A modeling approach to sustainable forest management: "Virtual Forest" predicts forest growth and canopy structure

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Abstract

A modeling approach is essential for quantifying the heterogeneity and complexity of forest composition and dynamics, both spatially and temporally. Simulation models also facilitate the development of guidelines for forest management. To aid in the introduction of indigenous trees on degraded land after the establishment of fast growing tree plantations, we developed models to quantify thinning effects on the growth of canopy trees (*Acacia mangium*) and understory trees (*Hopea odorata, H. ferrea, Xylia xylocarpa* var. *kerrii*) in two-storied plantation forests at the Sakaerat Silvicultural Research Station, Thailand. These models were validated partly using data collected during the monitoring of the 23-year-old *Acacia mangium* plantation. By employing these models, adequate forest management plans can be selected heuristically, prior to any activity. The models were as follows.

(1) A model to simulate the growth of canopy trees in response to thinning practices; this can predict biomass growth and structural development of forests. This model is applicable to plantation forests containing fast growing species.
(2) "Virtual Forest" to evaluate the light environment under the forest canopy. This is a graphical technique, creating a computer generated virtual forest with various tree sizes and structures. The light environment in the study plots was successfully modeled by "Virtual Forest", and validated using hemispherical photographs taken in the plots.
(3) A model to estimate the growth of understory trees. The height growth of understory trees depends mainly on the light environment under the forest canopy, particularly in darker conditions. Adopting a logistic growth curve, height growth patterns of understory trees were effectively modeled, demonstrating seasonal step-wise growth.

Keywords: canopy gap, hemispherical photography, stand structure, thinning, undergrowth

Introduction

A large area of exotic, fast-growing tree species has been established across Southeast Asia over the last half century, and much effort has been put into planting indigenous trees under this forest canopy (Montagnini & Jordan 2005; Sakai et al. 2009). The main fast-growing, short-rotation species used in plantations are in the genera *Eucalyptus* and *Acacia*, and to a lesser extent, *Gmelina* (Montagnini and Jordan 2005). This "two-storied forest management" is expected to provide suitable light conditions for indigenous tree seedlings by shading them in their initial stage of growth (Fujimori 2001).

In Thailand, an experimental two-storied forest plantation was established in 1987 in a Re-afforestation Project initiated by the Japan International Cooperation Agency (JICA) and the Royal Forest Department of Thailand. It was then necessary to develop effective management techniques, to evaluate thinning effects on the growth of canopy trees and to control the light environment so as to promote the growth of understory trees of indigenous species. The objective of the study described herein was to develop several modeling approaches: (1) to simulate the light environment in relation to forest canopy structure; (2) to quantify the growth response of seedlings of indigenous tree species to light conditions on the forest floor; and (3) to predict stand growth with respect to various thinning regimes in a plantation forest.

Material and Methods

1. Study site

The models were developed in order to simulate tree growth and the light environment on the forest floor in a two-storied plantation forest at the Sakaerat Silvicultural Research Station (14°30'19"N, 101°53'28"E, 630m a.s.l.), Nakhon Ratchasima Province, northeast Thailand.

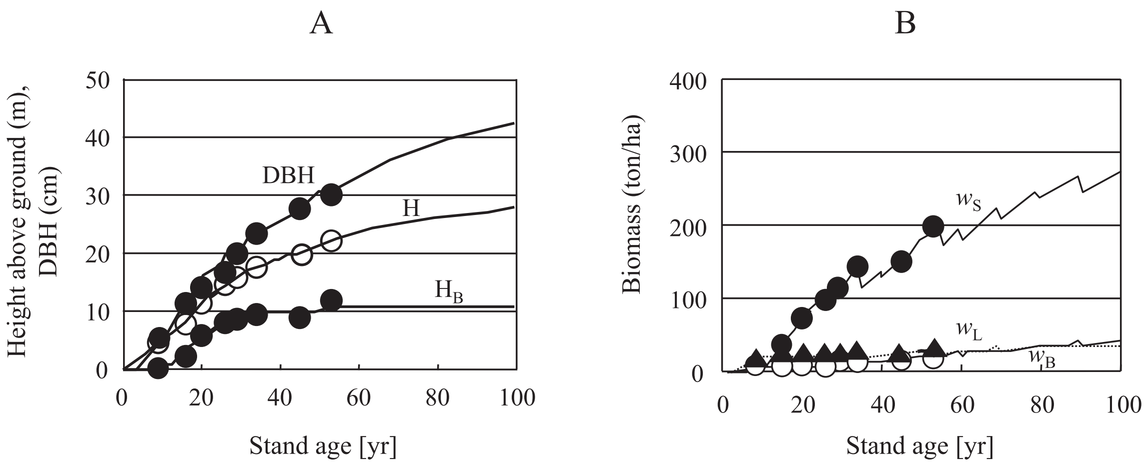

Fig. 1. Simulation of tree size development and biomass growth with different thinning regimes.
A: tree size (D, H, H_B); B: biomass growth of tree organs.
w_S: stem weight; w_L: foliage weight; w_B: branch weight

According to the records for the past 10 years from the nearby meteorological station, the annual mean air temperature and precipitation are 25.6°C and 1,395mm, respectively. This area experiences a monsoon climate with a dry season lasting roughly 4 months, from November to February. The study site is described in detail by Sakai et al. (2011).

This area was covered with dry evergreen forest until the 1950s (Kamo et al. 2002). Most of the forest area was converted to farmland in the 1950s and farmed for a couple of decades, and subsequently abandoned to become covered with tall grass species such as *Imperata cylindrical* and *Saccharum spontaneum*. In 1994, the Re-afforestation Project was initiated by the Japan International Corporation Agency (JICA) and the Royal Forest Department, Thailand (RFD), in order to re-afforest an area of 2,500 ha using exotic fast-growing tree species (Kamo et al. 2002).

2. Experimental design of the study plots and the data used

The details the study plot design are given in Sakai et al. (2011). In 2007, the study plots were established in a 23-year-old plantation forest of *Acacia mangium*, at a spacing of 2m by 3m. The ranges of mean tree heights and DBHs in each plot were 25.2-28.7m, and 21.5-25.9cm, respectively.

In late June 2007, three indigenous tree species (*Hopea odorata* Roxb., *Hopea ferrea* Lanessan and *Xylia xylocarpa* (Roxb.) Taubert var. *kerrii* (Craib & Hutch.)) were planted under the canopy trees at a spacing of 2m by 3m. In order to examine the growth response of the understory trees to the light environment, nine quadrates (18 m by 24 m) under the canopy and one and a canopy gap (50m by 60m) of canopy gap plot that was clear-felled were set up in the *Acacia mangium* plantation in June 2007. In the nine quadrats, the canopy trees were randomly thinned to create four different light environments: i.e. none, one-third or two-thirds of live trees were thinned randomly, and, in addition, there was one canopy gap plot.

The data used to analyze and validate the models were: the understory tree sizes (stem diameter at 30 cm above the ground (D30) and height (H)) and the sky factor (Inoue 1996; Yamamoto 2003), a measure of the light environment under the forest canopy. The sky factor was determined by means of hemispherical photographs.

Results and Discussion

1. Model of canopy tree growth in response to thinning

After the forest canopy has closed in a plantation, tree crowns will retreat upwards from the base of the crown. Provided that an almost constant stand density (number of trees per ha) remains after canopy closure, the mean crown length will stay almost constant so that the height at the crown base increases along with the tree height. However, once the canopy is opened as a result of thinning, the height at the crown base H_B will stay as it is until the canopy closes again. After the canopy closes again, the height of the crown base may move upwards with tree height. Hence, crown length will increase stepwise in association with every thinning operation (Chiba 2006).

The plantation forest growth model was developed on the basis of such processes of crown development in relation to thinning treatments. (Chiba 1990b; Chiba 2006). For typical thinning regimes in plantation forests, tree sizes (averages of tree height H, diameter at breast height D, height at the crown base H_B, crown length CL) in a stand can be predicted by the model (Fig. 1). At the initial planting stage, H_B is almost zero because the canopy has not closed yet. H_B then starts to increase at a stand age of about 10 years when the canopy closes. Subsequently, the crown length ($CL = H - H_B$) shows a gradual increase with repeated thinning treatments over the course of stand development. As shown in Fig. 1A, there was good correspondence between the simulated results and real data for Japanese cedar (sugi: *Cryptomeria japonica*) plantations. By employing a stem form model (Chiba 1990 a), *D* can also be determined for each stand age. Of course, plantations of fast growing trees exhibit much faster canopy closure than sugi plantations. However, since the development of stands subjected to thinning, with respect to tree size, crown structure and canopy closure, is likely to proceed in the same way irrespective of growth rate, it should be possible to apply this model to *Acacia mangium* plantations.

Mean crown length *CL* in a plantation forest can be approximated by a power function involving stand density (Chiba 2006). Employing the allometric relationship between *CL* values and the mean weight of tree organs, the weights of leaves and branches can be estimated from *CL*. In addition, stem weight exhibits a well known allometric relationship, being approximated by D^2H. The biomass development of the plantation forests was simulated on the basis of these relationships, as shown in Fig. 1B. The saw-tooth appearance of the growth pattern for each organ can be ascribed to the thinning treatments. Such modeling approaches could be applied to the plantation forests at the Sakaerat Experimental Station, although a data set including the biomass of fast growing tree species (e.g. *Acacia* and Eucalypts) is needed to parameterize the models mentioned above.

2. "Virtual Forest" for light environment evaluation

It would be useful to be able to examine various forest practices to find the best one without wasting time and resources. A modeling approach is, therefore, essential for managing forests with their heterogeneity, complex tree composition, and spatial and temporal dynamics. The "Virtual Forest" (VF) which can be customized to suit the user's preferences, could be a convenient and practical tool for evaluating the effects of thinning on the light environment in forests with various stand ages, canopy structures, and tree species. Since the VF exists as a computer model, it is possible to test as many thinning regimes as required in order to find the appropriate one to achieve specific goals.

The VF comprises a model tree with a given size: *H*, *D*, *CL* and crown structure. In order to determine the crown structure, the following assumptions were made. The number of branches in a unit length (one meter) is 30. Branch length is determined by a Mitscherlich curve with respect to the distance from the top of the tree:

$$LB(z) = L_{\max}\,(1 - \exp(-a / L_{\max}\, z)) \qquad (1)$$

where z is depth from the tree top (m), $LB(z)$ is branch length diverging from the stem at z (m), $L_{\max}$ is maximum branch length (m) and a is a constant (dimensionless). In addition, branch orientation angle could be a significant factor to make crown structure appear natural. After examining the branch orientation angle in relation to adjacent branches, we adopted an angle of 132° (Fig. 2). In the VF, tree locations can be specified: e.g. even, random locations, rows or clusters (Fig. 3).

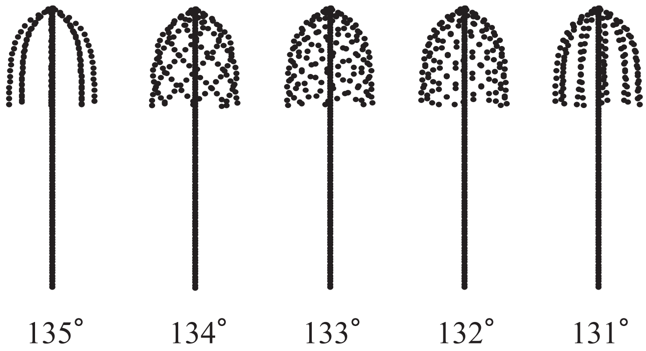

Fig. 2. Spatial distributions of branch apices depending on the angles between adjacent branches of a model tree.
Numbers in the figure are the angles between adjacent branches. An angle of 132° is the best to achieve a natural branch distribution.

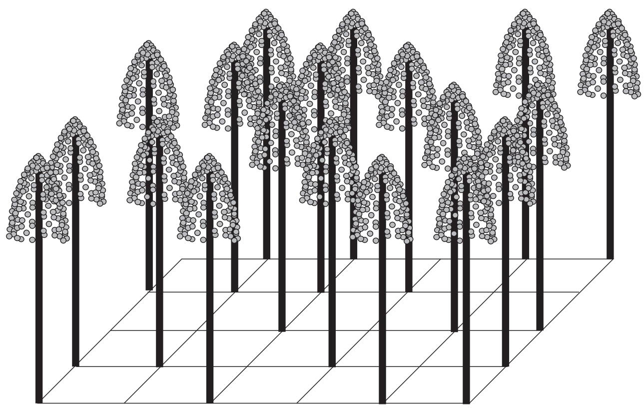

Fig. 3. An example of "Virtual Forest" comprising computer models of canopy trees.
Tree size and location in the forest can be specified.

Since all points in the VF have 3D coordinates, it can be transformed geometrically into a hemispherical view to determine canopy openness. Using the data for tree locations along with hemispherical photographs obtained in the study plots at Sakaerat (Sakai et al. 2011), the simulated canopy openness at several locations was compared with the real data (Fig. 4). These photographs were taken near the canopy gap, so that each photo includes a gap on the left. The lower diagrams in Fig. 4 were derived from the VF, using the actual tree locations in the plot. In this study, the "sky factor" (SF) was used as an indicator of canopy openness and light environment, according to Yamamoto (2003). Comparing the SF values of these actual photos with the simulation, we find that the VF can effectively simulate the light environment under a variety of forest

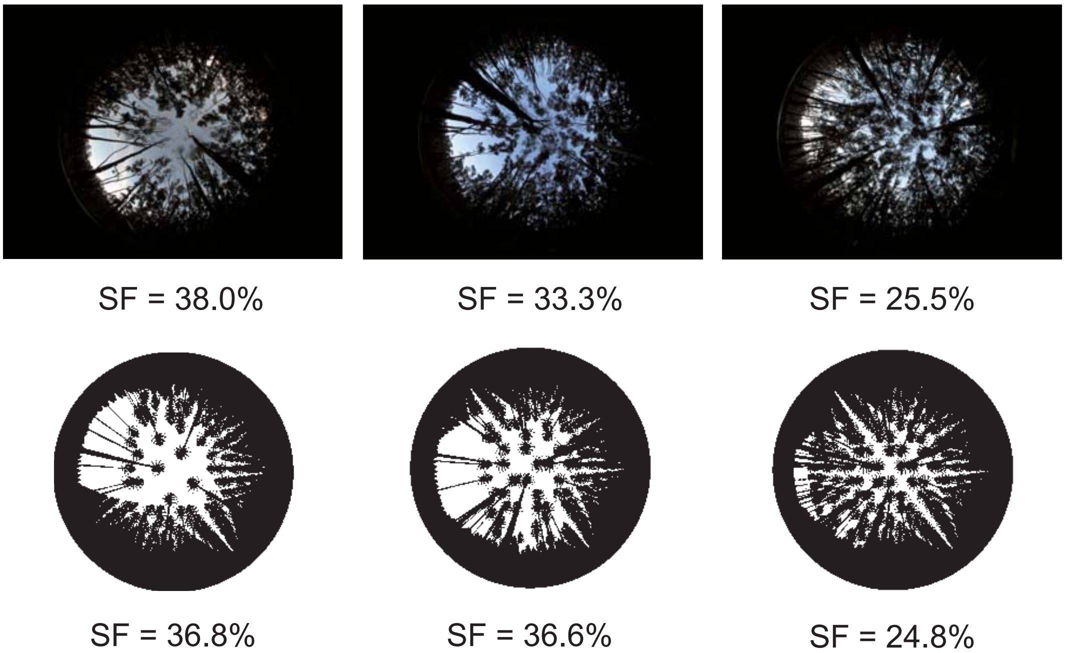

Fig. 4. Examples of hemispherical views of forest canopies simulated on the basis of actual tree locations in an *Acacia mangium* plantation.
The upper figures show the hemispherical photos taken in the plots, and the lower figures show the simulated hemispherical views at the same locations. SF denotes the "sky factor" (see text for detail).

canopies.

3. Height growth of understory seedlings

Understory trees planted in a multi-storied forest are affected by microclimate, including air temperature, light environment, soil moisture and nutrient conditions. Of these factors, the light conditions are likely to be a critical for understory trees, particularly in dark conditions, which strongly affect height growth rate (see Fig. 5). Even in a tropical forests, tree growth exhibits seasonal variation as a result of differences in precipitation and humidity through the year.

Height growth of understory trees at the experimental sites in Sakaerat has been monitored since July 2007. The data exhibit a step-wise pattern of height growth following the dry seasons (Fig. 6). The height growth rate of understory trees was approximated by a simple logistic growth curve incorporating growing period (day of the year):

$$\Delta H(t) = \frac{\Delta H_{max}}{1 + (\Delta H_{max} / \Delta H_0 - 1)\exp(-\lambda t)} \qquad (2)$$

where $\Delta H(t)$ is height growth rate at time (day of the year) t, ΔH_{max} is the maximum height growth rate for $\Delta H(t)$, ΔH_0 is initial height growth rate and λ is a growth coefficient. It should be noted that since height growth of understory trees

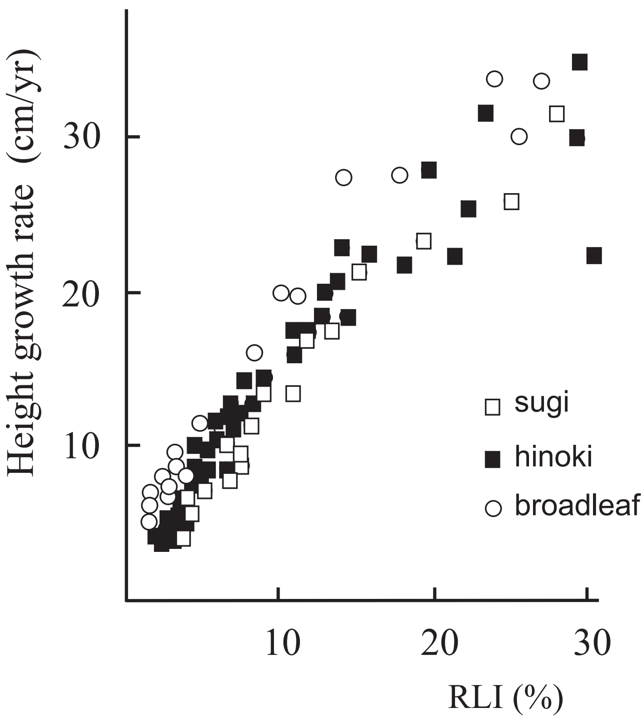

Fig. 5. Relationship between relative light intensity (*RLI*) and height growth rate of sugi seedlings under the forest canopies of sugi, hinoki and deciduous broadleaved trees.
Sugi seedlings measured were under the canopies of sugi (□), hinoki (■), and broadleaved (○) trees. Data from Waseda (1983).

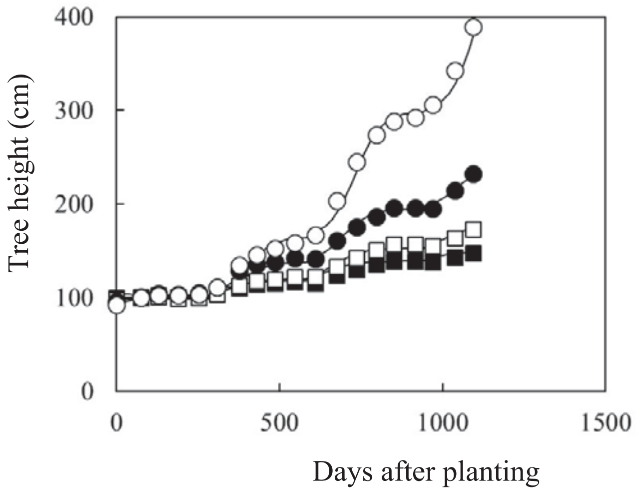

Fig. 6. Tree height of understory *Hopea odorata* trees beneath the forest canopy at different thinning intensities.
Solid lines show the regression curves expressed by a logistic function Eq.(2).
Symbols denote ○: GAP; ●: 2/3 thinning; □: 1/3 thinning; ■: no thinning.

should be closely correlated with the light environment under the canopy, ΔH_{max} is defined as being proportional to canopy openness or the sky factor. When we used equation (2), the simulated height growth rates of understory trees closely mirrored the actual data, even for the study plots with different thinning intensities (Fig. 6). Examining the values of the parameters λ, ΔH_0 and ΔH_{max}, it appears that λ and ΔH_0 may be constant irrespective of light environment and tree age. However, the ΔH_{max} values could be changed, as shown in Fig. 7. Although height growth rate in the gap increased steadily over the years, in the plots under forest canopy (2/3 thinning, 1/3 thinning or no thinning) the maximum rate was reached around three years after planting. This suggests that available light under the canopy decreased each year after the study plots were established in 2007. Although more careful parameterization is required, and environmental conditions should be recorded in detail at the study sites, the growth patterns of understory trees were well represented in the simulation (solid curves in Fig. 6).

4. Simulation approach for predicting forest development

The modeling tools for predicting the growth of understory trees were developed to take account of the canopy trees. That is, the models incorporate the effect of thinning on the canopy trees of plantation forests in order to evaluate light conditions under the forest canopy, and thus predict the growth patterns of understory trees. It appears that these models perform well with respect to simulating forest structure and growth associated with a variety of thinnings regimes, thus facilitating the selection of management strategies to promote the growth of understory

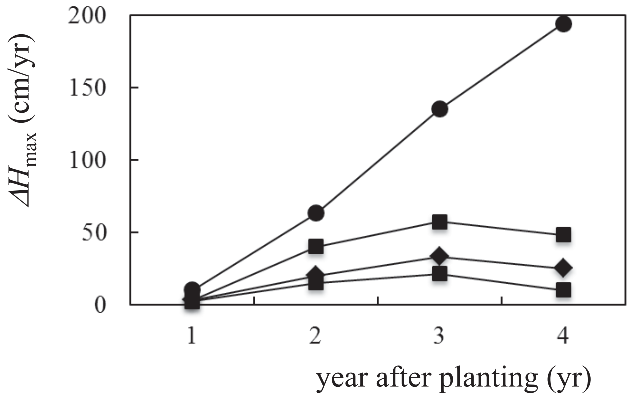

Fig. 7. Maximum height growth rates ΔH_{max} from Eq.(2) for the study plots with different thinning intensities.
Symbols are the same as in Fig.5.

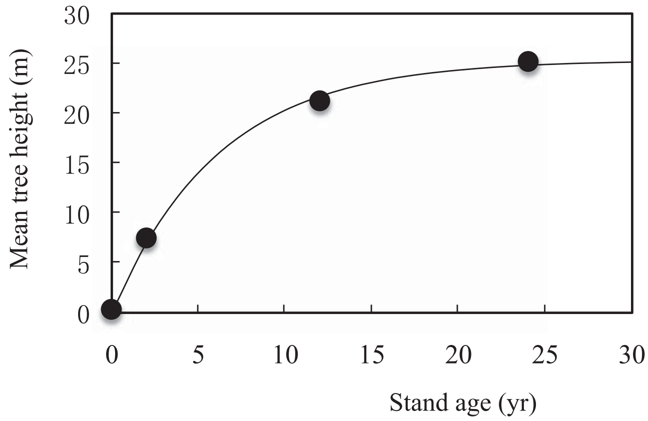

Fig. 8. Height growth of *Acacia mangium* in the plantation at Sakaerat Experimental Research Station.
Solid line shows the Mitscherlich growth curve approximated by Eq.(3).
Data from Kamo et al. (2009) and the present study.

trees.

However, additional measurements are required in order to evaluate the process of canopy closure and the response of understory trees after thinning and to validate the models. In particular, height growth of canopy trees is a key parameter for predicting the canopy closure of a study plot, through its correlation with crown width and crown length. Although most plantation forests in the tropics have been established using fast growing tree species such as *Acacia* and *Eucalyptus*, data pertaining to height growth rates of these genera after planting are lacking for Thailand. Fig. 8 illustrates the height growth data obtained at the Sakaerat Experimental Research Station, suggesting the maximum tree height in a 20-year-old stand to be about 25 m. However, the maximum tree height varies according to site conditions, which encompass factors such as nutrient availability, soil water status, and meteorological parameters.

$$H(t) = H_{max} (1 - \exp(- a/H_{max}\, t)) \quad (3)$$

where $H(t)$ denotes mean tree height in a stand age t, H_{max} is the maximum $H(t)$ and a is a constant. The parameters H_{max} and a for Fig. 8 were 25.3m and 4.09m/yr, and the coefficient of determination r^2 was 0.98.

In order to rehabilitate indigenous tropical forests via plantations of fast growing tree species, it will be necessary to model the tree growth process and the development of forest structure. This approach should allow us to simulate and examine the effects of thinning treatments on understory trees. Such simulations should be conducted in order to identify desirable forest management strategies to facilitate a succession from fast growing exotic species to indigenous canopy species.

Conclusions

It is required to introduce indigenous tree species on degraded land after the establishment of fast growing tree plantations. In an experimental two-storied plantation with the canopy trees (*Acacia mangium*) and the understory trees (*Hopea odorata*, *H. ferrea*, *Xylia xylocarpa* var. *kerrii*) in Thailand, the following simulation models were developed to evaluate thinning effects on the growth of canopy trees and to control the light environment so as to promote the growth of understory trees of indigenous species.

(1) A model to simulate the growth of canopy trees in response to thinning practices.
(2) “Virtual Forest” to evaluate the light environment under the forest canopy.
(3) A model to estimate the growth of understory trees.

These models were validated partly using the data collected in the plantation. By employing the models, adequate forest management plans can be selected heuristically, prior to any activity.

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