

## Simulating Harvest Schedule for Timber Management and Multipurpose Management in Teak Plantations

Tatang Tiryana

Department of Forest Management, Faculty of Forestry, Bogor Agricultural University, Academic Ring Road, Campus IPB Dramaga, PO Box 168, Bogor, Indonesia 16680

Received November 24, 2015/Accepted January 19, 2016

### Abstract

*Sustainable management of teak plantations in Java requires an improvement of the existing yield regulation method to optimize multiple benefits of the plantations at risk of stand destruction. This study was therefore aimed to formulate an alternative harvest scheduling model that integrates risk of stand destruction for supporting multipurpose management of teak plantations. The proposed model used a state-space planning model to simulate the dynamic of plantations due to timber harvesting and stand destruction, and then sought optimal solutions for 2 management scenarios, i.e. timber management that optimized total harvest volume and multipurpose management that optimized net present value (NPV) while increasing carbon stocks. Using a case study on a typical teak plantation, this study confirmed that increasing destruction rates reduced harvest volumes, NPV, carbon stocks, and resulted in imbalanced ending age-class structures. Reducing cutting-age limit increased harvest volumes and NPV, but it also reduced carbon stocks of the plantations. Although the multipurpose management generated lower financial benefit, it maintained carbon stocks and produced better ending age-class structures compared to timber management. The proposed harvest scheduling model provides a useful planning tool for managing teak plantations.*

*Keywords: Burns method, yield regulation, annual allowable cut, linear programming*

*\*Correspondence author, email: tangtir@apps.ipb.ac.id, ph.: +62-85697902773*

### Introduction

In recent years, there has been an increasing public concern on sustainability of teak plantations in Java, Indonesia. This concern emerged mainly because most of the plantations are dominated by young stands ( $\leq 30$  years old) and always face the risk of stand destruction (Tiryana *et al.* 2011a; Rohman *et al.* 2014). In the presence of stand destruction, it is unclear whether the plantations could achieve a sustained timber yield (Smartwood 2000) and perpetually produce social and environmental benefits. Thus, forest managers (*i.e.* Perum Perhutani, PP) are facing a greater challenge to sustainably manage teak plantations.

Although the paradigm of sustainable forest management (SFM) has been recently adopted by Perum Perhutani, the sustained timber yield is still becoming a main concern on managing teak plantations. PP uses a neoclassical yield regulation method called Burns method (Perum Perhutani 1974), which is a combination of area and volume controls, to determine annual allowable cut (AAC) for a 10-years planning period. In this method (Perum Perhutani 1974; Parthama 1995), AAC area is simply calculated by dividing total standing forest areas with a rotation age, whereas AAC volume (AAC-v) is determined using 2 steps from Burns (1951). In the first step, an initial AAC-v is computed by

dividing total harvest volumes at a mean-cutting-age with a rotation age. The mean-cutting-age is defined as the average weighted age (by age-class areas) of growing stocks plus one-half of the rotation age. In the second step, an iterative cutting-time test (also called tabular check) is carried out to determine the cutting-time of each age-class. The initial AAC-v is accepted if it results in a small deviation ( $\leq 2$  years) between the sum of cutting-times of each age-class and the rotation age. Otherwise, the initial AAC-v is adjusted by repeating the cutting-time test several times, resulting in a tedious and cumbersome work.

The Burns method is relatively simple, but it has some drawbacks. First, it ignores the risk of stand destruction during a rotation period. Like other classical harvest scheduling methods, this method assumes no forest disturbances, so that a normal forest condition (balanced age-class structure) might be expected after a certain rotation period. This assumption, however, is not valid for the current condition of teak plantations because stand destruction always occurs from time to time. The current age-class structures of teak plantations (similar to Figure 1) provide an empirical evident that the plantations have never reached a normal forest condition. Second, like other volume control methods, the Burns method only includes the objective of



Figure 1 Initial age-class structure of teak plantations in Kebonharjo FMU in the planning period 2007–2016.

achieving harvest volumes (Davis *et al.* 2001); hence, it has no ability to include other management objectives, such as optimizing financial benefits or environmental benefits. In the context of SFM, forest managers have a greater challenge to be able to manage their forests for achieving sustainability of multiple benefits. Thus, the Burns method is less appropriate so that an alternative method is required to support a better management of teak plantations.

Few studies have attempted to develop alternative harvest scheduling models for teak plantations in Java. Parthama (1995) proposed a harvest scheduling model based on linear and chance-constrained programming methods to include risks due to timber yield variability of teak plantations. The proposed model, however, ignored the risk of stand destruction and only concerned with optimizing timber benefits. Kuncahyo (2006) proposed a simulation model using system dynamic approach by considering stand destruction and focusing on social benefits of teak plantations. He argued that the simulation model was more appropriate because the Burns method produced static and overestimated harvest volumes for disturbed plantations. Such model, however, requires many data on forest resources and socio-economic conditions, and formulating dynamic equations to describe relationships among model components would be not an easy task for forest managers. Although a simulation model provides a greater flexibility to develop management scenarios, such model may not produce optimal solutions because “there are no general solution algorithms to identify an optimal solution” (Buongiorno & Gilless 2003). Thus, an alternative harvest scheduling model is still needed to assist forest managers in achieving multiple benefits of teak plantations at risk of stand destruction.

The objective of this study was to formulate an alternative harvest scheduling model for simulating and optimizing multiple benefits (i.e. timber volume, financial benefit, and carbon sequestration benefit) of teak plantations at risk of stand destruction. Specifically, by using the proposed harvest scheduling model for a typical teak plantation, this study were aimed:

- 1 to analyze the effect of stand destruction and cutting-age limit on optimal harvest volumes, financial benefits, carbon stocks, and ending age-class structures, and
- 2 to evaluate trade-offs between timber management that

optimize harvest volume and multipurpose management that optimize financial benefit while maintaining carbon sequestration benefit of teak plantations.

This study extended the basic model of Reed and Errico (1986) by including harvest volumes from thinning, financial benefits, environmental benefits from carbon sequestration, and various cutting-age limits, which were not considered in some previous harvest scheduling studies (Reed & Errico 1986; Armstrong 2004; Leduc *et al.* 2014).

## Methods

This study developed a harvest scheduling model using a case study in teak plantations of Kebonharjo Forest Management Unit (FMU). There are 3 main phases in developing the model:

- 1 simulating the dynamic of age-class structures from period to period
- 2 formulating optimization models to develop management scenarios, and
- 3 using the optimization models to simulate harvest schedules for timber management and multipurpose management of the plantations.

**Case study area** The Kebonharjo FMU is one of the most productive FMUs for producing high quality teak timber in Central Java. The total area of teak plantations in this FMU is 12,678.8 ha with an imbalance age-class structure (Figure 1), indicating that young stands are more dominant (81%) than mature stands (Perum Perhutani 2007).

Similar to other FMUs in Java, this FMU also uses the Burns method for determining AAC of teak plantations. For the period 2007–2016, the FMU uses a rotation of 60 years to obtain AAC volume of 11,168.6 m<sup>3</sup> year<sup>-1</sup> (with AAC area of 69.1 ha year<sup>-1</sup>) from clear-cuttings and thinning volume of 1,921.2 m<sup>3</sup> year<sup>-1</sup> (Perum Perhutani 2007).

**Model formulation: Simulating dynamic of age-class structures** The dynamic of teak plantations from one period to another was simulated using a state-space planning model (Garcia 1990), which is also called Model III (Boychuk & Martell 1996; Davis *et al.* 2001). In this planning model, the state of plantations at period  $t$  is described by plantation areas in each age-class. This study used a 5-year age-class and period (with 15 age-classes) to minimize variation in stand yields due to area grouping and to account for 5-year thinning treatments.

During period  $t$ , forest managers may conduct clear-cutting of some productive stands, salvage-cutting of damaged stands, and thinning of standing forests. While harvested stands are then regenerated as age-class 1 (under an assumption of no delay in regeneration), remaining stands move to the next age-classes at period  $t+1$  (Garcia 1990). If the area of plantations in age-class  $j$  at period  $t$  is  $x_{j,t}$  ( $j = 1, 2, \dots, k$ ; and  $t = 1, 2, \dots, N$ ), area of clear-cutting in age-class  $j$  at period  $t$  is  $h_{cj,t}$ , and destruction rate in age-class  $j$  at period  $t$  is  $q_{j,t}$ , then salvage-cutting area ( $h_{sj,t}$ ) and standing forests area ( $x_{j,t+1}$ ) are formulated as Equation [1] and Equation [2]:

$$h_{sj,t} = q_{j,t}(x_{j,t} - h_{cj,t}) \quad [1]$$

$$x_{j,t+1} = (1 - q_{j,t})(x_{j,t} - h_{cj,t}) \quad [2]$$

The age-class structure of plantations at the beginning of period  $t+1$  is then modeled as shown in Equation [3] (adapted from Reed & Errico 1986):

- 1 The area of age-class 1 is composed of the harvested areas of clear-cutting and salvage-cutting in period  $t$ :

$$x_{1,t+1} = q_{1,t}x_{1,t} + \dots + q_{k,t}x_{k,t} - (-1+q_{1,t})h_{c1,t} - \dots - (-1+q_{k,t})h_{ck,t} \quad [3a]$$

- 2 The area of age-class 2, 3, ...,  $k-1$  is composed of the surviving areas that were not harvested in period  $t$ :

$$x_{2,t+1} = (1-q_{1,t})x_{1,t} - (1-q_{1,t})h_{c1,t}$$

$$x_{k-1,t+1} = (1-q_{k-1,t})x_{k-1,t} - (1-q_{k-1,t})h_{ck-1,t} \quad [3b]$$

- 3 The area of age-class  $k$  (including older stands) is composed of the surviving areas of age-class  $k-1$  and  $k$  that were not harvested in period  $t$ :

$$x_{k,t+1} = (1-q_{k-1,t})x_{k-1,t} + (1-q_{k,t})x_{k,t} - (1-q_{k-1,t})h_{ck-1,t} - (1-q_{k,t})h_{ck,t} \quad [3c]$$

Reed and Errico (1986) showed that Equation [3a], Equation [3b], and Equation [3c] can be formulated into Equation [4], and the age-class structure at the beginning of period  $t$  can be predicted from an initial age-class structure ( $\mathbf{x}_1$ ) using Equation [5]:

$$\mathbf{x}_{t+1} = \mathbf{R}\mathbf{x}_t - \mathbf{S}\mathbf{h}_{ct} \quad [4]$$

$$\mathbf{x}_t = \mathbf{R}^{t-1}\mathbf{x}_1 - (\mathbf{R}^{t-2}\mathbf{S}\mathbf{h}_{c1} + \mathbf{R}^{t-3}\mathbf{S}\mathbf{h}_{c2} + \dots + \mathbf{S}\mathbf{h}_{ct-1}) \quad [5]$$

where  $\mathbf{x}_t$  is a column vector of age-class areas at period  $t$ ,  $\mathbf{h}_{ct}$  is a column vector of clear-cutting areas at period  $t$ ,  $\mathbf{R}$ , and  $\mathbf{S}$  are the  $k \times k$  matrices, which are defined in Appendix 1a.

This study assumed that destruction rates at age-class  $j$  ( $q_j$ ) of a certain destruction level in matrix  $\mathbf{R}$  and  $\mathbf{S}$  were constant for all periods (Reed & Errico 1986), which represent 5 year destruction rates that were calculated using Equation [6]

$$q_j = 1 - \frac{S(t'+5)}{S(t')} \quad [6]$$

$S(t')$  is a survival probability at age  $t'$  years, which was estimated using one of the following survival functions (Equation [7a], Equation [7b], and Equation [7c]) depend on an assumed destruction rate (adopted from Tiryan *et al.* 2011a):

- a) Low destruction rate (Weibull model):

$$S(t') = \exp(-(t'/96.793)^{0.847}) \quad [7a]$$

- b) Medium destruction rate (Log logistic model):

$$S(t') = \frac{1}{1+0.00359t'^{1.74212}} \quad [7b]$$

- c) High destruction rate (Log logistic model):

$$S(t') = \frac{1}{1+0.00034t'^{3.18770}} \quad [7c]$$

In addition, a zero destruction rate was also used to analyze optimum harvest levels at no risk of stand destruction.

**Developing optimization models** To find optimal solutions for harvest levels at risk of stand destruction, this study used a linear programming (LP) model, which was proposed by Reed and Errico (1986), with a basic model formulation as Equation [8] and Equation [9]:

Objective:

$$\text{Maximize } Z = \mathbf{c}\mathbf{h}_c \quad [8]$$

Subject to:

$$\mathbf{A}\mathbf{h}_c \leq \mathbf{b} \text{ and } \mathbf{h}_c \geq 0 \quad [9]$$

where  $\mathbf{c} = [c_1 \ c_2 \ \dots \ c_N]$  is a  $kN$ -dimensional row vector of stand values (e.g., timber volumes) for  $k$  age-classes and  $N$  periods,  $\mathbf{h}_c$  is a  $kN$ -dimensional column vector of clear-cutting areas, and matrix  $\mathbf{A}$  is specified in Appendix 1b. Equation [8] represents an objective function, whereas the first term of Equation [9] means that optimized harvest areas must less than or equal to standing forest areas at each period and the second term of Equation [9] means that optimal harvest areas must greater than or equal to zero. This study extended such basic LP model by formulating 2 objective functions and imposing some constraints related to harvest volumes, minimum cutting-age limits, and carbon stocks.

**Formulation of objective functions** This study analyzed 2 management objectives, *i.e.* maximizing total harvest volume and maximizing total net present value (NPV) of timber harvest while increasing carbon stocks. The objective of maximizing total harvest volume or NPV was explicitly formulated in the objective function of LP models, whereas the objective of increasing carbon stocks was formulated as a model constraint (Baskent *et al.* 2008; McCarney *et al.* 2008).

**Total harvest volume** To optimize total harvest volume (THV) from clear-cutting, salvage-cutting, and thinning, the following objective function (Equation [10]) was used in LP models (modified from Reed & Errico 1986):

$$Z_{THV} = \sum_{t=1}^N (\mathbf{v}_c \mathbf{h}_{ct} + \sum_{j=1}^k \mathbf{v}_s \mathbf{q}_j (x_{j,t} - h_{cj,t}) + \sum_{j=1}^k \mathbf{v}_g (1 - q_j) (x_{j,t} - h_{cj,t})) \quad [10]$$

$\mathbf{v}_c$ ,  $\mathbf{v}_s$ , and  $\mathbf{v}_g$  are volume-at-age vectors of clear-cutting, salvage-cutting, and thinning:

$$\mathbf{v}_c = [v_{c1} \ v_{c2} \ \dots \ v_{ck}]$$

$$\mathbf{v}_s = [v_{s1} \ v_{s2} \ \dots \ v_{sk}]$$

$$\mathbf{v}_g = [v_{g1} \ v_{g2} \ \dots \ v_{gk}]$$

The elements of these vectors are average timber volumes ( $\text{m}^3 \text{ha}^{-1}$ ) in age-class  $j$  from clear-cutting ( $v_{cj}$ ), salvage-cutting ( $v_{sj}$ ), and thinning ( $v_{gj}$ ). These timber volumes were derived from the existing yield table (Wulffing 1938) by assuming that timber volumes of site class 3.5 (medium site class) represented clear-cutting and thinning yields, while those of site class 1 (the lowest site class) represented salvage-cutting yields.

**Net present value** The objective function of maximizing NPV of timber harvest was formulated as Equation [11]:

$$Z_{NPV} = \sum_{t=1}^N (\text{NPV}_{ct} + \sum_{j=1}^k \text{NPV}_{sj,t} + \sum_{j=1}^k \text{NPV}_{gj,t} - \mathbf{F}_t) \quad [11]$$

where  $\text{NPV}_{ct}$ ,  $\text{NPV}_{sj,t}$ ,  $\text{NPV}_{gj,t}$ , and  $\mathbf{F}_t$  is NPV of clear-cutting, NPV of salvage-cutting, NPV of thinning, and total fixed cost (for administration, production activities, social services, and environmental services) at period  $t$ , respectively, which were calculated using Equation [12a] Equation [12b], Equation [12c], and Equation [12d]:

$$\text{NPV}_{ct} = (1/(1+r)^t)(\mathbf{p}_c \mathbf{v}_c - \mathbf{c}_n \mathbf{v}_c - \mathbf{c}_p) \mathbf{h}_{ct} \quad [12a]$$

$$NPV_{sj,t} = (1/(1+r)^t) \{ (\mathbf{p}_s \mathbf{v}_s - \mathbf{c}_h \mathbf{v}_s - \mathbf{c}_p) (q_j (x_{j,t} - h_{c,j,t})) \} \quad [12b]$$

$$NPV_{gj,t} = (1/(1+r)^t) \{ (\mathbf{p}_g \mathbf{v}_g - \mathbf{c}_h \mathbf{v}_g) ((1 - q_j)(x_{j,t} - h_{c,j,t})) \} \quad [12c]$$

$$\mathbf{F}_t = (1/(1+r)^t) (\mathbf{c}_f l) \quad [12d]$$

In this case,  $r$  is an interest rate;  $\mathbf{p}_c$ ,  $\mathbf{p}_s$ , and  $\mathbf{p}_g$  are timber price-at-age vectors of clear-cutting, salvage-cutting, and thinning, respectively;  $\mathbf{c}_h$ ,  $\mathbf{c}_p$ , and  $\mathbf{c}_f$  are cost-at-age vectors of harvesting, planting, and fixed cost, respectively; and  $l$  is the length of period.

This study assumed an interest rate of 8% per year, timber prices, and activity costs that were constant over the planning horizon. Timber prices according to stand age were approximated using log prices based on log's diameter classes applied in the FMU. The log diameters at a certain stand age were estimated from the existing yield table at site class 3.5 (for logs of clear-cutting and thinning) and site class 1 (for logs of salvage-cutting). In addition, harvesting cost, planting cost, and total annual fixed cost were calculated based on financial data from the FMU.

**Formulation of model constraints** The LP models used 4 constraints: area (Equation [9]), harvest volume flow, minimum cutting-age limit, and carbon stocks flow. The use of these constraints depended on the management scenarios used in the LP models (Table 1).

**Harvest volume flow** The sequential flow of clear-cutting volume (SFV) was used to control the variation of harvest volumes by allowing clear-cutting volumes ( $V_c$ ) to decrease or increase within a specified percentage from one period to the next (Reed & Errico 1986). The SFV constraint (Equation [13]) reflected the objective of forest managers in maintaining continuous flows of timber volume from scheduled harvestings.

$$(1 - \alpha) V_{c,t-1} \leq V_{c,t} \leq (1 + \beta) V_{c,t-1} \quad [13]$$

This study used a 10% maximum proportional volume decrease ( $\alpha$ ) and volume increase ( $\beta$ ) to facilitate a greater flexibility for the LP models in finding optimal solutions. To accommodate the SFV constraint, the lower parts of matrix  $\mathbf{A}$  and vector  $\mathbf{b}$  were modified as shown in Appendix 1c (Reed & Errico 1986).

**Minimum cutting-age limit** This study used minimum cutting-age limits (MCA, an analogue of rotation age) of 71, 61, and 51 years to analyze the effect of cutting-ages to

harvest levels. To implement this constraint, the elements of vector  $\mathbf{h}_c$  at age-classes below a specified MCA limit (i.e.  $j \leq 14$  for MCA 71 years,  $j \leq 12$  for MCA 61 years, and  $j \leq 10$  for MCA 51 years) were set equal to zero, meaning no clear-cuttings at these age-classes.

**Carbon stocks flow** The use of carbon stocks flow (CSF) constraints was aimed to reflect the objective of forest managers to maintain environmental benefits from carbon sequestration. The flow of total carbon stocks ( $C$ ) of standing forests from one period to another was formulated using Equation [14]:

$$(1 - \gamma) C_{t-1} \leq C_t \leq (1 + \theta) C_{t-1} \quad [14]$$

where  $\gamma$  and  $\theta$  denote the maximum proportions of carbon stocks decrease and increase, respectively. This study used  $\gamma = 0$  and  $\theta = 0.1$ , meaning that the carbon stocks stored in standing forests were increase by 10% from period to period to represent the increasing role of forest ecosystems in maintaining environmental balances. The carbon stocks at period  $t$  ( $C_t$ ) were calculated using Equation [15a]:

$$C_t = \mathbf{u} \mathbf{x}_t - \mathbf{w} \mathbf{h}_{ct} \quad [15a]$$

$$= [u_1 \quad u_2 \quad \dots \quad u_k] \begin{bmatrix} x_{1,t} \\ x_{2,t} \\ \vdots \\ x_{k,t} \end{bmatrix} - [w_1 \quad w_2 \quad \dots \quad w_k] \begin{bmatrix} h_{c1,t} \\ h_{c2,t} \\ \vdots \\ h_{ck,t} \end{bmatrix}$$

where the elements of vector  $\mathbf{u}$  and  $\mathbf{w}$  were calculated using Equation [15b]:

$$u_j = c_{gsj} - (c_{sj})(q_j) - (c_{gj})(1 - q_j) \quad [15b]$$

$$w_j = c_{cj} - (c_{sj})(q_j) - (c_{gj})(1 - q_j)$$

To accommodate the CSF constraint, the lower parts of matrix  $\mathbf{A}$  and vector  $\mathbf{b}$  were modified as shown in Appendix 1c. The average carbon stocks (tons ha<sup>-1</sup>) at age-class  $j$  that are stored in standing forests ( $c_{gsj}$ ) and removed by harvestings (denoted by  $c_{cj}$  for clear-cutting,  $c_{sj}$  for salvage-cutting, and  $c_g$  for thinning) were estimated from merchantable timber volumes ( $v_{cj}$ ,  $v_{sj}$ , and  $v_{gj}$ ) using a biomass model from Tiryana *et al.* (2011b).

**Formulating management scenarios** This study developed 2 management scenarios: timber management (TM) that optimizes harvest volumes and multipurpose management (MM) that optimize financial benefit (i.e. total NPV) while increasing carbon stocks. For each scenario, this study

Table 1 Specification of the LP models for each management scenario

Scenario	Destruction rate	Objective	Constraints
TM: timber management	Zero, low, medium, high	Maximize total volume	MCA 71 year and SFV MCA 61 years and SFV MCA 51 years and SFV
MM: multipurpose management	Zero, low, medium, high	Maximize total NPV	MCA 71 years, SFV, and CSF MCA 61 years, SFV, and CSF MCA 51 years, SFV, and CSF

assumed four destruction rates that might occur during the planning horizon: zero (no destruction), low (4.4–6.3% per period, Equation 7a), medium (9.4–15.9% per period, Equation 7b), and high (18.5–49.6% per period, Equation 7c). Thus, to find optimal solutions for the possible combinations of scenarios, destruction rates, and cutting-age limits, this study analyzed 24 LP models as specified in Table 1.

Each LP model was run for a 140 year planning horizon (28 periods), which was 2–2.8 times the considered rotation lengths (50, 60, and 70 years); hence, it was a sufficiently long time to assess the sustainability of plantations (Clutter *et al.* 1983; Vanclay 2015). To avoid LP models liquidated forest stands at the last period (Garcia 1990), additional 25 years (5 periods) were added to the planning horizon but their solutions were then ignored from the models (Reed & Errico 1986; McCarney *et al.* 2008). The LP models were programmed in the R software (R Core Team 2015).

## Results and Discussion

The LP-based harvest scheduling models generated optimal solutions for each scenario in relation to harvest volumes, financial benefits, carbon stocks, and ending age-class structures of teak plantations. The optimal solutions of each scenario were not only affected by the rate of stand destruction but also by the cutting-age limit of teak plantations.

**The effect of stand destruction** All scenarios confirmed that total harvest volumes (THV) during the planning periods generally decrease with increasing destruction rates. The decrease in THV corresponded to clear-cutting volumes (CCV) that decreased from period to period with increasing destruction rates (Figure 2 and Figure 3). For example, in TM scenario CCV at MCA 61 years decreased from 39,140–217,610 m<sup>3</sup> period<sup>-1</sup> at no destruction to 30,590–162,800 m<sup>3</sup> period<sup>-1</sup> at low destruction rates, to 25,560–80,210 m<sup>3</sup> period<sup>-1</sup> at medium destruction rates, and to only 4,130–18,820 m<sup>3</sup> period<sup>-1</sup> at high destruction rates (Figure 2). Similarly, in MM scenario CCV at MCA 61 years decreased from 41,330–113,210 m<sup>3</sup> period<sup>-1</sup> at no destruction to 38,970–93,830 m<sup>3</sup> period<sup>-1</sup> at low destruction rates, to 18,440–46,880 m<sup>3</sup> period<sup>-1</sup> at medium destruction rates, and to only 2,330–18,780 m<sup>3</sup> period<sup>-1</sup> at high destruction rates (Figure 3). This finding is reasonable, because when the plantations were damaged by various destruction agents (Tiryana *et al.* 2011a), some portions of productive stands were no longer available so that the areas and volumes of clear cuttings become considerably less. Meanwhile, the areas and volumes of salvage-cuttings increase with increasing destruction rates (Figure 2 and Figure 3) because the LP models emulated the PP's management policy (Perum Perhutani 1974) that permit the salvage-cutting of damaged stands at age-classes below an MCA limit. Reed and Errico (1986) also reported that annual harvest volumes and areas of clear-cuttings decreased when the probability of fire destruction increased.

Interestingly, except for high destruction, periodic harvest volumes (especially under TM scenario) tended to gradually increase from period to period until certain peaks at about rotation ages and then decrease towards the end of

planning horizon. This behavior is reasonable because the plantations, which are initially dominated by young stands (Figure 1), continuously grow that eventually increase the growing stock of harvestable mature stands from period to period. Because of a lack of mature stands at initial periods, the LP models allocated less harvest volumes for some initial periods and then allocated more harvest volumes for the next periods when mature stands increased. Armstrong (2004) also confirmed that forests with less mature stands produced allowable harvest volumes that gradually increased from period to period in the presence of wildfire disturbances. This finding, however, contrasts to Reed and Errico (1986) who observed that annual harvest volumes at a certain destruction rate were initially decrease and then either slightly increase or relatively stable towards the end of planning horizon. A possible reason for this discrepancy is that the initial age-class structure used by Reed and Errico (1986) had dominant mature and over-mature stands, which contradicts to the initial age-class structure of this study. For a forest with surplus mature stands, Armstrong (2004) also observed a gradual decline of harvest levels. These findings confirm that optimal harvest levels may also depend on the initial age-class structures (Uusivuori & Kuuluvainen 2005). The uneven flow of timber volumes during a planning horizon could also reflect fluctuation in market demand that would not impact on the sustainability of plantations (Vanclay 2015).

The dynamic of harvest volumes due to stand destruction has affected total NPV, which decreased with increasing destruction rates (Table 2). Depending on the MCA limits, total NPV of TM scenario decreased up to 16.6–18.4% at low destruction rates, 26.3–33.4% at medium destruction rates, and 68.9–69.7% at high destruction rates. Similarly, the decrease in NPV of MM scenario reached up to 9.1–9.4% at low destruction rates, 38.5–45.8% at medium destruction rates, and 69.1–70.3% at high destruction rates. These findings confirmed that financial loss is inevitable when the plantations experienced stand destruction. Thus, to ensure a stable or increased income in the future, forest managers must be able to eliminate or minimize the risk of stand destruction.

Stand destruction greatly affected the carbon stocks of standing forests (Figure 4). At zero, low, and medium destructions, carbon stocks in each scenario generally increased up to period 10–15 and then decreased towards the end of planning horizon. At high destruction rates, however, all scenarios showed that standing forests stored similar amounts of carbon, which decreased from about 205,000 tons period<sup>-1</sup> (at the first period) to about 145,000 tons period<sup>-1</sup> (at the end of planning horizon). In each period, however, MM scenario generated more carbon stocks than TM scenario. The increase in destruction rates lead to the increase in salvage-cuttings, which then remove some amount of carbon stocks in standing forests. Similarly, thinning and clear-cuttings contribute to the removal of carbon stocks within a period. These results (Figure 4) confirmed that at high destruction rates, it seems impossible to store more carbon stocks in standing forests because the LP models allocated greater harvest areas from salvage-cutting that increased over time. These findings suggest that an effective

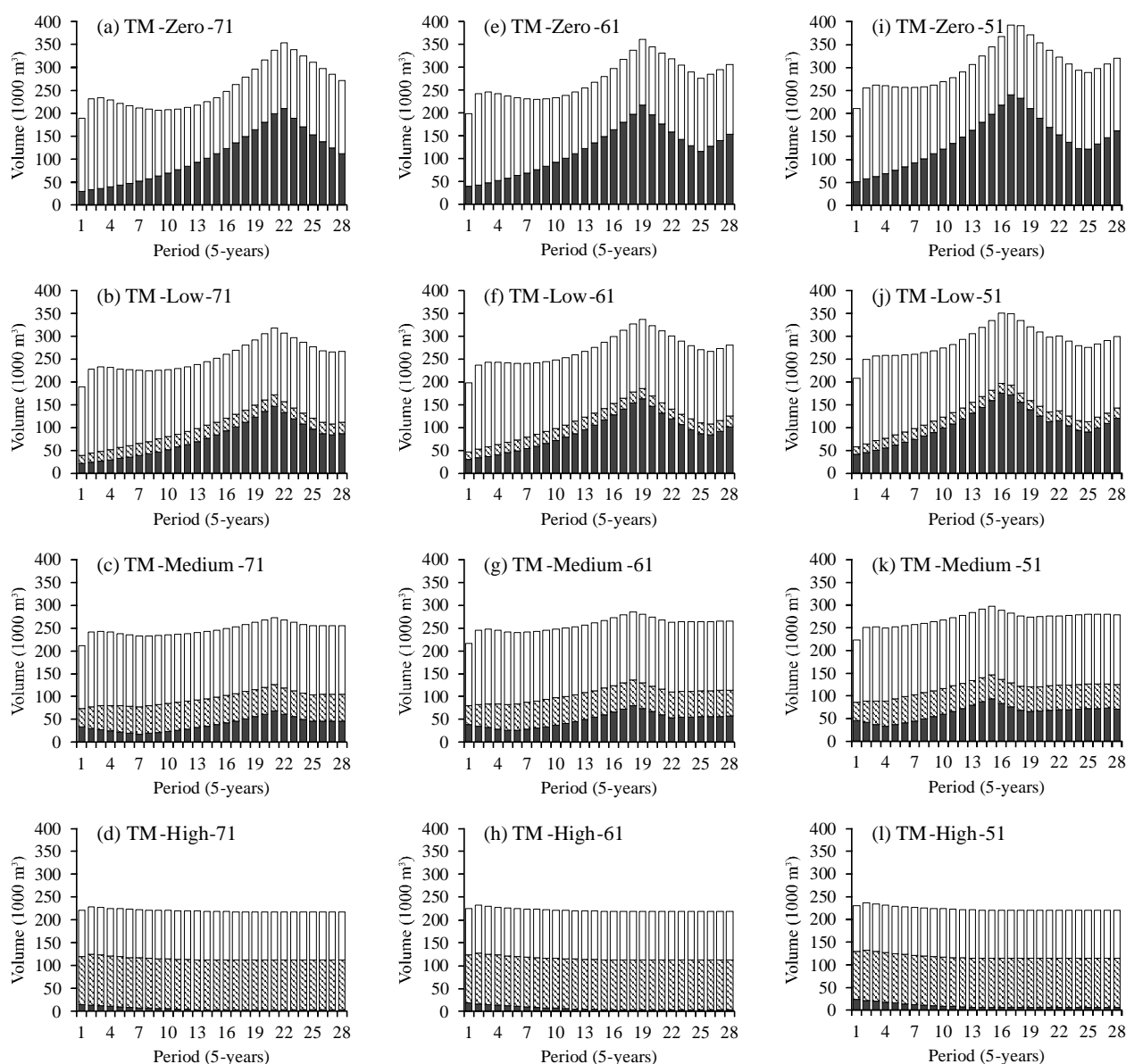


Figure 2 Optimal harvest volumes of the timber management (TM) scenario from clear-cutting (■), salvage-cutting (▣), and thinning (□). The left (a–d), middle (e–h), and right (i–l) figures show the harvest volumes of four destruction rates (zero, low, medium, and high) at minimum cutting ages (MCA) of 71, 61, and 51 years, respectively.

strategy to save carbon in the plantations is to eliminate or reduce stand damage (Boscolo *et al.* 2001; Martin *et al.* 2015).

The effect of stand destruction is also obvious to age-class structures at the end of planning period (Figure 5, after regrouping the 15 age-classes for simplifying the results). The increase in destruction rates generally resulted in imbalanced ending age-class structures (EAS). In TM scenario, EAS were fairly good (where young and mature stands were exist in the plantations) when the destruction rates were zero (Figure 5a) or low (Figure 5b). But, the EAS of TM scenario at the other destruction rates showed negative

exponential distributions (Figure 5c, Figure 5d), indicating that young stands were more dominant than mature stands. The MM scenario generally generated better EAS than those of TM scenario, in which mature stands ( $\geq 71$  years old) were dominant when zero destruction rates (Figure 5e). At high destruction rates, however, all scenarios consistently showed similar EAS in which the plantations were mostly dominated (95–96%) by young stands (Figure 5d and Figure 5h). These findings are similar to those of Reed and Errico (1986), who observed that at no risk of stand destruction the EAS was close to that of a normal forest condition; but at the presence of destruction, the EAS was dominated by young stands.

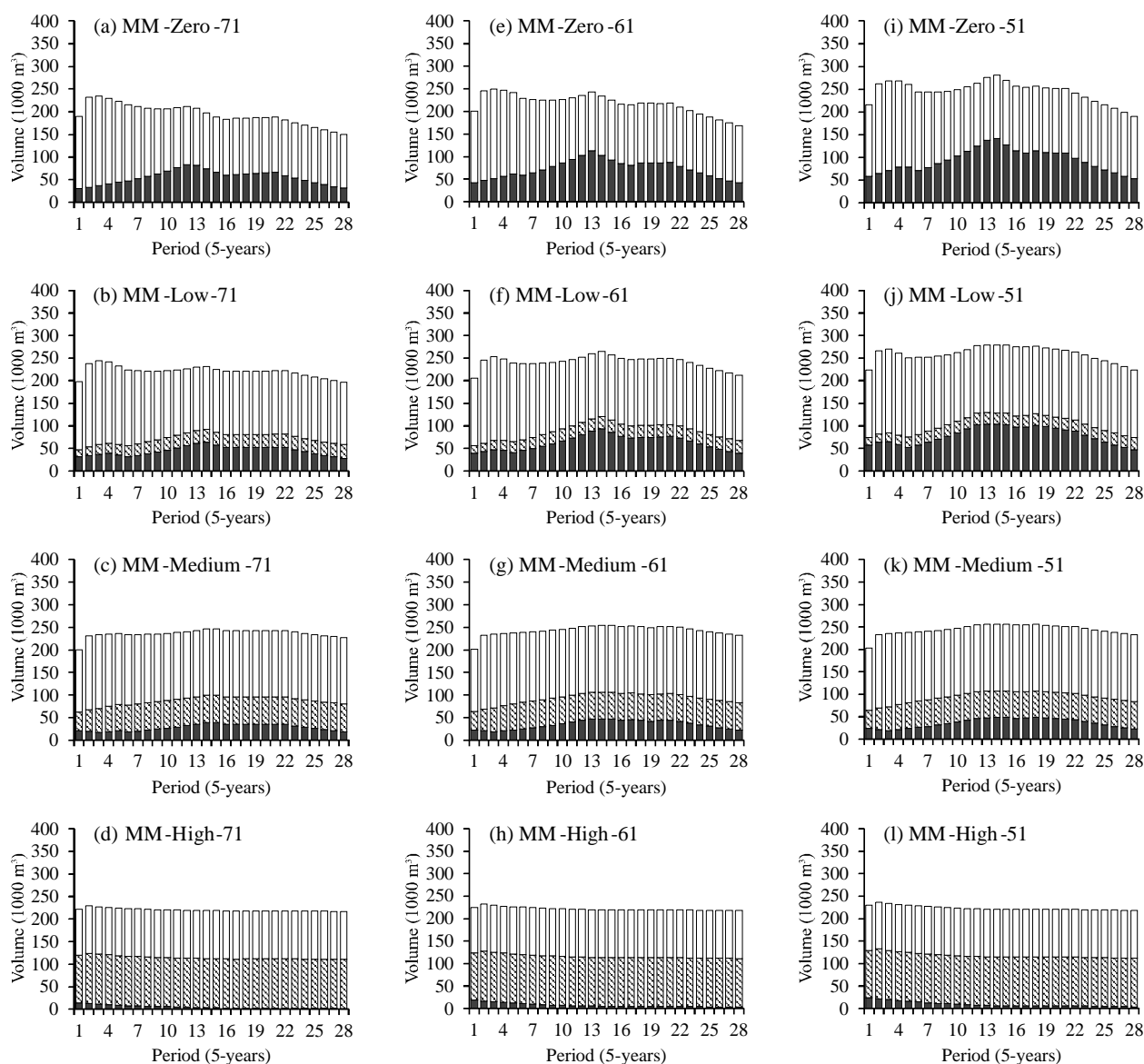


Figure 3 Optimal harvest volumes of the multipurpose management (MM) scenario from clear-cutting (■), salvage-cutting (▨), and thinning (□). The left (a–d), middle (e–h), and right (i–l) figures show the harvest volumes of four destruction rates (zero, low, medium, and high) at minimum cutting age (MCA) of 71, 61, and 51 years, respectively.

Table 2 Total NPV during 140 years for each scenario according to destruction rates and MCA limits

Destruction rate	TM's NPV (million IDR)			MM's NPV (million IDR)		
	MCA-71	MCA-61	MCA-51	MCA-71	MCA-61	MCA -51
Zero	543,685.85	637,447.61	752,219.57	545,498.76	650,085.26	761,727.17
Low	443,408.49	525,739.64	627,657.78	495,727.39	567,562.09	690,084.49
Medium	400,867.30	444,184.80	500,674.84	335,702.34	352,637.31	352,969.62
High	168,814.82	193,411.65	228,659.26	168,814.24	192,761.75	227,732.56

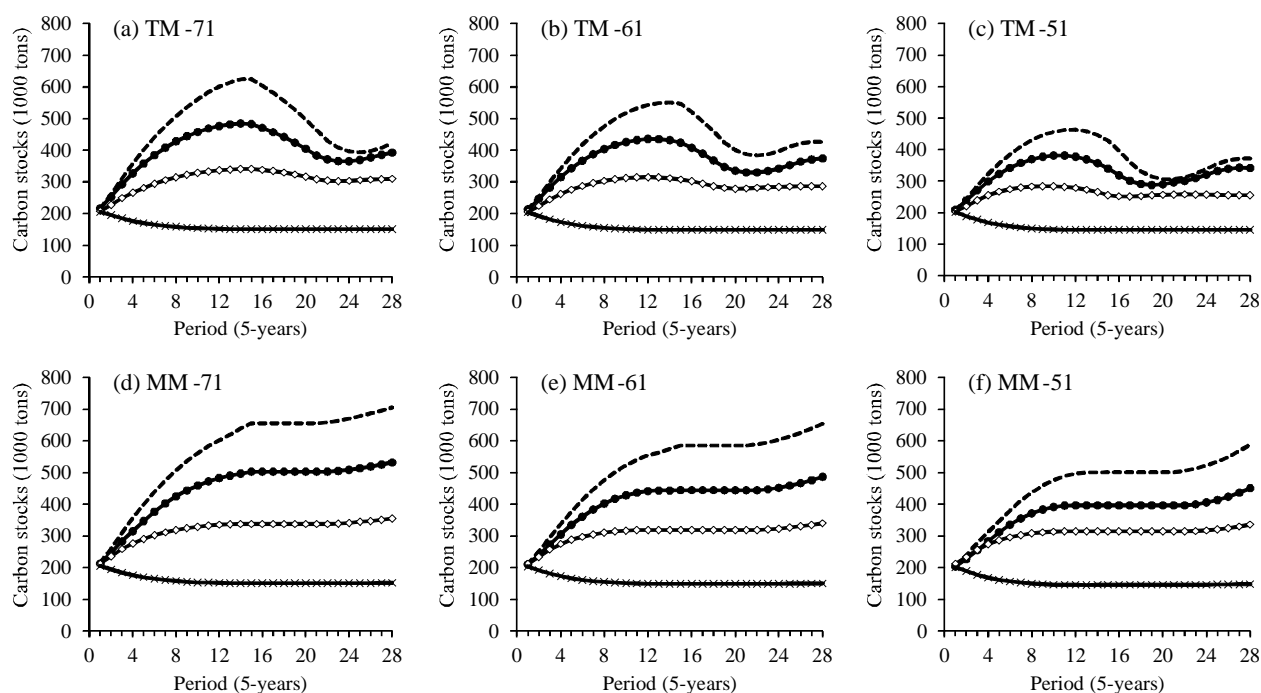


Figure 4 Carbon stocks of standing forests at zero (---), low (—●—), medium (—◇—), and high (—×—) destruction rates of the timber management (TM) scenario (a–c) and multipurpose management (MM) scenario (d–f). The left, middle, and right figures of each scenario show the carbon stocks at minimum cutting age (MCA) of 71, 61, and 51 years, respectively.

Parthama (1995) also observed imbalanced EAS for teak plantations in Cepu FMU. Thus, it seems to be impossible for teak plantations to reach a normal forest condition when stand destruction always occurs from time to time. Forest managers are then face a great challenge if they insist to achieve a normal age-class structure and a fully stocked forest with even flow timber volumes. However, forest managers may obtain fairly good EAS if they are able to eliminate stand destruction and willing to reduce harvest levels to some extents in order to increase standing forests (Boyчук & Martell 1996; Leduc *et al.* 2014) and carbon stocks from one period to another.

**The effect of cutting-age limit** Another factor affecting harvest volumes is a cutting-age limit, in which reducing the MCA limits generally increase total harvest volumes (Figure 2 and Figure 3) and total NPV (Table 2). When a lower MCA limit (*e.g.* 51 years) is used in the LP models, more harvest areas are available, greater harvest volumes are obtained, and higher NPV are then generated for each period. Parthama (1995) also reported that total NPV increased up to 43.9–96.8% when the rotation age of teak plantations was reduced from 80 to 60 years. Similarly, Boscolo *et al.* (2001) showed that reducing diameter limits (analogue of MCA limits) of a natural forest increased NPV.

Although the reduction of MCA limit is financially profitable, this management option negatively affects the carbon stocks of standing forests (Figure 4), because the LP models allocated more harvest volumes for each period that

resulted in greater removals of carbon stocks. Liski *et al.* (2001) also reported that reducing rotation lengths decreased carbon stocks of European forests. Therefore, increasing an MCA limit (lengthening a rotation period) would be an effective way to increase carbon stocks (Boscolo *et al.* 2001; Liski *et al.* 2001; Raymer *et al.* 2011), even though it reduces the financial benefit of timber productions.

All scenarios also showed that reducing MCA greatly affected the pattern of EAS at zero and low destruction rates; but, it slightly affected the patterns of EAS at medium and high destruction rates (Figure 5). In TM scenario, reducing MCA from 71 years to 61 and 51 years removed the availability of mature stands over 70 and 60 years old, respectively, because the LP models allocated more harvest volumes and areas for mature stands in order to maximize the total harvest volumes. This is contradict to MM scenario, which still kept some mature stands over 80 years old (except at high destruction rates), because the optimization of timber volumes for generating NPV was constrained by the objective of increasing carbon stocks. As the result, timber harvests at each planning period only removed some portions of mature stands that accumulated to the end of planning horizon.

**Trade-offs between timber management and multipurpose management** Regardless of the effect of destruction rates and cutting-age limits, this study also reveals some trade-offs related to the management scenarios. In MM scenario, the financial benefit of timber productions



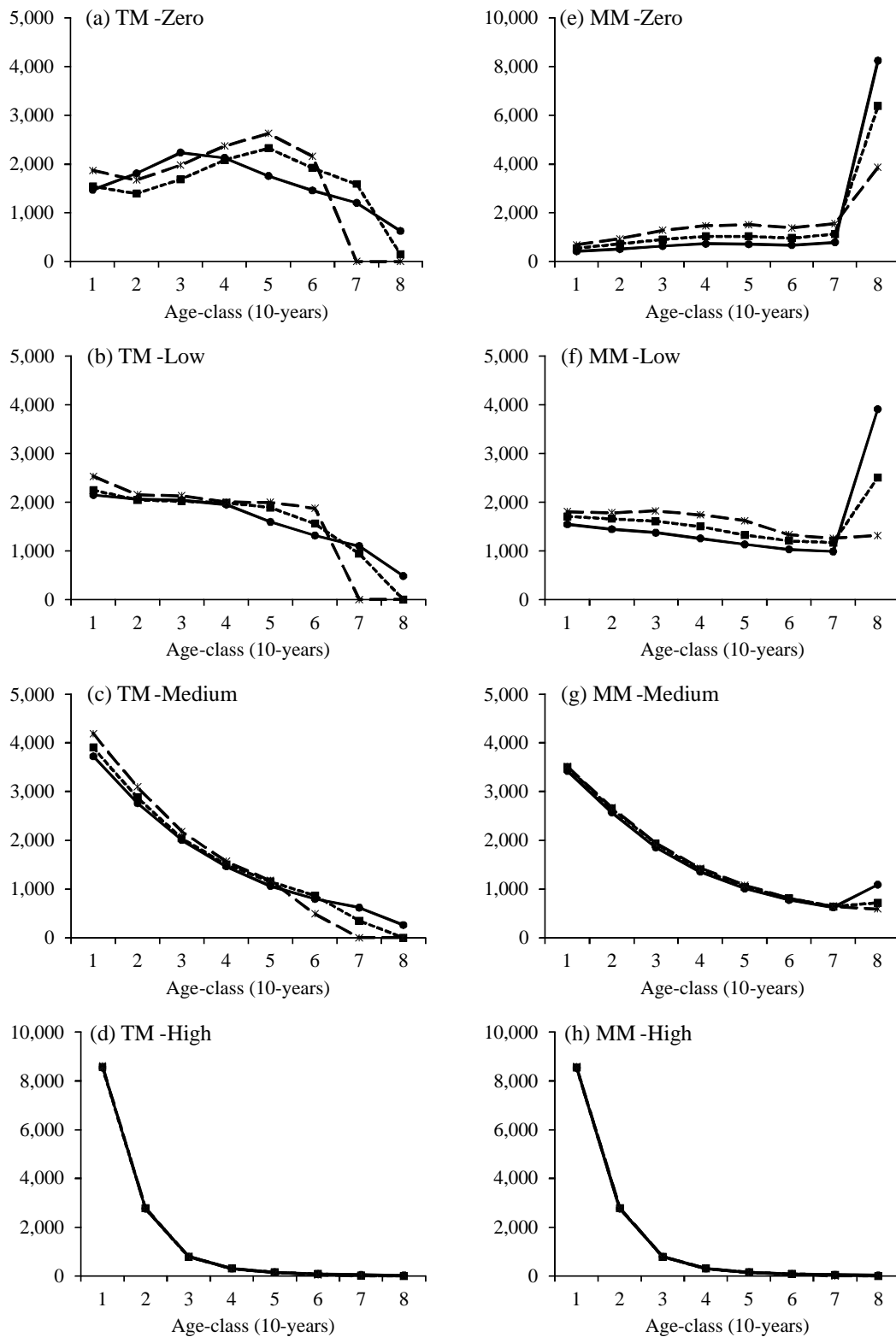


Figure 5 Ending age-class structures from the timber management (TM, a–d) and multipurpose management (MM, e–h) scenarios at zero (a, e), low (b, f), medium (c, g), and high (d, h) destruction rates and at minimum cutting ages (MCA) of 71 (—●—), 61 (---■---), and 51 (—\*—) years

are generally lower than those of TM scenario; but, this management scenario provides greater environmental benefits from increasing carbon stocks of standing forests from period to period. Furthermore, the MM scenario produces better ending age-class structures (Figure 5e–h) compared with the TM scenario (Figure 5a–d). Many previous studies have also reported that some trade-offs occur when forests are managed for multiple-uses. For example, Baskent *et al.* (2008) reported that a multipurpose management reduced the NPV of timber by 42% compared with a timber management. The lower financial benefit of MM scenario in this study is due to the lost of timber revenue that was not compensated by the financial benefit of increasing carbon stocks. In a recent climate initiative called reducing emission from deforestation and forest degradation (REDD+), forest managers could get financial benefits from conserving and enhancing carbon stocks. For production forests, however, forest managers need to determine appropriate opportunity costs and allocate most suitable areas for REDD+ projects to make a balance between timber production and conservation objectives (Aziz *et al.* 2015). Indeed, tradeoffs between timber and non-timber benefits are inherent features of SFM (Luckert & Williamson 2005).

#### Applicability of the proposed harvest scheduling model

The proposed harvest scheduling model provides some advantages compared to the Burns method. The model takes into account the risk of stand destruction, which is urgently required to determine a reliable AAC (Smartwood 2000) when the plantations always suffer from destruction. The proposed model also offers some flexibilities for forest managers to develop appropriate management scenarios by simulating several destruction rates, cutting-age limits, management objectives, and constraints. The flexibility of developing management scenarios is not an inherent feature of the Burns method, which is only capable to calculate annual harvest volumes.

This study only provides a case study of multipurpose management for optimizing financial and carbon sequestration benefits, partly because of a lack of basic models for quantifying other forest benefits. Further studies may extend the proposed harvest scheduling model by integrating other forest benefits. For example, the model can be extended to include social benefits of timber-sharing mechanism, which is currently practiced by PP through a community-based forest management program. Another possible extension of the model is integrating environmental concerns on maintaining protected areas, such as riparian zones, water springs, and wildlife habitats.

#### Conclusion

The proposed harvest scheduling model confirmed that optimal harvest volumes generally decreased with increasing destruction rates, resulting in financial losses. The increase in destruction rates resulted in imbalanced ending age-class

structures. In the presence of stand destruction, it seemed impossible for teak plantations to reach a normal forest condition. Although reducing cutting-age limits increased the financial benefit of timber production, this management option resulted in greater removals of carbon stocks. The financial benefits of timber production were decrease under the multipurpose management. Nevertheless, the multipurpose management maintained carbon stocks and produced better ending age-class structures compared to the timber management. The proposed harvest scheduling model can be used to assist forest managers in determining optimal harvest volumes and developing relevant management scenarios for teak or other plantations at risk of stand destruction. Thus, it provides a useful forest planning tool to support SFM of plantation forests in Java or other regions with similar problems.

#### Acknowledgement

The author thanks Perum Perhutani, especially staff of Kebonharjo FMU for their kind assistances in providing necessary data and documents for this study. Valuable inputs and comments from Dr. Satoshi Tatsuhara, Dr. Norihiko Shiraiishi, Dr. Teddy Rusolono, Dr. Bahruni, and anonymous reviewers are greatly appreciated.

#### Appendix

1 a) In Equation [4] and Equation [5], the vector  $\mathbf{x}_t$ , vector  $\mathbf{h}_c$ , matrix  $\mathbf{R}$ , and matrix  $\mathbf{S}$  are defined as follows (adapted from Reed & Errico 1986):

$$\mathbf{x}_t = \begin{bmatrix} x_{1,t} \\ x_{2,t} \\ \vdots \\ x_{k,t} \end{bmatrix}, \quad \mathbf{h}_c = \begin{bmatrix} h_{c1,t} \\ h_{c2,t} \\ \vdots \\ h_{ck,t} \end{bmatrix}$$

$$\mathbf{R} = \begin{bmatrix} q_1 & q_2 & q_3 & \cdots & q_{k-1} & q_k \\ (1-q_1) & 0 & 0 & \cdots & 0 & 0 \\ 0 & (1-q_2) & 0 & \cdots & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & (1-q_{k-1}) & (1-q_k) \end{bmatrix}$$

$$\mathbf{S} = \begin{bmatrix} (-1+q_1) & (-1+q_2) & (-1+q_3) & \cdots & (-1+q_{k-1}) & (-1+q_k) \\ (1-q_1) & 0 & 0 & \cdots & 0 & 0 \\ 0 & (1-q_2) & 0 & \cdots & 0 & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & (1-q_{k-1}) & (1-q_k) \end{bmatrix}$$

1 b) In the constraint of LP model, matrix  $\mathbf{A}$  (with  $kN \times kN$  elements) is composed of identity matrix  $\mathbf{I}$  (with  $k \times k$  elements), matrix  $\mathbf{R}$ , and matrix  $\mathbf{S}$ , while vector  $\mathbf{b}$  (with  $kN \times 1$ ) is composed of matrix  $\mathbf{R}$  and vector,  $\mathbf{x}_1$  which are concatenated as follows (see also Reed & Errico 1986):



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