, families with soft wood species tended, on average, to have higher $RGRD$.

**DISCUSSION**

**Growth traits of tropical secondary forest species**

Trees with lower stem hardness showed higher dbh growth rates, particularly for small trees (Table 5). Stem hardness as a physical characteristic is proportional to the bulk density of stem wood (Yoneda, 1997; Yoneda *et al.*, 1999). Softer wood trees can take higher growth rates in diameter by investing organic matter in their stem volume over stem hardness correlating to architectural strength, though the anatomical structure of wood as arrangement of vessels would affect these relationships. This is an advantageous strategy for trees under unstable conditions to allow them to overcome competition for light resources at early stages of the regeneration process. This would be one of the major reasons for large differences in stem hardness between rural and mature forests. The trade-off between growth rates in stem volume and strength of stem wood could be detected among families in the closed forest. This could well explain the higher dominance of the family with lower stem hardness in the open forest under higher disturbance (Yoneda, 2000).

A negative correlation could be observed in the relationships between two parameters of the dbh–$H$ regression, $a$ and $H^*$ of Eq. (1), in both the mature and rural closed forests (Fig. 3). The relationship can be approximated by one empirical formula $aH^* = \text{constant}$ showing the constant aboveground biomass among them (Ogawa, 1980). These parameters for families including many climax species in the rural closed forest could also satisfy the formula as well as most of the families in the mature forest in this area (Fig. 3). Families with many secondary species in the rural closed forest tended to be higher in $a$ and lower in $H^*$ than major families in the mature forest, and to have a negative correlation between the parameter $a$ and average stem hardness of each family though not significantly stochastically ($R^2 = 0.200$, $N = 9$, $P = 0.221$). These results suggest that secondary species are more slender than climax species at their small-size stages and the slenderness is higher for species with lower stem hardness. This allometric trait could achieve the fast height growth of soft wood species as well as their higher growth rate of dbh at small stages. However, how does a soft wood species physically sustain the slender stem with higher tree height over hard wood species at their small-size stages? A tree form would be a considerable factor for effective growth in tree height. A monopodial tree form, for an example, could gain the trait by investing most of its organic matter into the stem without big branch systems. When soft wood species achieve higher advantages in the competition for light resources, they could change their major investment from stems and branches to reproductive organs at lower tree-height conditions than hard wood species. This would be a growth strategy for a tree species with precocity in a secondary forest.

**Evaluation of biomass and productivity of a tropical secondary forest**

We try to evaluate biomass and productivity of a rural forest in comparison with a mature forest. When we apply the allometric regression for a lowland tropical

<table>
<thead>
<tr>
<th>dbh class (cm)</th>
<th>Tree number</th>
<th>Coefficient of correlation</th>
<th>Significance level</th>
</tr>
</thead>
<tbody>
<tr>
<td>10–15</td>
<td>136</td>
<td>-0.264</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>15–20</td>
<td>95</td>
<td>-0.305</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>20–30</td>
<td>65</td>
<td>-0.129</td>
<td>0.5</td>
</tr>
<tr>
<td>over 30</td>
<td>57</td>
<td>-0.201</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Table 6. Comparison of biomass between the closed rural forest of Kandis plot, KAN, and the mature forest of Angkang plot, ANK, with four dimensions at the first census of each plot. BA, Hd and Ys are basal area, stem hardness and stem biomass with allometric regression, respectively. Hd dbh’H is a measure for biomass calculated from the product of dbh’H and Hd of each tree.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>BA (m$^2$ ha$^{-1}$)</th>
<th>dbh’H (m$^2$ ha$^{-1}$)</th>
<th>Ys (Mg ha$^{-1}$)</th>
<th>Hd dbh’H (kg m$^2$ ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAN</td>
<td>24</td>
<td>595</td>
<td>150</td>
<td>403</td>
</tr>
<tr>
<td>ANK</td>
<td>46</td>
<td>1730</td>
<td>424</td>
<td>1571</td>
</tr>
<tr>
<td>KAN / ANK ratio (A)</td>
<td>0.52</td>
<td>0.34</td>
<td>0.35</td>
<td>0.26</td>
</tr>
<tr>
<td>Relative value of A</td>
<td>1</td>
<td>0.66</td>
<td>0.67</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Table 7. Stem biomass and productivity of secondary and mature forest stands in the study area. B, I, N, P, D and G are the average values for stem organs during the observation period. For details of sites refer to the text.

<table>
<thead>
<tr>
<th>Site</th>
<th>Altitude (m)</th>
<th>Observation period (year)</th>
<th>Area (ha)</th>
<th>Biomass B (Mg ha$^{-1}$)</th>
<th>Increment I (Mg ha$^{-1}$ y$^{-1}$)</th>
<th>Newcomer N (Mg ha$^{-1}$ y$^{-1}$)</th>
<th>Productivity P = I + N (Mg ha$^{-1}$ y$^{-1}$)</th>
<th>Death D (Mg ha$^{-1}$ y$^{-1}$)</th>
<th>Growth G = P – D (Mg ha$^{-1}$ y$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open*</td>
<td>200</td>
<td>7.71</td>
<td>1.23</td>
<td>51</td>
<td>1.9</td>
<td>1.3</td>
<td>3.2</td>
<td>4.0</td>
<td>-0.8</td>
</tr>
<tr>
<td>PBA**</td>
<td>480</td>
<td>12.1</td>
<td>0.09</td>
<td>65</td>
<td>8.1</td>
<td>0.7</td>
<td>8.8</td>
<td>3.6</td>
<td>5.2</td>
</tr>
<tr>
<td>SCF***</td>
<td>400</td>
<td>7.85</td>
<td>0.23</td>
<td>110</td>
<td>6.5</td>
<td>0.5</td>
<td>7.0</td>
<td>3.9</td>
<td>3.1</td>
</tr>
<tr>
<td>KAN*</td>
<td>270</td>
<td>7.08</td>
<td>0.75</td>
<td>121</td>
<td>5.7</td>
<td>1.1</td>
<td>6.8</td>
<td>3.2</td>
<td>3.6</td>
</tr>
<tr>
<td>PATc**</td>
<td>470</td>
<td>12.1</td>
<td>0.30</td>
<td>182</td>
<td>10.7</td>
<td>1.0</td>
<td>11.7</td>
<td>17.9</td>
<td>-6.2</td>
</tr>
<tr>
<td>PIN**</td>
<td>500</td>
<td>7.88</td>
<td>1.00</td>
<td>351</td>
<td>7.9</td>
<td>1.0</td>
<td>9.0</td>
<td>8.0</td>
<td>1.0</td>
</tr>
<tr>
<td>ANK*</td>
<td>650</td>
<td>0.86</td>
<td>1.02</td>
<td>496</td>
<td>8.0</td>
<td>0.4</td>
<td>8.5</td>
<td>1.1</td>
<td>7.3</td>
</tr>
</tbody>
</table>

*: this study. **: Yoneda et al. (1999). ***: SCF is a closed rural forest stand in the school forest of Andalas University (unpublished).

Rain forest at Pasoh in Malaysia (Kato et al., 1978), the stem biomass of KAN is around one third of that of ANK (Table 6). Even if we use the regression for a warm-temperate secondary evergreen oak forest in Japan (Nagano & Kirigawa, 1980) to KAN, the ratio is different from the former one. This ratio is nearly equivalent to the ratio of dbh’H because the relative growth coefficient of allometry (m: stem weight $\sim b (dbh’H)^a$) is nearly equal to m = 1 for both regressions. When however we consider the large differences in stem hardness between these two plots, stem biomass of KAN would be an overestimation against ANK consisting of relatively harder wood species. Stem hardness by the method in this study was approximately in direct proportion to the bulk density of stem wood of trees in an evergreen oak forest in Japan (Nakajima, 1998). When we evaluate the stem weight of a tree as the production of dbh’H multiplied by the observed stem hardness at each plot, the biomass of KAN decreases down to one fourth of ANK. This shows that stem biomass in the closed rural forest is only half of that of the mature forest even under the same basal area conditions (Table 6).

The average stem biomass of KAN during the study period is estimated to be 121 Mg ha$^{-1}$ with correction for their hardness (Table 7). This value corresponds to one fourth of ANK and one third of PIN being mature forests in this area, though the two parameters a and H$^*$ of these three forests satisfy the empirical equation by Ogawa (1980: Fig. 3-A) showing the same aboveground biomass. The stem biomass in another rural forest near Padang City, SCF, was estimated at 110 Mg ha$^{-1}$ with the same average stem hardness as KAN (Table 7), and the two parameters of Eq. (1) at SCF also satisfy the empirical regression irrespective of having a lower biomass than mature forests. This suggests that the empirical equation in our study might be caused by some biological factor other than the constant aboveground biomass.

Table 7 shows the average stem productivities of some secondary and mature forest stands in this area. The open forest consists of a 0-500 m zone in ALT, BLT and CLT in this study. SCF is a closed rural forest stand in the school forest of Andalas University. Two small stands of PBA and PATc are secondary forest stands after clear cutting (Yoneda et al., 1999). Stem biomass and productivity at these four stands were calculated by the same procedure as for KAN using the average stem...
hardness at KAN. Their productivity tended to increase with increase of biomass, though the differences of productivity between PBA and PATc were largely affected by different soil conditions instead of stand biomass (Yoneda et al., 1999). When we consider dimensionally the productivity of two mature forest stands of PIN and ANK as a sequential one in the regeneration process, the biomass-productivity relationship tends to follow an optimum curve (Fig. 4). Similar optimum relationships between total aboveground biomass and productivity have been represented in sub-arctic fir forests in Japan (Sato, 1963; Tadaki et al., 1970). The natural death rates of these secondary forests increased with increase in stem biomass. A small stand of PATc drastically degraded its biomass within the last few years of observation because of a mass death of canopy trees, after which death rates

Fig. 4. The relationships between stem biomass and productivity (circles) or natural death rates excluding logging (triangles) of stems in secondary and mature forest stands in the study area (see Table 7). The two solid curves in a diagram show model time-trends of productivity and death rate, with the shaded area being the net increment in stem biomass. The two broken curves show relationships for the simulation of Fig. 5.

Fig. 5. Time trends of E-Index, average growth rates and biomass on the regeneration process after clear cutting under the conditions of $c = 1$ of Eq. (2), $\lambda = 0.06 \, \text{yr}^{-1}$ and $k = 99$ of Eq. (3). $B(t)$, $E(t)$ and $G(t)$ are biomass, E-Index and average growth rate, respectively. For details, refer to the text. $TE_{\text{max}}$ and $TG_{\text{max}}$ are the times showing the maximum value for E-Index and average growth rate, respectively.
Table 8. Comparison between properties of the E-Index at $TE_{\text{max}}$ and $TG_{\text{max}}$. Ratio of the properties at $TE_{\text{max}}$ and $TG_{\text{max}}$ is shown for different conditions of parameter $c$, relative importance of biomass against growth rate. $TE_{\text{max}}$ was determined by numerical calculation from Eqs. (2) and (3) at $k = 99$. These ratios tend to be constant irrespective of $\lambda$ value of Eq. (3).

<table>
<thead>
<tr>
<th>Properties</th>
<th>$c = 0$</th>
<th>$c = 1$</th>
<th>$c = 2$</th>
<th>$c = 10$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting age, $TE_{\text{max}}/TG_{\text{max}}$</td>
<td>1</td>
<td>1.14</td>
<td>1.24</td>
<td>1.50</td>
</tr>
<tr>
<td>Biomass, $B(TE_{\text{max}})/B(TG_{\text{max}})$</td>
<td>1</td>
<td>1.10</td>
<td>1.14</td>
<td>1.18</td>
</tr>
<tr>
<td>Growth rate, $G(TE_{\text{max}})/G(TG_{\text{max}})$</td>
<td>1</td>
<td>0.97</td>
<td>0.92</td>
<td>0.79</td>
</tr>
<tr>
<td>Average biomass, $\frac{\int_{T_{\text{max}}} B(t) dt}{TE_{\text{max}}} / \frac{\int_{T_{\text{max}}} B(t) dt}{TG_{\text{max}}}$</td>
<td>1</td>
<td>1.23</td>
<td>1.36</td>
<td>1.67</td>
</tr>
</tbody>
</table>

exceeded growth rates (Yoneda et al., 1999). There is not enough information to evaluate this phenomenon as a general performance in the regeneration process, however. When we consider that the natural death rates of a secondary forest could be assumed to be hyperbolic with an asymptote being the net production of a mature forest, these data suggest that the growth process of the stem biomass in the regeneration process could be approximated by a logistic equation (Figs. 4 and 5: Shinozaki, 1961).

From the viewpoint of the management of secondary forests after clear cutting, we try to examine the considerable time for logging based on its time trends in carbon budget. An average growth rate of biomass, $G(0)$, during $t$ years after clear cutting is $G(0) = B(0)/t$, of which $B(t)$ is the biomass at time $t$. High average growth rates would be expected not only economically for timber production but also environmentally as a carbon sink for carbon dioxide in the atmosphere. The cutting age is usually determined at a time that maximizes $G(t)$, $TG_{\text{max}}$, being named in forestry as the Rotation of Maximum Volume Production (Evans, 1992). From another evaluation of the secondary forest as a carbon reservoir, large biomass would be expected. When we evaluate a secondary forest with these two functions of $G(t)$ and $B(t)$, the sum of these two could be another criterion for evaluating a secondary forest. We assess the standard by

$$E(t) = G(t)/G_{\text{max}} + c \times B(t)/B_{\text{max}},$$

(2)

of which $G_{\text{max}}$ and $B_{\text{max}}$ are the maximum values of $G(t)$ and $B(t)$ respectively through the whole process of regeneration. $E(t)$ is an integrated parameter of economic and environmental functions of a secondary forest named the E-Index. The constant $c$ is a parameter showing the relative importance of biomass against growth rates. The condition of $c = 1$ means that evaluation of the biomass is more-or-less equivalent to average growth rate.

When we assume the following logistic equation for the growth process of stem biomass, time trends of $E(t)$ show optimum curves except infinity for $c$ (Fig. 5).

$$B(t) = B_{\text{max}} / (1 + k \exp(-\lambda \ t))$$

(3)

where $\lambda$ is the growth coefficient and $k$ is a constant for the initial biomass. $k = B_{\text{max}} / B(0) - 1$. The time at which $E(t)$ is maximized, $TE_{\text{max}}$, would be the proper time for logging, under the conditions for each $c$ value depending on each purpose for forest management.

When we evaluate the function of a secondary forest as a carbon reservoir to be equivalent to the function of a carbon sink being satisfied with $c = 1$ by the numerical calculation, an extension of the logging interval by 14% ($TE_{\text{max}}/TG_{\text{max}} = 1.14$) could achieve the increase of biomass by 10% ($B(TE_{\text{max}})/B(TG_{\text{max}}) = 1.10$) at the cost of decrease of growth rate by 3% ($G(TE_{\text{max}})/G(TG_{\text{max}}) = 0.97$) irrespective of $\lambda$ at $k = 99$ (Table 8). The function of carbon reservoir evaluated by the average biomass during the interval could increase by 23% ($\int_{T_{\text{max}}} B(t) dt / T_{\text{max}} / \int_{T_{\text{max}}} B(t) dt / T_{\text{max}} = 1.23$, Table 8). The extension up to 1.5 times $TG_{\text{max}}$ at $c = 10$ could achieve the increase of biomass and average biomass by 18% and 67% at the cost of the decrease of growth rate by 21%, respectively (Table 8). Average biomass during the logging interval might be a more important parameter over biomass not only as a carbon reservoir but also for various environmental functions such as conservation of water and soils. This analysis shows that a shorter extension of logging interval could produce higher rate of increase of the average biomass at the cost of the lower rate of growth rate. An evaluation with this E-Index could be a new criterion for the management of both natural and artificial forests. This would be also available for the management of tree plantations under the Clean Development Mechanisms (CDM-R) in the Kyoto Protocol 1997.

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