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CONSERVATION OF FOREST, BASED ON A FUELWOOD SUBSTITUTE AS WELL AS CONSIDERING THE CULTURAL AND SPIRITUAL VALUES: AN OPTIMAL FUELWOOD HARVEST MODEL

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Excessive fuelwood harvest is a major cause of deforestation in developing countries. To mitigate this, various preventive measures have been introduced in different countries. The availability of affordable substitutes to the community dependent on the forest for domestic energy consumption may prevent further forest degradation. A stock-dependent optimal control model of fuelwood harvest from a natural forest is presented here and comparative statics has been used to show that the presence of a fuelwood substitute will reduce its harvest and increase the forest stock. The model indicates that the availability of cheaper and high-energy content alternatives for fuelwood can substantially reduce fuelwood extraction from a forest. Also, a lower discount rate and higher cultural and spiritual values (CSV) will keep the optimal forest stock close to its carrying capacity and reduce fuelwood harvest. The model reveals that the maximum sustainable yield of forest stock and the ratio of energy content per unit mass of fuel plays a central role in the fate of forest stock and the level of fuelwood harvest. An empirical example of the Southeast Asian Forest growth model along with Liquid Petroleum Gas (LPG) as a substitute has been used to illustrate the results. The outcomes of this study can be incorporated into forest conservation policies.

Keywords: fuelwood, optimal control theory, comparative statics, maximum sustainable yield

Introduction

Forest plays a central role in meeting the social and economic needs of the people living in its vicinity. Along with timber, the forest provides Non-Timber Forest Products (NTFP) like fuelwood, fodder and medicinal plants to these people. Also, people through their cultural and spiritual values (CSV) are aware of the socioecological functions played by the forest (Daniel et al., 2012; Laird, 1999).

A lot of literature has been devoted to understanding the impact of timber harvesting on the size and health of forest stock (Amacher, Ollikainen and Koskela, 2009; Faustmann, 1849; Hartman, 1976). However, in developing countries, one of the major reasons for deforestation is excessive fuelwood extraction (Pattanayak, Sills and Kramer, 2004; Lefevre, Todoc and Timilsina, 1997; Troncoso et al., 2007; Ullah et al., 2021). For instance, fuelwood constitutes 76.3% and Liquid Petroleum Gas (LPG) is only 11.5% of the energy mix in Indian rural households (National Sample Survey Organization (NSSO), 2012; Singh et al., 2021). Much of this dependence on fuelwood comes from the tribal and poor communities living in the proximity of forests. Also, the increase in the population and lack of appropriate and affordable energy options and the very nature of the state-owned natural forests as an open access land resource have aggravated the situation (Heltberg, Arndt and Sekhar, 2000; Jagger and Kittner, 2017). Fuelwood extraction-induced deforestation has several ecological consequences viz. loss of biodiversity, deterioration of watershed, soil erosion and release of carbon dioxide into the atmosphere (Brown et al., 2009; Pandey, 2002; Rasquinha and Mishra, 2021).

Several factors determine the per capita fuelwood consumption viz. household income, availability of alternatives to fuelwood, use of efficient cooking/heating equipment, proximity to forest and climatic conditions. However, in recent times increase in the income of households has facilitated switching from fuelwood to relatively cleaner and more convenient energy options like LPG and Biogas, provided such options are readily available (Pandey, 2002; Singh, M. et al., 2021). Studies in developing countries have shown that appropriate fuelwood substitutes or efficient use of fuelwood can prevent deforestation (Adhikari, 2002; Agarwala et al., 2017; Roy, 2008). Thereby, understanding the role of fuelwood extraction on the forest stock and the determinants of fuelwood harvesting remains an essential question for sustainable policy decision-making. Moreover, the role of non-monetary forest values like cultural and spiritual values (CSV) on forest health needs further studies (Agnoletti and Santoro, 2015; Lowman and Sinu, 2017; Torres et al., 2016). Often forest-dependent communities in developing countries have religious, taboo and myth-based forest values that can be captured by CSV. Considering fuelwood substitutes and CSV into forest conservation policies together may have better outcomes than otherwise.

Several modelling techniques have been used to evaluate the multifunctional role of forests (including fuelwood harvest) in meeting the socioeconomic needs of the communities dependent on them (Brahma et al., 2021). The utility maximization model has been used for the analysis of household production, consumption and substitution of fuelwood (Joshee, Amacher and Hyde, 2000). However, the study ignores the importance of the dynamic nature of the forest and focuses on the static utility model. The role of socioeconomic and physical factors and the interaction of these factors on the forest regime have been analysed using optimal control theory (Gompil, Tseveen and Almasbek, 2022; Kant, 2000). The impacts of non-timber valuation on the forest stock and timber harvest have been analysed using optimal control theory and comparative statics (Gan, Kolison and Colletti, 2001). A discrete optimal control model has been used to evaluate the role of fuelwood burning on the climate (Lyon, 2004). Dynamic optimization techniques have been used to model the non-timber forest extraction in a Spatio-temporal context (Robinson, Albers and Williams, 2008). Dynamic system modelling-based study indicates that fuelwood harvesting causes forest degradation, forest fire, institutional failure and socio-ecological problems in forest-dependent communities (Ranjan, 2018). Most of these studies consider fuelwood under the broad heading of non-timber benefits and do not exclusively analyse the impact of fuelwood extraction on the forest stock and harvest decision. Also, the role of the consumer's choice between fuelwood and its substitute on the forest stock and harvest decision has not been studied using optimal control theory and comparative statics. Moreover, conventionally forest growth is considered the function of time. Such considerations are appropriate when the forest is private property and the objective of the owner is to harvest timber at an optimal rotation period (Amacher, Ollikainen and Koskela, 2009). Such an approach is not appropriate for open-access resources like a large natural forest with uneven age classes and multiple uses. Thereby, a more appropriate determinant for harvest decision should be forest stock size rather than time.

This article considers a present value maximization problem where the households living in the vicinity of an open-access natural forest are to maximize their CSV and utility of fuelwood harvest in the presence of a substitute. Optimal control theory is used to analyse the role of the discount rate, CSV function, the marginal utility of fuelwood (MUF) and the marginal utility of substitute (MUS) on the marginal forest growth. Also, comparative statics is used to evaluate the impact of a marginal change in the discount rate and CSV, marginal utility of fuelwood and substitute on the optimal forest stock and optimal fuelwood harvest. An empirical example of the impacts of fuelwood harvest in the presence of a substitute on the biomass stock of the Southeast Asian Forest has been used to illustrate the theoretical results. The outcomes of this model can be generalised to all forms of forest wood products and forest values other than CSV.

Materials and methods

In the present model, the households living in the vicinity of the state-owned open-access natural forest and accessing the forest fuelwood for domestic purposes are considered consumers (Bhutia, 2021). The consumers, along with fuelwood also reap forest benefits in the form of timber and other NTFP. Moreover, consumers have a system of CSV that encourages forest conservation (Ihemezie et al., 2021; Shoddo, 2022). This model is an extension of the work of Gan, Kolison and Colletti (2001), incorporating the role of non-monetary forest values and fuelwood substitutes in the exploitation of wood products, like fuelwood, from the open-access forests in developing countries.

The model

The objective of the consumer is to maximize his utility, $U(.)$ and the CSV, $V(.)$ by selecting the optimal rate of fuelwood harvest, $h(t)$ subject to various constraints given below:

$$P: \max_h \int_0^\infty \left[U\left(h(t), s(t)\right)+V\left(x(t)\right)\right]e^{-\delta t} \tag{1}$$

Subject to:

$$\frac{dx}{dt}=g\left(x(t)\right)-h(t) \tag{2}$$

$$x(0)=x_0 \tag{3}$$

$$x(t)\geq 0 \tag{4}$$

$$s(t)\geq 0 \tag{5}$$

$$0\leq h(t)\leq h_{\max} \tag{6}$$

$$d=ph(t)+\rho s(t) \tag{7}$$

where: the forest stock, $x(t)$ follows a quasiconcave growth function, $g(x(t))$ such as logistic growth function (Amacher, Ollikainen and Koskela, 2009; Gan, Kolison and Colletti, 2001). The instantaneous forest growth, $\frac{dx}{dt}$ is a function of its growth function, $g(x(t))$ and fuelwood harvest, $h(t)$. $h_{\max}$ is the maximum fuelwood harvest rate defined by the availability of capital and labour for the extraction of fuelwood. The utility function, $U(.)$ is a quasiconcave function over fuelwood harvest, $h(t)$ and its substitute, $s(t)$. The daily domestic energy demand, d is the sum of the product of fuelwood harvest, $h(t)$ and its energy content per unit biomass, p and the product level of consumption of its substitute, $s(t)$ and the energy content of the substitute per unit mass, ρ

The following assumptions are made for the convenience of the model:

1. $g_x \begin{cases} >0, \text{ when } x< x_{msy} \\ = 0, \text{ when } x = x_{msy} \text{ and } g_{xx}<0 \\ <0, \text{when } x>x_{msy} \end{cases}$
2. $V_x>0$, when $V_{xx}<0$
3. $U_h>0$, when $U_{hh}<0$
4. $U_s>0$, when $U_{ss}<0$

where: $g_x=\frac{\partial g}{\partial x}$ and $g_{xx}=\frac{\partial}{\partial x}\frac{\partial g}{\partial x}$ and so on, are partial derivatives. Assumption (1) states that there exists a forest stock size, x_{msy} called Maximum Sustainable Yield (MSY) stock, below which the marginal forest growth increases while above this value the marginal forest growth decreases. The marginal forest growth is zero when forest stock is at MSY stock size. Marginal change in the marginal forest growth is negative. Similarly, assumptions (2), (3) and (4) state that, CSV function, MUF and MUS are increasing functions over their variables and their rate of increase is decreasing over their variables respectively

Analysis of the model

The current-value Hamiltonian corresponding to equation (1) is given by:

$$H=\left(x(t), h(t), \mu(t)\right)=U\left(h(t), s(t)\right)+V\left(x(t)\right)+\mu(t)\left[g\left(x(t)\right)-h(t)\right] \tag{8}$$

where: $\mu(t) = \lambda e^{\delta t}$; λ – the adjoint variable; δ – the discount rate; t – the time and $\mu(t)$ – the shadow price of the forest growth function. The shadow price captures the non-market value of the forest in the form of ecological, cultural, spiritual, health and to some extent recreational services provided by the forest. Substituting $s(t)$ in $U(.)$ by rearranging equation (7), modifies the utility function as:

$$U\left(h(t), s(t)\right)=U\left(h(t),\frac{d}{\rho}-\kappa h(t)\right) \tag{9}$$

where: $\kappa=\frac{\rho}{p}$ the ratio of energy content per unit mass of the substitute to that of fuelwood. The first-order condition of $H(.)$, as given in equation (8), is given by:

$$\frac{\partial H}{\partial h}=U_h-\kappa U_s-\mu=0 \tag{10}$$

$$-\frac{\partial H}{\partial h}=-V_x-\mu g_x=\frac{d\mu}{dt}-\delta\mu \tag{11}$$

Rearranging equations (10) and (11) give:

$$\mu(t) = U_h - \kappa U_s \tag{12}$$

$$\frac{d\mu}{dt} = (\delta - g_x)\mu(t) - V_x \tag{13}$$

Equation (12) suggests that at the optimal utility level the shadow price of the forest stock is equal to the difference between, κth-times the MUS from the MUF. Equations (2), (3), (12) and (13) along with inequations (4) to (6), constitute a simultaneous equation system. By setting $dx/dt = dh/dt = 0$, we can solve for the optimal steady-state solution, (x^*, h^*). If the forest stock is not at its optimal stock level, then the fuelwood harvest decision can follow any of the two optimal paths. These are the Asymptotic Approach Path or the Most Rapid Approach Path (MRAP), to reach the optimal forest stock (Clark, 1990). As per the MRAP or 'Bang-Bang' control approach, the optimal harvest, h^* is:

$$h^* = \begin{cases} h_{\max}, & \text{when } x > x^* \\ g(x^*), & \text{when } x(t) = x^* \\ 0, & \text{when } x(t) < x^* \end{cases} \tag{14}$$

Equation (14) suggests that the optimal harvest is equal to the maximum harvest rate whenever the forest stock is above the optimal forest stock. At the sub-optimal forest stock level, fuelwood harvest is not appropriate. Lastly, under optimal forest stock conditions, the fuelwood harvest rate equals the natural growth rate of the forest.

Results and discussion

Effect of fuelwood harvest on forest stock

Total differentiation of equation (12), equating it with equation (13) and setting $dh/dt = 0$ gives:

$$(\delta - g_x)(U_h - \kappa U_s) - V_x = 0 \tag{15}$$

Rearranging equation (15) gives the discount rate as:

$$\delta = g_x + \frac{V_x}{U_h - \kappa U_s} \tag{16}$$

Equation (16) establishes the relationship of discount rate with the marginal growth of forest stock, g_x, a marginal growth of CSV, V_x, MUF and MUS. In the absence of CSV, $V_x = 0$:

$$\delta = g_x \tag{17}$$

Equation (17) implies that, in the absence of CSV, to maximize the fuelwood harvest under steady-state conditions, the marginal forest growth should be equal to the discount rate. Since $g(x(t))$ is a quasiconcave function, there exists a relation between optimal forest stock and MSY:

$$\left.\begin{aligned} x^* > x_{msy}, &\ causes\ g_x < 0 \\ x^* = x_{msy}, &\ causes\ g_x = 0 \\ x^* < x_{msy}, &\ causes\ g_x > 0 \end{aligned}\right\} \tag{18}$$

Equation (18) implies that, depending on the nature of the marginal forest growth function, the optimal forest stock will be below, equal to or above the MSY of the forest (Gan, Kolison and Colletti, 2001). Moreover, as:

$$\delta \to 0,\ g_x \to 0 \Rightarrow x^* \to x_{msy} \tag{19}$$

The limiting condition (19) implies that, as the discount rate approaches zero, the marginal forest growth also approaches zero. From equation (18), this change suggests that as the forest growth rate approaches zero, the optimal forest stock approaches MSY stock size.
In the absence of MUF, equation (16) is expressed as:

$$\delta = g_x - \frac{V_x}{\kappa U_s} \tag{20}$$

Equation (20) implies that in the absence of MUF the discount rate is less than the marginal forest growth by a factor equal to the ratio of a marginal change in CSV to κ-times the MUS. In the absence of fuelwood harvest, the lowered discount rate will help in conserving the forest. In the absence of MUS, $U_s = 0$, equation (16) is expressed as (Gan, Kolison and Colletti, 2001):

$$\delta = g_x + \frac{V_x}{U_h} \tag{21}$$

Equation (21) implies that in the absence of MUS the discount rate is more than the marginal forest growth by a fraction equal to the ratio of marginal growth of CSV to the MUF. Comparing equation (21) with equation (17) we observe that, in the absence of a substitute, even after considering CSV, the MUF pushes the discount rate above the marginal forest growth, leading to the exploitation of the forest for fuelwood, timber and NTFP. Rearranging equation (16) gives:

$$g_x = \delta - \frac{V_x}{U_h - \kappa U_s} \tag{22}$$

Equation (22) suggests that at equilibrium the marginal forest growth, g_x could be positive, negative or zero.

Case I: if $\delta = 0$ or $\delta < \frac{V_x}{U_h - \kappa U_s}$, then $g_x < 0$, indicating that the optimal forest stock has exceeded the MSY stock size. Such a situation will prevail if $\frac{U_h}{U_s} > \kappa$. Under such circumstances, the optimal forest stock will be above MSY stock. This will cause the utility-maximizing consumer to harvest fuelwood using the MRAP strategy as given in equation (14).

Case II: if $\delta = \frac{V_x}{U_h - \kappa U_s}$ then $g_x = 0$, indicating that the optimal forest stock is equal to the MSY stock size and the harvest rate is equal to MSY.

Case III: if $\delta > \frac{V_x}{U_h - \kappa U_s}$ or $\frac{U_h}{U_s} < \kappa$ then $g_x > 0$. Under such circumstances, the optimal forest stock will be below the MSY stock size. This will cause the consumer to harvest fuelwood using the MRAP strategy as given in equation (14) and will discourage further fuelwood harvest.

Effect of model parameters on optimal forest stock and optimal harvest

At equilibrium, let us consider that V_x, U_h and U_s approaches certain steady-state values. Hence, let $V_x = \varphi$, $U_h = \alpha$ and $U_s = \beta$. Then equation (16) is accordingly modified to:

$$\delta = g_x + \frac{\varphi}{\alpha - \kappa\beta} \tag{23}$$

Total differentiation of equation (23) and equation (2) at $\frac{dx}{dt} = 0$, constitute a simultaneous equation system:

$$\begin{pmatrix} g_x & -1 \\ g_{xx} & 0 \end{pmatrix} \begin{pmatrix} dx \\ dh \end{pmatrix} = \begin{pmatrix} 0 \\ d\delta - \frac{(\alpha-\kappa\beta)d\varphi - \varphi(d\alpha - \kappa d\beta)}{(\alpha-\kappa\beta)^2} \end{pmatrix} \tag{24}$$

Effect of discount rate

Comparative statics is used to analyse the effect of changes in discount rate alone on the optimal forest stock and optimal harvest, by letting $d\varphi = d\alpha = d\beta = 0$ in equation (24). Also, let:

$$\mathbf{A} = \begin{pmatrix} g_x & -1 \\ g_{xx} & 0 \end{pmatrix} \tag{25}$$

Thus, $|A| = g_{xx} < 0 \Rightarrow |A| \neq 0$. Hence, equation (24) is solved using Cremer's rule:

$$\frac{\partial x^*}{\partial \delta} = \frac{1}{g_{xx}} < 0 \tag{26}$$

and:

$$\frac{\partial h^*}{\partial \delta} = \frac{g_x}{g_{xx}} \begin{cases} >0, \; x < x_{msy} \\ =0, \; x = x_{msy} \\ <0, \; x > x_{msy} \end{cases} \tag{27}$$

Considering assumption (1), equation (26) suggests that an increase in the discount rate will encourage deforestation. On the other hand, equation (27) implies that the optimal harvest increases with an increase in discount rate when forest stock is below MSY stock, while it decreases when forest stock is above MSY stock and optimal harvest is not affected by the change in discount rate when forest stock equals MSY stock.

Table 1 Changes in the sign of $\frac{\partial h^*}{\partial \varphi}$ with change in g_x and value of $\frac{\alpha}{\beta}$ as compared to κ

$\frac{\alpha}{\beta}$ \ g_x	<0	=0	>0
$<\kappa$	>0	=0	<0
$=\kappa$	N.D	N.D	N.D
$>\kappa$	<0	=0	>0

Effect of CSV

Considering, $d\delta = d\alpha = d\beta = 0$, in equation (26) and solving:

$$\frac{\partial x^*}{\partial \varphi} = -\frac{1}{(\alpha-\kappa\beta)g_{xx}} \begin{cases} <0, \; \frac{\alpha}{\beta} < \kappa \\ \text{N.D}^1, \; \frac{\alpha}{\beta} = \kappa \\ >0, \; \frac{\alpha}{\beta} > \kappa \end{cases} \tag{28}$$

and:

$$\frac{\partial h^*}{\partial \varphi} = -\frac{g_x}{(\alpha-\kappa\beta)g_{xx}} \tag{29}$$

From equation (28) it is observed that the optimal forest stock decreases with an increase in CSV when the MRS (marginal rate of substitution) is below the ratio of energy value per unit mass of fuelwood to its substitute (κ). In contrast, optimal forest stock increases when MRS is above κ. The condition is unknown when MRS is equal to κ. Table 1 shows the possible outcomes of equation (29). If the MRS is below κ, the optimal harvest increases remain unaffected or decrease with an increase in CSV when marginal forest growth is negative, zero or positive respectively. If MRS is above κ, the optimal harvest decreases remain unaffected or increase with an increase in CSV when marginal forest growth is negative, zero or positive respectively. There is no solution for change in the optimal harvest of fuelwood with a change in CSV when MRS equals κ.

Effect of marginal utility of fuelwood

Considering $d\delta = d\varphi = d\beta = 0$, in equation (24) and solving:

$$\frac{\partial x^*}{\partial \alpha} = \frac{\varphi}{(\alpha-\kappa\beta)^2 g_{xx}} < 0 \tag{30}$$

and:

$$\frac{\partial h^*}{\partial \alpha} = \frac{\varphi g_x}{(\alpha-\kappa\beta)^2 g_{xx}} \begin{cases} >0, \; x < x_{msy} \\ =0, \; x = x_{msy} \\ <0, \; x > x_{msy} \end{cases} \tag{31}$$

Equation (30) suggests that the optimal forest stock decreases with an increase in MUF. Equation (31) implies that the optimal harvest increases with an increase in MUF when forest stock is below MSY stock and decreases when forest stock is above MSY stock. The optimal harvest remains unaffected by the change in MUF when forest stock equals the MSY stock.

Effect of marginal utility of substitute

Considering $d\delta = d\varphi = d\alpha = 0$, in equation (24) and solving gives:

$$\frac{\partial x^*}{\partial \beta} = -\frac{\varphi}{(\alpha-\kappa\beta)^2 g_{xx}} > 0 \tag{32}$$

[1] N.D means Not Defined.

and:

$$\frac{\partial h^*}{\partial \beta} = -\frac{\varphi g_x}{(\alpha-\kappa\beta)^2 g_{xx}} \begin{cases} <0,\ x<x_{msy} \\ =0,\ x=x_{msy} \\ >0,\ x>x_{msy} \end{cases} \tag{33}$$

Equation (32) suggests that the optimal forest stock increases with an increase in the marginal utility of the substitute. Equation (33) implies that the optimal harvest decreases with an increase in MUS when forest stock is below MSY stock and increases when forest stock is above MSY stock. The optimal harvest remains unaffected by the change in MUS when forest stock equals the MSY stock.

Empirical examples

The theoretical model discussed above requires further illustration using an empirical model. For this, the Southeast Asian forest model was considered, as it fits the scenario of forest conditions prevalent in developing countries (Figure 1) (Kallio, Dykstra and Binkley, 1987):

$$g(x) = \frac{dx}{dt} = b_0 x - b_1 x^2 \tag{34}$$

where: $b_0 = r$, the biotic potential of the forest, $b_1 = \frac{r}{K}$, and K is the carrying capacity. According to this model the natural regenerative growth of the forest, $b_0 x$ is restricted by the interspecific competition, $b_1 x^2$ leading to a sigmoidal growth of forest biomass. The (b_0, b_1) of Southeast Asian forests is (0.035, 0.000136). Equation (34) is a logistic equation which is strictly quasiconcave and meets the need of the model discussed here (Figure 1)

Let us assume that $V_x = \varphi$, $U_h = \alpha$ and $U_s = \beta$, under optimum conditions where:

$\alpha = \{10, 20, 30, 40, 50, 60, 70, 80, 90\}$;
$\beta = \{90, 80, 70, 60, 50, 40, 30, 20, 10\}$;
$\varphi = \{0, 2, 4, 6, 8, 10, 12\}$;
$\delta = \{0, 2, 4, 6, 8, 10\}$,

thereby, $\alpha/\beta = \{0.111, 0.250, 0.429, 0.667, 1, 1.5, 2.333, 4, 9\}$ are the MRS values considered. Using equations (2), (4), (5), (12), (13) and (34) the optimal forest stock, x^* and optimal harvest, h^* are given as:

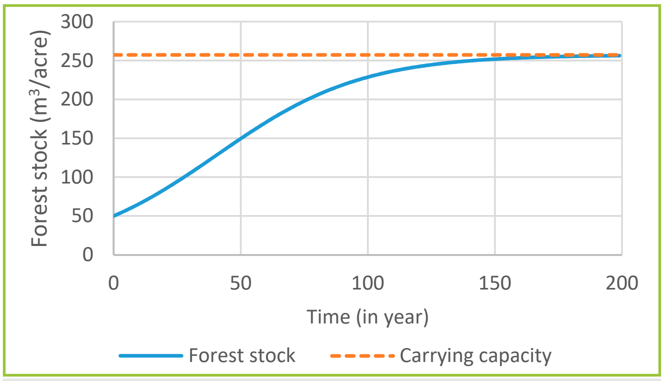


Figure 1 Logistic growth models of the Southeast Asian forest expressed by the relation $x_t = \frac{x_0 K}{x_0 + (K - x_0)e^{-rt}}$, where x_0 is the initial forest biomass stock, K is the carrying capacity, r is the biotic potential and t is the time in years

$$x^* = \frac{1}{2b_1}\left(\frac{\varphi}{\alpha-\kappa\beta} - \delta + b_0\right) \tag{35}$$

$$h^* = \frac{x^*}{2b_1}\left(b_0 - \frac{1}{2}x^*\right) \tag{36}$$

The value of κ is the ratio of the energy content of forest biomass to substitute. The value of κ was considered, based on the energy content of substitutes like LPG (= 46.1 MJ/kg) and fuelwood of tropical trees (= 20.90 MJ/kg) (Bauer, 1996; Duruaku et al., 2016; Spîrchez, Lunguleasa and Croitoru, 2017). κ value for fuelwood to LPG was estimated as 0.453. A similar empirical analysis was done using Southeast Asian Forest model and Biogas. The outcomes of the analysis yielded similar results as in the case of the Southeast Asian Forest model and LPG. Using equations (35) and (36), the effect of MRS of fuelwood by LPG, under various levels of CSV and discount rates on optimal harvest and optimal forest stock of the forest model was estimated (Figure 2A, B). The figure suggests how much to harvest in the long run for one acre of the forest at a given discount rate and MRS for a specific CSV. Based on the values of (b_0, b_1) the carrying capacity of the Southeast Asian Forest was estimated as 257.353 m³/acre. Considering $K/2$ as the MSY stock, the MSY stock and MSY for Southeast Asian forests were estimated as 128.676 m³/acre and 2.252 m³/acre/year, respectively.

Figure 2A, B indicates that in the absence of CSV ($\varphi = 0$) and zero discount rate, optimal forest stock reaches MSY stock and optimal harvest reaches MSY of the forests. A marginal rise in the discount rate, such as ($0 < \delta < 4$), triggers rapid fuelwood harvesting at all MRS, leading to clear-cutting of the forest. Under conditions where MRS $= \frac{\alpha}{\beta} < \kappa$ leads to $\frac{\varphi}{\alpha-\kappa\beta} < \delta$. This is shown in all cases of non-zero CSV with MRS<0.453. These conditions cause deforestation. The conditions where the discount rate is substantially greater than $\frac{\varphi}{\alpha-\kappa\beta}$ leads to a clear-cutting of the forest. For Conditions where $\frac{\varphi}{\alpha-\kappa\beta} = \delta$, it causes optimal forest stock to approach MSY stock. On the other hand, $\frac{\varphi}{\alpha-\kappa\beta} - \delta \geq r$ causes optimal forest stock approach to the carrying capacity and optimal harvest to zero. For instance, a non-zero CSV and MRS at 0.667, leads to optimal forest stock reaching the carrying capacity of Southeast Asian Forest, while optimal harvest to zero. These conditions are prevalent at higher CSV. optimal forest stock and optimal harvest will remain constant for any combination (α, β, φ) as long as $\left(\frac{\varphi}{\alpha-\kappa\beta} - \delta\right)$ remain unchanged.

Figure 2A, B indicates that with an increase in CSV, the optimal forest stock is progressively maintained at its carrying capacity, even at a higher MRS and discount rate. At a higher CSV, a high MRS does not lead to a decline in the optimal forest stock. Similarly, the effect of a progressive increase in the discount rate is nullified by the CSV of forest stock and maintains the forest stock at its carrying capacity. On the other hand, at a lower CSV, a combination of a high discount rate and a high MRS ratio facilitated the decline of the forest stock. CSV of 12 and above, the forest is protected from deforestation. Regarding optimal harvest, an increase in CSV delays the harvest for a higher MRS value. Also, optimal harvest reaches MSY at a still higher MRS with the increase in CSV. A higher discount rate facilitates harvest at a lower MRS. However, a greater CSV deflects the effect of a higher discount rate and delays the harvest to a higher MRS.

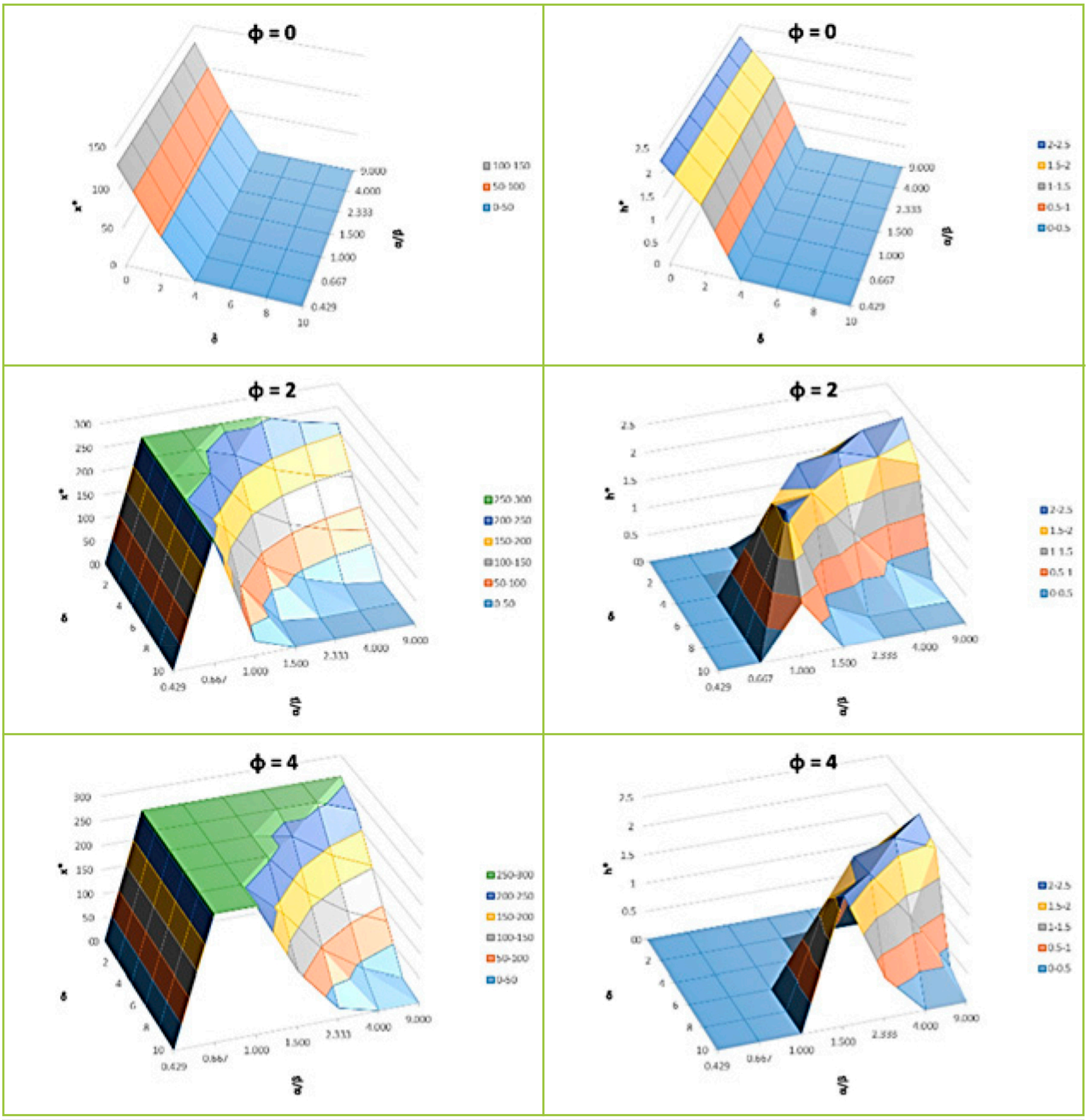


Figure 2A Optimal Forest stock (m^3/acre) (first column) and optimal harvest (m^3/acre/year) (second column) of Southeast Asian Forest with LPG as fuelwood substitute, under varied CSV (φ), MRS (α/β) and discount rates (δ) scenarios

Figure 3A/a and 3A/b, gives a cross-section of optimal forest stock and optimal harvest of Southeast Asian Forest. Figure 3A/a indicates that at a fixed discount rate and CSV, a rise in MRS causes a decline in optimal forest stock. In the case of optimal harvest, the initial increase in optimal harvest quickly declines due to a fall in the optimal forest stock (Figure 3A/b). An increase in the discount rate causes a further and steeper decline in optimal forest stock over MRS. A proportionate amount of optimal harvest also increases with the rise in the discount rate. Figure 3A/c illustrates the effect of the discount rate on optimal forest stock. Optimal forest stock declines over discount rate. The effect gets pronounced with the rise in MRS. optimal harvest initially rises over the discount rate, followed by a sharp decline due to a fall in the optimal forest stock (Figure 3A/d). A rise in MRS shifts the optimal harvest towards a lower discount rate. A rise in CSV promotes higher optimal forest stock and keeps the forest stock close to the carrying capacity (Figure 3B/e). A rise in discount rate delays this process to a higher CSV. Optimal harvest is higher at lower CSV. But with a rise in the discount rate, fuelwood harvest continues at a higher CSV, though at a lower intensity (Figure 3B/f).

Discussion

Open-access natural forests such as the state-owned revenue forests in developing countries play a central role in meeting the basic social and economic needs of the landless and marginal farmers as well as the poor

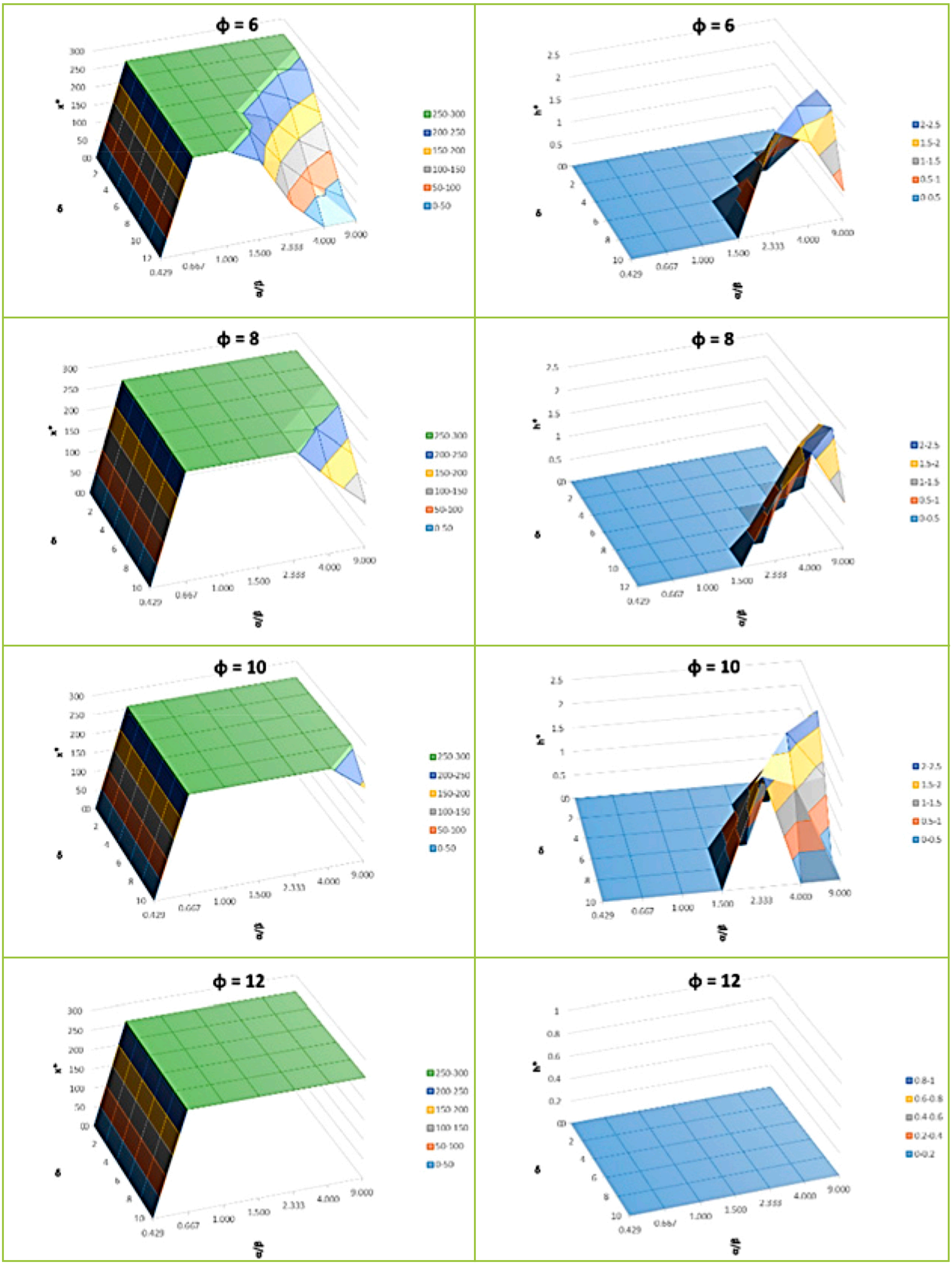


Figure 2B Optimal Forest stock (m³/acre) (first column) and optimal harvest (m³/acre/year) (second column) of Southeast Asian Forest with LPG as fuelwood substitute, under varied CSV (φ), MRS (α/β) and discount rates (δ) scenarios

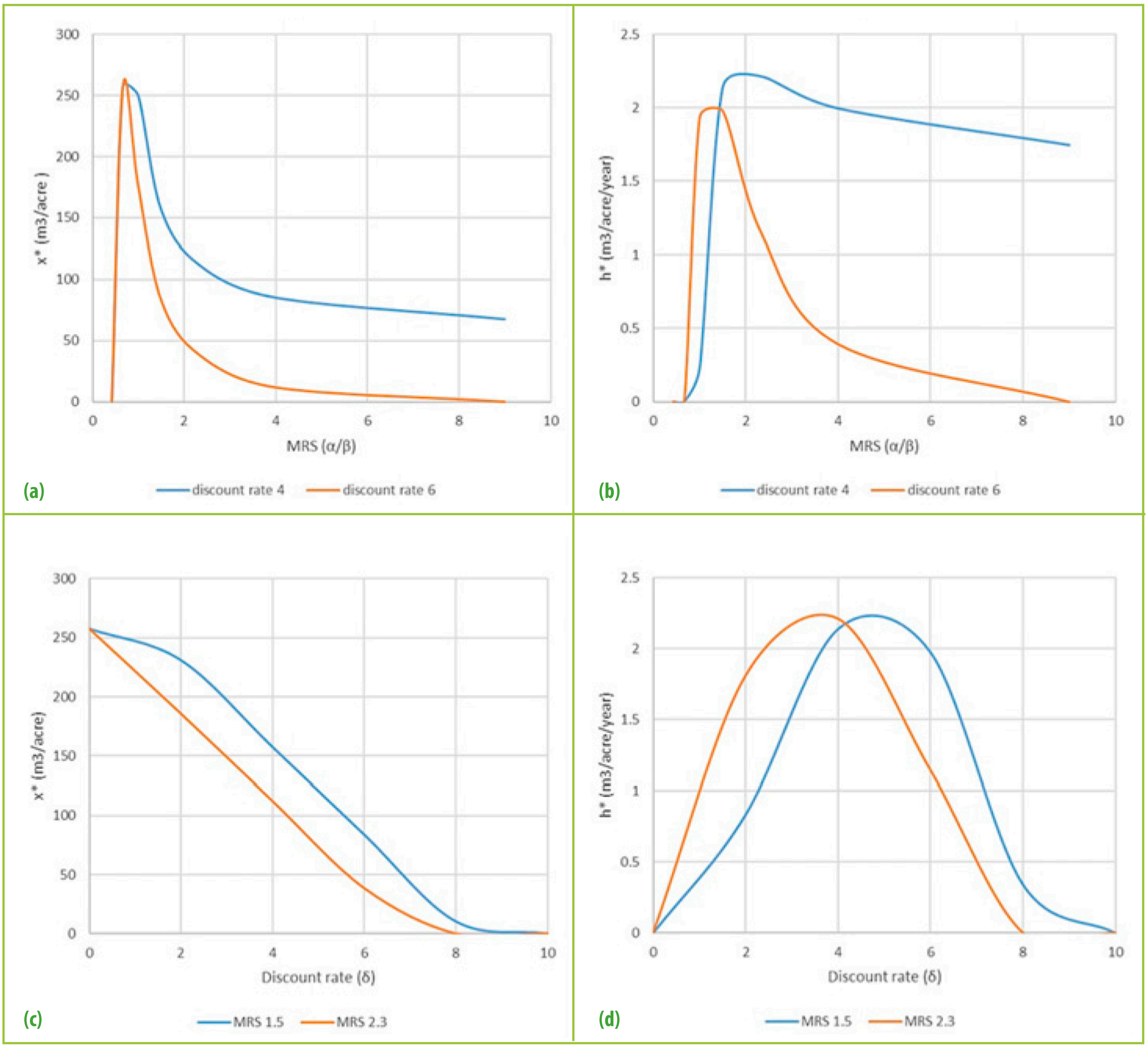
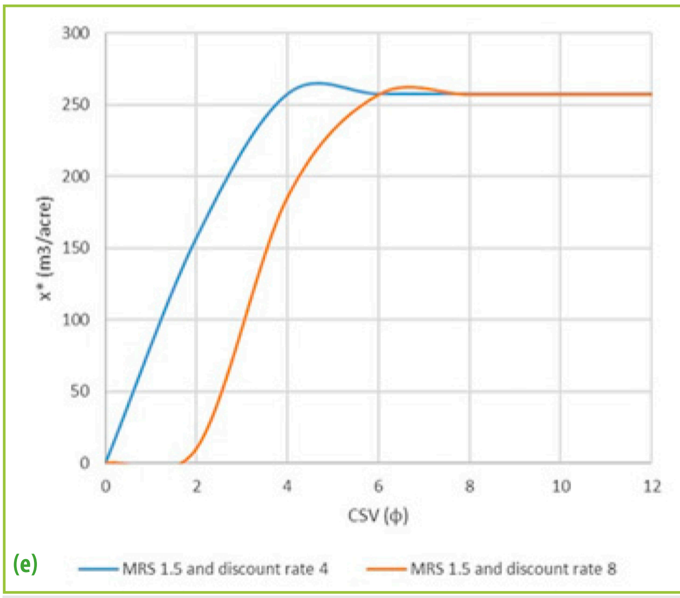


Figure 3A (a) Optimal Forest stock and (b) optimal harvest, of Southeast Asian Forest over MRS, when discount rate $\delta = 4$ and 6, and CSV $\varphi = 2$. (c) Optimal forest stock and (d) optimal harvest of Southeast Asian Forest over discount rate, when MRS $\alpha/\beta = 1.5$ and 2.33, and CSV $\varphi = 2$. (e) Optimal forest stock and (f) optimal harvest of Southeast Asian Forest over CSV, when discount rate $\delta = 4$ and 8, and MRS $\alpha/\beta = 1.5$



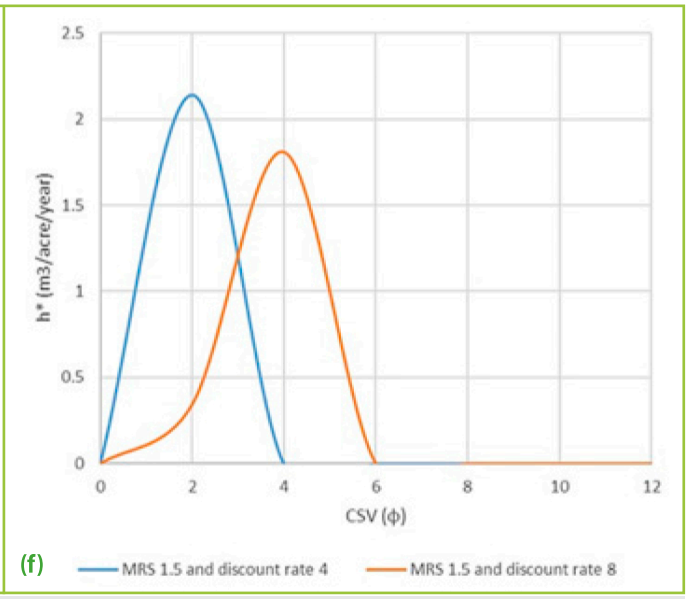


Figure 3B (a) Optimal Forest stock and (b) optimal harvest, of Southeast Asian Forest over MRS, when discount rate δ=4 and 6, and CSV φ=2. (c) Optimal forest stock and (d) optimal harvest of Southeast Asian Forest over discount rate, when MRS α/β=1.5 and 2.33, and CSV φ=2. (e) Optimal forest stock and (f) optimal harvest of Southeast Asian Forest over CSV, when discount rate $\delta = 4$ and 8, and MRS α/β=1.5

habitants living in the vicinity of forests. Along with low-grade timber, these forests provide them with fodder, fuelwood, and other forms of non-timber benefits. Excessive population increase and remoteness of such habitations from proper domestic energy amenities have caused over-dependence on fuelwood extraction. Under this scenario, the provision of subsidised alternatives to fuelwood like LPG can substantially reduce the dependency on fuelwood and exempt the forest from further exploitation.

In Gan, Kolison and Colletti (2001), the effects of the discount rate, silvicultural cost, timber benefits and non-timber forest benefits on forest stock, silvicultural effort and harvest were studied. On the contrary, the present study assesses the effect of fuelwood substitute, forest values and discount rate on forest stock and biomass harvest in terms of fuelwood extraction. To do this, a theoretical model was constructed to analyse the impact of MRS of fuelwood, discount rate and CSV on the forest stock and level of fuelwood harvest. An empirical example of the Southeast Asian Forest and LPG as the fuelwood substitute was used to illustrate the results.

The first-order condition of optimal control theory indicated that in the absence of CSV, the fuelwood extraction should be such that the marginal forest growth equals the discount rate (Gan, Kolison and Colletti, 2001). The model showed that the discount rate decreases in the absence of MUF and increases in the absence of MUS. This observation has a direct relation to the conservation policy. A low discount rate promotes deforestation while a high discount rate delays deforestation (Bulte and van Soest, 1996; Greģe-Staltmane and Tuherm, 2010).

Marginal growth of the forest was influenced by the κ value, the ratio of energy per unit of the substitute to that of fuelwood. MRS greater than κ promoted fuelwood harvest and led to a decline in the marginal growth of the forest. An opposite condition of MRS, lesser than κ discouraged fuelwood harvest and maintained greater forest stock. Hence, the κ value can be considered a critical value that switches consumer behaviour from exploitation to conservation. Thus, while considering fuelwood substitutes forest managers should consider a substitute that yields greater energy per unit mass to maintain healthy forest stock. Apart from the κ value, marginal forest growth and harvesting decision were also influenced by the discount rate. Marginal growth in forest stock was negative when the discount rate was zero. It was positive when $\dfrac{V_x}{U_h - \kappa U_s}$ was less than the discount rate. This aspect of the relationship between instantaneous forest stock and discount rate needs further studies.

Comparative statics indicated that the optimal forest stock and optimal harvest were sensitive to changes in the discount rate, MUF, MUS and marginal change in CSV. However, unlike Gan, Kolison and Colletti (2001) the determinant of the matrix of simultaneous equations, **A** in this paper was negative. Hence, apart from model variables like fuelwood substitute and CSV, the present model intrinsically deviates from the work of Gan, Kolison and Colletti (2001). The marginal rate of change of optimal forest stock to discount rate was negative (Gan, Kolison and Colletti, 2001). The marginal rate of change of optimal fuelwood harvest to discount rate was positive, zero or negative whenever the forest stock was below, equal to or above the MSY stock respectively. These outcomes indicate that forest stock has a critical role to play in the decision of consumers (Clark, 1990).

The marginal rate of change of optimal forest stock to CSV was negative or positive depending on whether the MRS was less than or greater than the κ value. This indicates that a low energy-yielding substitute will promote deforestation even when the forest is valued through CSV. On the other hand, a high-energy substitute complemented with high CSV will promote forest conservation. The unexplained relations between the marginal rate of change of optimal forest stock and marginal change in optimal harvest when MRS equals κ are probably due to non-economic exogenous variables (Lee et al., 2015).

The marginal rate of change of optimal forest stock to MUF was negative. This indicated that continuous fuelwood extraction eroded the forest stock. In contrast, the relationship between forest health and MUF remained ambiguous in the study of Gan, Kolison and Colletti (2001). The marginal change of optimal harvest to MUF was positive, zero or negative when forest stock was above, equal to or below the MSY stock. The marginal change in optimal forest stock to MUS was positive. While the marginal change of optimal harvest to MUS was negative, zero or positive when forest stock was below, equal to or above the MSY stock.

The empirical example of the Southeast Asian Forest and LPG as a substitute for fuelwood showed that an increase in discount rate led to optimal harvest at a lower value of MRS of fuelwood by LPG. Moreover, the increase in the CSV delays the optimal harvest to a higher value of MRS. The effect of the discount rate was offset by an increase in CSV. At zero CSV and discount rate, the optimal harvest approached MSY, and optimal forest stock approached MSY stock. However, at higher values of discount rate when CSV was not considered, the optimal forest stock quickly declined towards the complete clear-cutting condition. With the decrease in forest stock, the harvest also declined. The decline in harvest was further encouraged by a higher discount rate. A very low MRS, such as 0.434 or below led to a clear cut of the forest in all values of discount rate and CSV. A value of MRS between 0.434 and 0.667 led to rapid recovery of the forest stock as the optimal harvest was not viable in all values of discount rate and CSV. However, with MRS being above 0.667 the optimal harvest increased with an increase in the discount rate and a decrease in CSV. The effect of the discount rate as well as higher MRS was completely offset by a high CSV of 12 and above. These observations are in harmony with the results of the theoretical model constructed here.

The outcomes of this study are in harmony with field studies. For instance, a study in Uganda suggests that forest degradation is more intense due to fuelwood extraction in the absence of suitable substitutes (Sassen, Sheil and Giller, 2015). Furthermore, a study on the role of improved chulla, a form of cooking oven, on the fuelwood consumption in Chunati Wildlife Sanctuary in Bangladesh by female forest user groups indicated that efficient fuelwood use can reduce dependence on the forest (Roy, 2008). Contrary to this study, other studies indicate that subsidised fuel for households may not necessarily prevent deforestation and forest degradation. There can be other non-economic drivers that may negate the effects of fuelwood substitutes (Lee et al., 2015). Considering the importance of forest value, as stated in this study, non-monetary forest values like CSV have positive impacts on forest conservation (Lowman and Sinu, 2017). Forest conservation policies should include and promote such forest values (Agnoletti and Santoro, 2015). On the contrary, ignoring such forest values may erode such value systems and promote deforestation (Torres et al., 2016). The model presented in this study theoretically supports the observation of the above studies.

The model discussed here is essentially classic and deterministic. Moreover, the analysis is based on the comparative statics of steady-state conditions of the forest stock. These conditions were adopted for ease of analysis, at the cost of ignoring the dynamic and stochastic nature of the forest system. Consideration of steady-state conditions is appropriate for long-term equilibrium and sustainable forestry. However, in many cases, a forest may not be or is not intended to be in a steady-state condition.

The theoretical model and empirical example as discussed here provide relevant insights into the role of the discount rate, CSV and MRS on the optimal forest stock and optimal harvesting of fuelwood. It showed that the MSY stock and ratio of energy values per unit mass of fuelwood to its substitute play a critical role in the fate of the forest and the level of fuelwood extraction. Furthermore, it was observed that providing a relevant and subsidised energy option like LPG to the households can substantially reduce fuelwood extraction and maintain the forest stock close to its carrying capacity. Also, the high CSV of the forest to the community can significantly reduce the exploitation of the forest. Thereby, a state may develop welfare schemes to provide subsidised and better substitutes like LPG, biogas or energy plantation to the forest-dependent communities to protect the forest from further exploitation. Moreover, conservation agencies can encourage the CSV of the forest through festivals and folk culture that promotes forest conservation.

Conclusion

The present study provides certain insights into the relationship between fuelwood substitute, CSV, and forest conditions. The optimal forest stock and optimal harvest critically depend on the ratio of the energy value of the substitute to that of the fuelwood. In addition to that, the level of CSV of the consumers' community and the discount rate of the forest has a significant role to play in the fate of a forest. These findings can act as policy interventions toward prevailing forest conservation policies. The model is deterministic, and the analysis is static. These limitations can be overcome by introducing stochastic modelling and performing sensitivity analysis. This study can be further extended by analysing the effects of varied substitutes and forest types on the forest stock and harvest decision. The introduction of stochasticity can present a more realistic model. The role of CSV in optimal harvest needs further analysis. Based on these findings, efforts can be made by government agencies and NGOs to promote subsidised alternatives to fuelwood extracted from the forest. Alternatives like subsidised LPG cylinders, microfinancing of fuelwood-producing agroforestry or energy plantation schemes can spare the natural forests from further exploitation. Also, the promotion of CSV by upholding forest-friendly cultural values and conserving the current forest stock can improve the forest regime.

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