Wageningen University - Social Sciences

**Environmental Economics and Natural Resources (ENR)**

# Modelling tropical forest management with a finite time horizon model using GAMS

Transforming a steady state forest model into a finite time horizon model

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## Abstract
There is a large literature on bioeconomic modelling of forest management. However, these models either use a steady state model or a finite time horizon model. There is not yet a good comparison between the two approaches. In this thesis, the steady state model used in Indrajaya et al. (2016) used for determining the effect of carbon pricing on carbon storage is transformed to a model with a finite time horizon. Results for the new model with a horizon of 120 years are obtained using the modelling software GAMS. The findings of the two models are compared. Similarities include the shape of the carbon supply curve and the optimal carbon price in the case of no harvest, while the finite time horizon model reports lower carbon prices are needed to increase carbon storage when the forest manager has the option to periodically harvest the forest. When the initial forest stand is known, the finite time horizon approach may better reflect optimal carbon pricing.

## Acknowledgement
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# 1. Introduction

## 1.1 Background

Forestry plays an important role in mitigating climate change. Where global annual greenhouse gas emissions were about 9.8Gt $CO_2e$ in 2014 (Boden et al. 2017), Pan et al. (2011) estimate that about 861Gt of carbon, which equates to 3157 Gt $CO_2$, is stored in forests, whether it be its biomass, deadwood, litter or soil. Furthermore, Van der Werf et al. (2009) estimate that 6-17% of annual $CO_2$ emissions are caused by deforestation and the loss of carbon storage as its result. Therefore, preventing deforestation and increasing forest stands can be an effective tool in climate mitigation. Since 2005, the United Nations Framework Convention on Climate Change (UNFCCC) has been working on the *Reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries (REDD+)* programme. This programme creates opportunity for developing countries to receive financial benefits from a broad scale of sources when these countries take measures to reduce deforestation.

It is important to determine how high these financial benefits should be to improve the amount of carbon stored in forests. Benefits which are too high are inefficient and benefits which are too low can have no meaningful impact on forest stands. Therefore, broad research on (tropical) forest growth is necessary to understand what dynamics influence forest stands, both from ecology and social sciences. Forest management incorporates both ecological aspects (such as forest growth, damage from harvesting and forest composition) and economic decision making (such as maximizing profits and discounting future benefits).

Bio-economic modelling allows for combining these two different disciplines. In my thesis, I will aim to improve on the already vast literature on bio-economic forest modelling. This is relevant for two different reasons. The first reason is that it adds to the literature of compensating for indirect use values of forests. Pearce et al. (2003) identify four different values of forestry. These are direct use values (e.g. timber extraction and tourism), indirect use values (e.g. protection of watersheds and storing of carbon), option values (the value of having the option to use the forest) and nonuse values (the willingness to pay for just having a forest, unrelated to any present or future planned use of the forest). Storing carbon is an indirect use value, because carbon storage is important in fighting climate change, but it is valuable for the global population and not so much for the forest manager. Awaiting the REDD+ programme being incorporated into the global carbon trade, an effective price for carbon credits is yet to be determined and this thesis aims to add additional understanding of how forest growth and economic decision-making affect forest stand composition.

Second, this thesis aims to be directly applicable for policy makers considering implementing a carbon remuneration policy. Determining optimal carbon prices can help governments implement efficient policies, and this thesis investigates how a carbon price can influence harvesting decisions. It can also help forest managers, when carbon remuneration is implemented, to research if either harvesting the forest or leaving the forest stand intact is the profit maximizing strategy. Last, governments for example in Southeast Asia typically use cutting cycle spans of about 25-35 years (Putz & Romero 2015), and by determining optimal cutting cycle regimes this thesis can help determine if the regime in place is efficient.

## 1.2 Problem statement

There are already numerous papers published on bio-economic modelling of forest growth. However, these papers tend to focus on either steady state modelling or finite time modelling of forest stands. There has been no research done on comparing the results of the two methods of modelling for carbon pricing and economic decision making for a similar forest stand and with the same forest growth model. This thesis aims to fill this gap by transforming a steady state model into a model with a finite time horizon. More information on the two different types of models can be found in Chapter 2.

More specifically, the thesis will focus on the recent papers by Indrajaya et al. (2016) and Van der Werf et al. (2019). These papers combine modelling of forest growth and economic behaviour of the forest manager. In these papers, the forest stand is determined endogenously by how optimal management of the forest will ultimately shape this forest, and the resulting forest approximates a typical forest for this region. The papers also investigate the impact of damages from harvesting regimes to forests on the steady state forest stand, cutting cycle and the carbon supply curve, which plots the additional amount of carbon stored under increasing carbon prices. They use a matrix stand growth model for the forest, allowing for two commercial tree species and non-commercial trees.

The model used by Indrajaya et al. (2016) concerns an uneven-aged, multi-species model. When a forest is even-aged (which is the case for plantation forests), the whole forest is cut at the end of the cutting cycle. For uneven-aged forests, however, there can be restrictions regarding which trees are cut, and extraction may only be profitable for certain trees inside a forest. The multi-species aspect of the forest is also important to note, because the existence of different tree species has important consequences for how the forest grows and the value of timber production (e.g. some trees do not hold commercial value). How these aspects impact the modelling of forest management is explained in more detail in Chapter 2.

In this thesis, I aim to extend the analysis from Indrajaya et al. (2016) by shifting from a steady state model towards a model with a finite time horizon, allowing an exogenously determined forest stand. I will use data on forest stands in Kalimantan by Sheil et al. (2010) to construct the composition of the forest. The model will be programmed and analysed using GAMS, a software package which can be used to solve optimization problems.

## 1.3 Main question and sub-questions

The main research question of this thesis will be:

*How do the results of the steady state model used by Indrajaya et al. (2016) for forest management in Kalimantan, Indonesia, change with regard to cutting cycle length and carbon storage when transformed to a model with a finite time horizon?*

To answer this main question, a number of subquestions have to be answered, which are:

a) *What are the key elements of steady state and finite time horizon models for forest management according to literature?*
b) *How is the model used by Indrajaya et al. (2016) structured with a finite time horizon?*
c) *What are the model parameters and what are the values of these parameters to be used in the model?*
d) *What are the results of the new model in terms of economic behaviour of the forest manager and the resulting forest stand?*
e) *How do the results of the new model compare to the results of the model used by Indrajaya et al. (2016)?*

## 1.4 Data and method

For the data on forest stand composition and forest growth in Kalimantan, Indonesia, I will use data from Sheil et al. (2010) and Indrajaya et al. (2016), where Sheil et al. (2010) provides the initial forest stand data and Indrajaya et al. (2016) both forest growth and economic parameters. There will be a finite time horizon for this model, set to 120 years. As profits and costs are discounted over time, I expect that going beyond this time horizon has little consequences for the outcome of the model. The forest manager in this model optimizes his Net Present Value (NPV), which is the value of the revenues and costs over time. As the manager chooses how long the cutting cycles are and the size of the harvest, these will be the endogenous variables of the model. The model will be solved using the software package GAMS. The GAMS files for different scenarios are accompanied with this version of the thesis, as well as an Excel-sheet containing data from solves of these GAMS-files.

## 1.5 Thesis outline

The thesis is constructed in the following manner:

In chapter 2, I provide a literature review in which key elements for modelling of forest management are discussed and which will be used as the theoretical basis of this thesis. First, different approaches to forest growth and when to use which are approach are examined. Second, I show the fundamentals of forest economics. Third, I will discuss finite time horizon models and steady state models, their characteristics and how they differ.

In chapter 3, the model used by Indrajaya et al. (2016) is constructed using a finite time horizon instead of a steady state approach. First, the NPV-maximization problem for the case where there is not a carbon remuneration scheme is constructed. Then, a carbon price mechanism is implemented in the NPV-maximization problem.

In chapter 4, the parameters and their values for this model are described. This chapter is divided into descriptions of the initial forest stand, the forest growth model and the economic parameters.

In chapter 5, the results for the model are described. This chapter starts with the simple case of no carbon remuneration, after which scenario's with different carbon prices are discussed. Finally, a carbon supply curve for this model is constructed.

In chapter 6, the results will be compared with the results from Indrajaya et al. (2016) and the key similarities and differences between the two models are discusses.

Chapter 7 is the closing chapter, consisting of discussion and the conclusion. The discussion lays out the key takeaways from this thesis and also discusses some limitations of the model used in this thesis.

# 2. Bio-economic modelling of forest stands: key concepts

In this chapter I will answer subquestion a: *What are the key elements of steady state and finite time horizon models for forest management according to literature?* Bio-economic modelling in general is an interdisciplinary research method, combining ecology and economics. Ruben et al. (1998) identify two major components of a good integrated analytical framework in the field of bio-economic modelling: first, there has to be a (p.332) "thorough understanding of the biophysical processes". Second, the choices that managers make (in their paper, Ruben et al. (1998) apply this to farmers) and how these are influenced by socio-economic factors, objectives, markets, infrastructure and so on.

Both the ecological and economic parts of forest economic models are examined in this chapter. I will first look at how the ecological aspect can be modelled. After this, I will provide the basics for forest economics, after which models with finite time horizons and steady state models are investigated. I will finish this chapter with a conclusion, which will provide an answer to subquestion a.

## 2.1 Forest growth models

Forest growth models differ in how detailed they describe the ecological processes of forest growth. Peng (2000) compare three branches of uneven-aged forest growth models suitable for forest management modelling, in ascending order of complexity: (1) growth and yield functions, (2) size-class (or diameter class) models and (3) individual tree models. These three types of models and when these are applied will be explained below, with most attention going to the diameter class model as this will be used for the model in this thesis. Because this takes most attention in this section, I will first give examples of the other two models.

### *2.1.1 Growth and yield functions*

The first and most simple approach is growth and yield functions. According to Peng (2000), the robustness and simplicity of these growth and yield functions are useful for plantations (which are mostly single-species and even-aged) but are of limited use in multi-species and uneven-aged forest models as the number of species and diameter classes cannot easily be described by this type of models. Van Kooten et al. (1995) give an illustrating example of this kind of forest growth models. Their model takes the following form:

$$v(t) = kt^a e^{-bt} \tag{2.1}$$

Where $v(t)$ is the amount of timber at time $t$, $k$ is a growth parameter, and growth accelerates with $t^a$ and decelerates with $e^{-bt}$. They use a general timber growth function for forest growth (combining different species of trees) in coastal regions in Canada, which is estimated by Thompson et al. (1990) to be:

$$v(t) = 0.000573\, t^{3.7819}\, e^{-0.030965t} \tag{2.2}$$

Forest growth in this kind of models depends only on time. The authors chose this form for its simplicity: it can be easily estimated, differentiated and integrated. This allows for a mathematical analysis of optimal forest management given a certain growth function. For plantation models this form works, as the form exhibits reducing growth until an optimum is reached and the authors demonstrate this can be estimated quite accurately. However, it lacks details such as (but not limited to) tree mortality, accounting for different species and growth parameters for different tree sizes.

### *2.1.2 The individual tree model and ecosystem models*

Whereas the whole-stand model is used for its simplicity, individual tree models are used to model forest growth very precisely. One such model is the FORMIX model, constructed by Bossel and Krieger (1991). This model allows the modeller to assign coordinates to all single trees, and enter characteristics such as height and width for all these trees. Growth of these trees over time is influenced by pronounced spatial factors such as light and photosynthesis conditions (which is affected by the presence of larger trees nearby) and gap formation and closure between trees. This type of modelling therefore allows for very precise forecasts of growth of specific trees and plots, but because of its complexity, it can be very difficult to estimate all of the relevant parameters (Peng 2000). Because of the limited scope of this thesis, I will not explain the whole individual tree model in further detail.

### 2.1.3 The diameter class model

The final growth model, and the model used in this thesis is the diameter class model. The first to construct such a model was Usher (1966), after which plenty of papers, notably papers such as Boscolo et al. (1997), Buongiorno et al. (1995; 2012) and the subject of this thesis, Indrajaya et al. (2016), also used this approach. As this thesis focusses on the growth model used in Indrajaya et al. (2016), I will explain the growth model used in the remainder of this section.

The forest is represented by a vector $\boldsymbol{y_t} = [y_{ijt}]$, in which y is the number of trees per species i ∈ (1…m) and diameter class j ∈ (1…n) in time period t (Indrajaya et al. (2016) use a two-year time period, so one t is equal to two years). There are a number of things that change the forest stand in each growing period $\theta$, besides harvesting. A tree can either (1) die, (2) stay alive and grow, (3) stay alive and stay in the same diameter class, or (4) be introduced in the forest stand through ingrowth. Death happens with probability $o_{ij}$, growth happens with probability $b_{ij}$ and staying in the same diameter class happens with $a_{ij}$ = 1 – $b_{ij}$ – $o_{ij}$. Note that these parameters are different for each species in each diameter class.

For forest growth, the following set of equations is used:

$$y_{i1t+\theta} = I_{it} + a_{i1}(y_{it} - h_{i1t}) \quad (2.3)$$
$$y_{i2t+\theta} = b_{i1}(y_{i1t} - h_{i1t}) + a_{i2}(y_{i2t} - h_{i2t}) \quad (2.4)$$
...
$$y_{int+\theta} = b_{i(n-1)}\left(y_{i(n-1)t} - h_{i(n-1)t}\right) + a_{in}(y_{int} - h_{int}) \quad (2.5)$$

The first equation shows that all trees in the smallest diameter class are a result from ingrowth $I_{it}$ and trees which remain in this diameter class after harvest and have not grown in the previous time period. Equations 2 and 3 show that all trees in a specific diameter class $2 \ldots j$ in $t + \theta$ are from either growth or from staying in the same diameter class during the previous time period.

Ingrowth $I_{it}$ is given by the following equation:

$$I_{it} = \beta_{0i} - \beta_{1i} \sum_{j=1}^{n} B_{ij}\left(y_{ijt} - h_{ijt}\right) + \beta_{2i} \sum_{j=1}^{n}(y_{ijt} - h_{ijt}) \quad (2.6)$$

Where ingrowth parameters $\beta_{0i}, \beta_{1i}, \beta_{2i} > 0$ and $B_{ij}$ is the basal area of a tree. This equation means that ingrowth depends on an exogenous parameter ($\beta_{0i}$), the basal area of the other trees (which in this case means that forest density negatively affects ingrowth) and on the amount of trees (e.g. more trees of the same species means there is a higher chance of ingrowth of that species).

Indrajaya et al. (2016) substitute eq. 2.6 into eq. 2.3 to get:

$$y_{i1t+\theta} = \beta_{0i} + e_{i1}(y_{i1t} - h_{i1t}) + \cdots + e_{in}(y_{int} + h_{int}) \quad (2.7)$$

Where

$$e_{i1} = a_{i1} + \beta_{1i}B_{i1} + \beta_{2i} \quad (2.8)$$
$$e_{ij} = \beta_{1i}B_i + \beta_{2i} \text{ for j>1} \quad (2.9)$$

Forest growth in one period can therefore be expressed with eq. 2.10:

$$\boldsymbol{y}_{t+\theta} = \boldsymbol{G}(\boldsymbol{y}_t - \boldsymbol{h}_t) + \boldsymbol{c} \quad (2.10)$$

Harvest $\mathbf{h}_t$ = $[h_{ijt}]$ is the harvest at time t. **G** is the forest growth matrix representing forest growth, while **c** accounts for ingrowth, representing the number of trees which exogenously enter the smallest diameter class. The forest growth matrix **G** consists of the following matrices (eq. 2.11):

$$\boldsymbol{G} = \boldsymbol{A} + \boldsymbol{R} \quad (2.11)$$

**A** is a matrix consisting of upgrowth matrices $\mathbf{A}_i$ (eq. 2.12):

$$\mathbf{A} = \begin{bmatrix} \boldsymbol{A}_1 & 0 & \dots & 0 \\ 0 & \boldsymbol{A}_2 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & \boldsymbol{A}_m \end{bmatrix} ; \mathbf{A}_i = \begin{bmatrix} a_{i1} & 0 & \dots & 0 \\ b_{i2} & a_{i2} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & b_{in} & a_{in} \end{bmatrix} \quad (2.12)$$

$\mathbf{A}_i$ contains the probability for each species i for staying in the same diameter class ($a_{ij}$) or growing to the next diameter class ($b_{ij}$). **A** combines the data for these different species.

**R** is a matrix representing how the existing stand structure affects ingrowth:

$$\mathbf{R} = \begin{bmatrix} \boldsymbol{R}_{11} & \boldsymbol{R}_{12} & \dots & \boldsymbol{R}_{1m} \\ \boldsymbol{R}_{21} & \boldsymbol{R}_{22} & \dots & \boldsymbol{R}_{2m} \\ \dots & \dots & \dots & \dots \\ \boldsymbol{R}_{m1} & \boldsymbol{R}_{m2} & \dots & \boldsymbol{R}_{mm} \end{bmatrix} ; \mathbf{R}_{ik} = \begin{bmatrix} e_{i1} & e_{i2} & \dots & e_{in} \\ 0 & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 \end{bmatrix} \quad (2.13)$$

$\mathbf{R}_{ik}$ contains information on how the existence of a tree species in a specific diameter class affects the probability of ingrowth of a specific species k (note that the index k is used to show which species' ingrowth is affected by species i). **R** once again combines the data for these specific species.

Finally, we have the exogenous ingrowth vector **c**:

$$\mathbf{c} = \begin{bmatrix} \boldsymbol{c}_1 \\ \boldsymbol{c}_2 \\ \dots \\ \boldsymbol{c}_m \end{bmatrix} ; \boldsymbol{c}_i = \begin{bmatrix} \beta_{i0} \\ 0 \\ \dots \\ 0 \end{bmatrix} \quad (2.14)$$

Which just contains the exogenous ingrowth parameters.

Furthermore, Indrajaya et al. (2016) also use a damage function to account for damages caused by logging practices, which differs for conventional logging and reduced-impact logging. Many papers (such as Indrajaya et al. 2016, Boscolo et al. 1997, Boscolo & Vincent 2000) make a distinction between conventional logging (CL) and reduced impact logging (RIL). Whereas CL is cheaper to conduct, it causes more damage to trees than RIL, which through a number of planning measures and more sophisticated techniques aims to reduce the impact of logging on other trees. The predicted damage reduction from RIL differs per paper; Indrajaya et al. (2016) estimates RIL to cause on average 17% less damage to trees across all diameters, going up to 25% of all trees with a diameter of 50 cm and above, while Boscolo et al. (1997) uses the estimate of Pinard et al. (1995) of a reduction in damages from 40% to 15%.
This damage function is first formulated by Macpherson et al. (2010), which takes the following form:

$$\boldsymbol{d}_{st} = \left(\textstyle\sum_i \sum_j h_{ijt}\right)\boldsymbol{D}_s \boldsymbol{y}_t \quad (2.15)$$

Of which $\mathbf{D}_s$ is a damage coefficient matrix which is:

$$\boldsymbol{D}_s = \begin{bmatrix} \boldsymbol{E}_s & & 0 \\ & \boldsymbol{E}_s & \\ 0 & & \boldsymbol{E}_s \end{bmatrix} \quad (2.16)$$

$\mathbf{E}_s$ contains damage coefficients which describe which proportions of each diameter class is damaged by logging. Incorporating the damage function into the forest growth function of eq. 2.10 would give the forest growth function which is also used in Indrajaya et al. (2016) and this is shown in eq. 2.17:

$$\boldsymbol{y}_{t+\theta} = \boldsymbol{G}(\boldsymbol{y}_t - \boldsymbol{h}_t - \boldsymbol{d}_t) + \boldsymbol{c} \quad (2.17)$$

## 2.2 Fundamentals of forest economics

In this section, the fundamentals of forest economics are explained. First, the work by Faustmann is examined, after which some important concepts in forest economics are explained.

### *2.2.1 Single-species, single-aged forests, single rotation*

For bio-economic modelling of forest management, there are a number of important concepts to be taken into account when constructing a model. First, it is important to know if the forest is single-species and/or even-aged, or if it is multi-species and/or uneven-aged. For example, a planted forest is normally a single-species and even-aged forest, while a managed forest is not. Second, it is also important to determine whether to maximize profits or earnings for a single rotation or for multiple/infinite rotations. In this section, I will show how to determine the optimal single and infinite rotations for single species, single age forest stands. Even though the model in this thesis is multi-species and uneven-aged, it is important to know how the basic problem is solved.

First, consider a plantation forest. The manager wants to know what the optimal time is to harvest this forest. The forest in this first example will not be replanted after the harvest, i.e. there is only a single rotation of this forest. The forest is planted in year 0. The harvest at the end is equal to the size of the forest. The forest grows each time period, so harvest is time-dependent. Also, there is a fixed cost of planting the forest, and the revenues are discounted over time. The net present value (NPV) function therefore takes the following form:

$$\Pi(t) = \frac{vh(t)}{(1+r)^t} - F \qquad (2.18)$$

$$t \in \{0,1,2 \dots\} \qquad (2.19)$$

Where $\Pi$ is the net present value, $v$ is the value of a single $m^3$ harvested wood, $h(t)$ is both total harvests in $m^3$ wood and the size of the forest at time $t$, $r$ is the discount rate and $F$ are fixed costs for planting a forest. Note that the discount rate is not exponential: here we treat the problem in discrete time (eq. 2.18), instead of continuous time. Now it is important to determine what the optimal value of $t$ is, in other words at what time the forest should be harvested. Campbell (1999) suggests that in the optimum, $\Pi(t) = \Pi(t + dt)$, with $dt$ being a minimum increment in time. Therefore, it approximately holds that $\Pi(t) = \Pi(t + 1)$. With this knowledge, the optimal $t$ can be found (the following analysis follows Campbell (1999)):

$$\Pi\ (t) = \ \Pi(t + 1) \qquad (2.20)$$

Filling in the values for $\Pi\ (t)$ and $\Pi\ (t + 1)$ gives:

$$\frac{vh(t)}{(1+r)^t} - F = \frac{vh(t+1)}{(1+r)^{t+1}} - F \qquad (2.21)$$

Eliminating $-F$ and cross-multiplying both sides gives:

$$vh(t)(1 + r)^{t+1} = vh(t + 1)(1 + r)^t \qquad (2.22)$$

Dividing both sides by $(1 + r)^t$ gives:

$$vh(t)(r + 1) = vh(t + 1), \text{ or, } rvh(t) + vh(t) = vh(t + 1) \qquad (2.23)$$

Rearranging this formula gives:

$$vh(t + 1) - vh(t) = rvh(t) \qquad (2.24)$$

The term $vh(t + 1) - vht(t)$ can be interpreted as the growth of the value of the harvest during one time period, i.e. the marginal growth of the harvest. This means that we can also assume eq. 2.25:

$$\frac{v(dh(t))}{dt} = rvh(t) \qquad (2.25)$$

The left hand side of equation 2.24 represents the additional benefits of letting the forest grow one more year, while the right hand side represents the marginal costs, which is the loss of present value due to discounting. Dividing both sides by $vh(t)$, eq. 2.24 can also be rewritten as:

$$\frac{vh(t+1)}{vh(t)} - 1 = r \qquad 2.26)$$

Eq. 2.26 shows that the optimal time to harvest the forest is when the growth rate of the forest is equal to the discount rate. Also note that initial costs of planting the forest do not influence the result for a single rotation.

### 2.2.2 Single species, single-aged forests: infinite rotations

The analysis in 2.2.1 holds for a situation where there is only one cycle of production. If the manager decides to do perpetual rotations, the optimal rotation period is calculated differently. For this, I use the analysis by Perman et al. (2011), and use the discount rate for discrete time. First, construct the NPV-function for perpetual and infinite rotations.

$$\max NPV: \Pi = \frac{(vh_t)}{(1+r)^t} - F + \frac{(vh_t)}{(1+r)^{2t}} - \frac{F}{(1+r)^t} + \frac{(vh_t)}{(1+r)^{3t}} - \frac{F}{(1+r)^{2t}} + \cdots \quad (2.27)$$

The first term of eq. 2.27 is the first rotation, and it is the same as the right hand side of equation 2.18 where t is the time where harvest takes place. The second and third term are the terms for the second and third rotation. As time increases, future revenues are discounted more heavily and costs lag behind one period because it is assumed that costs for planting a new forest are all made right after the previous rotation has ended. Also, it is assumed that rotation periods are equal.

This equation can also be rewritten by factoring out the discount factors in each time period to get:

$$\Pi = \frac{(vh_t)}{(1+r)^t} - F + (1+r)^{-t}\left(\frac{(vh_t)}{(1+r)^t} - F\right) + (1+r)^{-2t}\left(\frac{(vh_t)}{(1+r)^t} - F\right) + \cdots \quad (2.28)$$

Again, this can be rearranged by factoring out $(1+r)^t$ of the second term of the right hand side of equation 2.28 onwards to get:

$$\Pi = \frac{(vh_t)}{(1+r)^t} - F + (1+r)^{-t}\{\frac{(vh_t)}{(1+r)^t} - F + (1+r)^{-t}\left(\frac{(vh_t)}{(1+r)^t} - F\right) + (1+r)^{-2t}\left(\frac{(vh_t)}{(1+r)^t} - F\right) + \cdots\} \quad (2.29)$$

The term between braces in eq. 2.28 is identical to the right hand side of eq. 2.28, which means that it is equal to $\Pi$. Therefore, we can rewrite the equation to get:

$$\Pi = \frac{(vh_t)}{(1+r)^t} - F + \frac{\Pi}{(1+r)^t} \quad (2.30)$$

The next few steps show how to simplify this equation:

$$\Pi - \frac{\Pi}{(1+r)^t} = \frac{vh_t}{(1+r)^t} - F \quad (2.31)$$

$$(1-(1+r)^{-t})\Pi = \frac{vh_t}{(1+r)^t} - F \quad (2.32)$$

$$\Pi = \frac{\frac{vh_t}{(1+r)^t} - F}{1-(1+r)^{-t}} \quad (2.33)$$

$$\Pi = \frac{vh_t - F(1+r)^t}{(1+r)^t - 1} \quad (2.34)$$

$$\Pi = \frac{vh_t - F}{(1+r)^t - 1} - F \quad (2.35)$$

Equation 2.35 is also known as the *Land Expectation Value* formulation, which is the value of land when used for perpetual timber production (Chang 1981). Now that the function is simplified to equation 2.35, we can determine the optimal rotation period by taking the first order conditions of harvest with respect to $t$, which will be (Campbell 1999, Perman et al. 2011):

$$v\left(\frac{dh_t}{dt}\right) = rvh_t + r\left(\frac{vh_t}{(1+r)^t - 1}\right) \quad (2.36)$$

This is also known as the Faustmann-rule. I will explain the intuition behind eq. 2.36. The left hand side of the equation is the marginal growth of the value of the harvest if the forest is grown for one more time period. In other words, if the forest manager waits for one more time period, the value of the forest increases with $v(\frac{dh_t}{dt})$. The right hand side of the equation consists of the opportunity costs associated with letting the forest growth one more time period: the first term on the right hand side, $rvh_t$, is the forgone interest of not harvesting the forest now, and the second term is the forgone interest from not selling the forest at its current value altogether. These two components together form the opportunity costs, and the optimal rotation period is when these marginal opportunity costs are equal to the marginal growth of the forest.

## 2.3 Finite time horizon models

The economic part of a bio-economic model aims for optimization of a certain objective variable, like revenues or profit. As explained in Chapter 1, the models used in forest economics take the form of finite time models or steady state models. Both are examined in this section and section 2.4, where I will also regard different model assumptions.

For finite time models, mainly net present values (NPV) or some derivation of the NPV is used to determine optimal management. Maximizing the LEV-formula, which is derived in section 2.2.2, is not appropriate because the LEV-formula is used in the case of infinite forest rotations, which is not the case when there is a finite time horizon. Instead, a NPV over a specific time horizon is calculated, in which all revenues and costs over this time period are summed and discounted over time. This is done for a given forest stand in year $t = 0$. This is a fundamental difference to how steady state models function, which is explained in section 2.4. A finite time horizon model takes the general form of eq. 2.37 (using the symbols used in eq. 2.18 and onwards), where T is the time horizon of the model:

$$\max_{h_t} NPV: \sum_{t=0}^{T} \left(\frac{vh_t - F}{(1+r)^t}\right) \tag{2.37}$$

In this case the endogenous variable is $h_t$, the harvest at time $t$. The forest manager tries to maximize his NPV by choosing how much to harvest and when to harvest, making $h$ in every time period the endogenous variable in this model. In the remainder of section 2.3, I will explain a few examples from literature to show how models with a finite time horizon are constructed.

### *2.3.1 Example from Boscolo et al. (1997)*

To illustrate how these models work, take a Boscolo et al. (1997) for example. This paper uses a model with a finite time horizon which maximizes NPV over a period of 200 years for an existing tropical forest in Malaysia. Their growth model is very similar to the growth model used in Indrajaya et al. (2016), and therefore provides some interesting insights and expectations for the model used in this thesis. Their model optimized the following NPV formula:

$$NPV = \sum_{t=0}^{T} \frac{TR_t - TC_t}{(1+r)^t} \tag{2.38}$$

Where $TR_t$ equals total revenues from timber sale in year $t$, $TC_t$ equals total cost in year $t$, $r$ is the yearly real interest rate, and $T$ is the time horizon. They used a time horizon of 200 years and cutting cycles between 30 and 70 years. As the manager in this model can choose how much of the forest he harvests, the revenues and costs are endogenous.

Revenues are calculated by first determining the volume V (in m$^3$) of the harvested tree, which depends on the diameter at breast height D in cm and which are estimated with the following equations:

$$V = 0.3211 - 0.002175D + 0.0003521D^2 \text{ for } 10 \le D \le 30 \text{ cm} \tag{2.39}$$

$$V = 0.1991 + 0.006148D + 0.0004081D^2 \text{ for } 30 \le D \le 60 \text{ cm} \tag{2.40}$$

$$V = 0.8602 - 0.03872D + 0.0013164D^2 \text{ for } D \ge 60\text{cm} \tag{2.41}$$

When the volume of wood harvested from trees is determined, the authors determine net revenues by taking commercial log prices and subtracting harvesting costs and taxes. Trees which would yield a negative net revenue are not harvested.

They found that cutting cycles, which they differed from 30 to 70 years, did not impact NPV too much, because the value from the first harvest in $t = 0$ extracted the most volume. This dominated the NPV calculation, especially since other revenues are discounted. However, the minimum diameter class for felling trees was more important in determining the NPV. Cutting cycles did impact carbon storage, with longer cutting cycles, as would be expected, increasing net present carbon accumulation (discounted carbon storage over time), as fewer harvests mean longer periods of growth for the forest. Furthermore, they found that whatever cutting cycle they chose, the forest stand tends to converge towards a dynamic steady state where growth and harvest are in balance.

### 2.3.2 Example from Tahvonen et al. (2010)

Another example of a diameter class model which can be used with a time horizon is given in Tahvonen et al. (2010). Their model actually uses an infinite time horizon, but the initial forest stand is exogenous which is similar to finite time horizon models and differs from steady state models. This article analyses uneven-aged, single-species (Norway spruce) forest management in Scandinavia. The maximization problem in this article is given as:

$$\max_{h_{st}, s=1\ldots n, t=0,1\ldots} V_1(\boldsymbol{x}_0) = \sum_{t=0}^{\infty}(R_t - C_t)b^t \tag{2.42}$$

With $h_{st}$ being the harvest of the number of trees of size class $s$ at each time period, $\boldsymbol{x}_0$ the initial forest stand, $R_t$ and $C_t$ revenues and costs and $b^t$ is the discount factor, equalling $\frac{1}{(1+r)^t}$. Note that even though the time horizon is set to infinity here, it can also be set to any finite time horizon (which is actually what the authors do, setting the time horizon to resp. 180 and 240 years for 12- and 15-year cutting cycles). The revenue function given by Tahvonen et al. (2010) is:

$$R_t = \sum_{s=1}^{n} h_{st}(\omega_{s1}p_1 + \omega_{s2}p_2) \tag{2.43}$$

Where $\omega_{s1}$ is the saw log volume of a trunk in size class $s$ in m$^3$, $\omega_{s2}$ is the pulpwood volume of a trunk in size class $s$ in m$^3$ and $p_1$ and $p_2$ are the corresponding prices in € per m$^3$. The function in eq. 2.42 sums up all revenues from harvests of all size classes executed at a given time period. The cost function is:

$$C_t = C(\boldsymbol{h}_t, \boldsymbol{d}) + C_f \tag{2.44}$$

Costs are divided into fixed harvesting costs $C_f$ and per tree harvesting costs $C(\boldsymbol{h}_t, \boldsymbol{d})$, which depends on the amount of trees harvested and the diameter of the trees.

In this model, every growth period lasts 3 years, and by including a cutting cycle variable $k$ for which means that $h_{st}$ = 0 when $t \neq k, 2k, 3k, \ldots$, the cutting cycle is chosen manually to determine the optimal cutting cycle. The authors use this model to calculate the maximum sustainable yield of cutting every growth period (by making $k$ the shortest growth period) and optimal management of the forest. One interesting finding, which corresponds with Boscolo et al. (1997), is that the forest stand converges to a steady state when using cutting cycles of 12 and 15 years.

## 2.4 Steady state models

The Faustmann formula maximizes a *Land Expectation Value*, which was explained in section 2.2.2. The LEV formula takes the following form in Indrajaya et al. (2016):

$$\max_{\boldsymbol{y}_T, \boldsymbol{h}_T, T} LEV = \frac{\boldsymbol{v}_S \boldsymbol{h}_T - F}{(1+r)^T - 1} - \boldsymbol{v}_s \boldsymbol{z}_T \tag{2.45}$$

This is a common formulation of steady state modelling, for example Boscolo and Buongiorno (1997) also use this formulation (although they name it the *Soil Expectation* Value, or SEV). Here, the value of the harvest in every rotation cycle is subtracted by the fixed costs in every rotation cycle and divided by the discount rate. Note that this formulation is very similar to equation 2.34, with the main difference being the inclusion of the term $-\boldsymbol{v}_S \boldsymbol{z}_T$. The term $-\boldsymbol{v}_S \boldsymbol{z}_T$ is included to account for the value of the forest stand after each cutting cycle, as this represents an opportunity cost of not harvesting this part of the forest. Chang (1981, p.740) calls this the "opportunity cost of the residual growing stock"). The index $s$ is used to indicate which type of logging practice is used: CL or RIL.

The endogenous variables in this model are the forest stand before harvest, the harvest at the end of each cutting cycle and the length of the cutting cycle. Because forest stand before harvest is endogenous, in fact, the whole forest stand in each time period is endogenous, which means that the initial forest stand is also constructed in this model and not a given.

The model uses the following constraints:

$$\boldsymbol{z}_T = \boldsymbol{y}_T - \boldsymbol{h}_T - \boldsymbol{d}_{sT} \tag{2.46}$$

$$\boldsymbol{d}_{sT} = f_s(h_{ijT}, y_{ijT}) \tag{2.47}$$

$\boldsymbol{y}_{t+\theta} = \boldsymbol{G}\boldsymbol{z}_t + \boldsymbol{c}\ ; \boldsymbol{y}_{t+2\theta} = \boldsymbol{G}(\boldsymbol{y}_{t+\theta}) + \boldsymbol{c} \ldots ; \boldsymbol{y}_{t+\gamma\theta} = \boldsymbol{G}\left(\boldsymbol{y}_{t+\theta(\gamma-1)}\right) + \boldsymbol{c}$ (2.48)

$\boldsymbol{y}_T \geq \boldsymbol{h}_T + \boldsymbol{d}_{sT}$ (2.49)

$\boldsymbol{h}_T, \boldsymbol{y}_T, \boldsymbol{z}_T \geq 0$ (2.50)

$\boldsymbol{h}_{ij} = 0$ for all $j < \eta$ (2.51)

$\boldsymbol{y}_t = \boldsymbol{y}_{t+\gamma\theta}$ for all $t = 1, \ldots, \infty$. (2.52)

Most of these symbols are explained in section 2.2. Eq. 2.46 makes sure that the stand after harvest is equal to the stand before harvest minus harvest minus damages from harvesting. Eq. 2.47 is the damage function, which depends on logging practice, size of the harvest across different trees and tree sizes and the forest stand (which is also explained in section 2.1.3). Eq. 2.48 describes how the stand grows in each growing period. Eq. 2.49 makes sure that the stand before harvest is always bigger than the amount harvested and damaged. Eq. 2.50 is a non-negativity constraint. Eq. 2.51 makes sure that only trees with a diameter size bigger than cutting limit $\eta$ are cut. Finally, eq. 2.52 is the steady state constraint, which makes sure that the forest is the same during each and every cutting cycle, where γ is the number of growth periods (θ) within the harvesting cycle. This also makes the initial forest stand endogenous: the model decides what the initial stand is, and this initial stand is repeated after each cutting cycle.

This last notion is a key difference with finite time horizon models, because finite time models require an initial forest stand in $t = 0$. While the articles examined in section 2.3 do show some convergence towards a steady state, this convergence takes time and this is not taken into account when using a steady state model.

## 2.5 Conclusion

This chapter answers subquestion a: *What are the key elements of steady state and finite time horizon models for forest management according to literature?* The chapter started off explaining some basic concepts of forest economic modelling, such as the Faustmann formulation and logging practices. Then, different types of forest growth models were examined, of which the diameter class model gained most attention because of its application in Indrajaya et al. (2016). After, I examined some models with finite time horizons and the steady state model used in Indrajaya et al. (2016).

The key elements of a forest management model include the forest growth model and the economic model. The key difference between the finite time horizon models and steady state models can be summarized by the determination of the initial forest stand. The finite time horizon allows for an exogenous initial state of the forest, while steady state model determines the initial state of the forest as the optimal initial state. However, finite time horizon models, if ran long enough, tend to also converge to a steady state in the long run. Another major difference is that a steady state model values the remaining stand after harvest, while a finite time horizon only values (discounted) revenues from the forest.

# 3. Model setup

This chapter answers subquestion b: *How is the model structured with a finite time horizon?* This means that in this chapter, just the model and its equations are regarded; discussing model parameters will be done in Chapter 4.

## 3.1 Forest growth part

The model in this paper replicates the forest growth model in Indrajaya et al. (2016), which is described in detail in section 2.2.3. Not only is this the most practical option, it is also necessary to use the same growth model to be able to compare the results of the steady state model and the finite time horizon model.

## 3.2 Economic part

As seen in the examples explained in Chapter 2, the economic decision maker wants to optimize his behaviour. For economic modelling with a finite time horizon, the examples by Boscolo et al. (1997) and Tahvonen et al. (2010) used maximization of the *Net Present Value* to determine the optimal harvesting strategy. To achieve the goal of this thesis of comparing steady state modelling to finite time horizon modelling, it is essential to rewrite the LEV-maximization problem stated in Indrajaya et al. (2016) to an NPV-maximization problem. In this section, first the NPV-formula in the case of no carbon remuneration is constructed, after which the NPV-formulas for carbon remuneration with harvest and without harvest are constructed. These three scenarios will be examined in chapter 5.

### *3.2.1 No carbon remuneration*

As explained in Chapter 2, the NPV is the sum of the discounted streams of revenues minus costs over the time horizon. Applying this to the approach of Indrajaya et al. (2016), the NPV-formula would take the functional form shown in eq. 3.1:

$$\max NPV = \sum_{t=0}^{T} \frac{\boldsymbol{v}_s \boldsymbol{h}_t - F_s}{(1+r)^t} \qquad (3.1)$$

Where **v** is the vector containing net values of the harvested trees under harvesting regimes s ∈ {CL, RIL} after taxes and variable costs in USD/m$^3$ of wood harvested, $\mathbf{h}_t$ is a vector containing the amount of trees harvested of each tree species and diameter class at time t, T is the time horizon, $F_s$ are the fixed costs for harvesting regimes s and r is the discount rate.

In the model, there are two decision variables: the length of the cutting cycle, for which the symbol k is used, and the amount of trees harvested at the end of each cutting cycle, $\mathbf{h}_t$. We also allow the model to harvest in t=0. Furthermore, it is assumed that fixed costs only occur at the end of each cutting cycle and at t=0. Finally, in the case of no carbon remuneration scheme, we assume that the forest manager uses either conventional logging practices or reduced impact logging, depending on which strategy is most profitable for the manager. Incorporating this into eq. 3.1, the NPV-maximization problem is shown in eq. 3.2:

$$\max_{k,\boldsymbol{h}_t} NPV = \sum_{t=0}^{T} \frac{\boldsymbol{v}_s \boldsymbol{h}_t - F_{s,t}}{(1+r)^t} \qquad (3.2)$$

In order to make this model function well, the following equations and restrictions are applied to the model:

$$\boldsymbol{y}_{t+1} = \boldsymbol{G}(\boldsymbol{y}_t - \boldsymbol{h}_t - \boldsymbol{d}_{s,t}) + \boldsymbol{c} \qquad (3.3)$$

$$\boldsymbol{d}_{s,t} = \left(\sum_i \sum_j h_{ijt}\right) \boldsymbol{D}_{CL} \boldsymbol{y}_t \qquad (3.4)$$

$$\boldsymbol{y}_t, \boldsymbol{h}_t, \boldsymbol{d}_{s,t} \geq 0 \qquad (3.5)$$

$$\boldsymbol{y}_t \geq \boldsymbol{h}_t + \boldsymbol{d}_{s,t} \qquad (3.6)$$

$$\boldsymbol{h}_{ij} = 0 \text{ for all } j<\eta \qquad (3.7)$$

$$\boldsymbol{h}_t = 0 \text{ when } t \neq 0, k, 2k, 3k, \ldots, \qquad (3.8)$$

$$F_{s,t} = 0 \text{ when } t \neq 0, k, 2k, 3k, \ldots, \qquad (3.9)$$

Note that most of these restrictions are also explained in section 2.4, but for completeness they will also be explained here. Eq. 3.3 is the forest growth equation which is also seen in eq. 2.17. Likewise, eq. 3.4 is the damage function which was shown in eq. 2.15. Eq. 3.5 is the non-negativity constraint, which makes sure that there can be no negative forest stand, harvest or damage. Eq. 3.6 is a harvest constraint which ensures that the total amount of harvest and damage cannot exceed the forest stand. Eq. 3.7 is also a harvest constraint which ensures that trees in the smallest diameter classes cannot be harvested. Finally, equations 3.8 and 3.9 are the cutting cycle constraints which make sure that harvest and fixed costs only occur at the end of each cutting cycle.

### 3.2.2 Carbon remuneration and harvesting

The NPV-formula in eq. 3.2 will be used in this thesis for the case where there is no carbon remuneration. In this section, the NPV-formula for the case where there is a carbon remuneration program is constructed. First, it is necessary to determine how much carbon is stored in the forest at a given time. This is done by first assuming the amount of *above ground biomass (agb)* that each tree in each diameter class contains. Above ground biomass is defined by FAO (2007) as "all living biomass above the soil including stem, stump, branches, bark, seeds and foliage." Following Indrajaya et al. (2016), *agb* in tonnes per tree for each diameter class is calculated by (eq. 3.10):

$$agb_j = \rho \exp(\alpha_0 + \alpha_1 ln\overline{DBH_j} + \alpha_2 ln\overline{DBH_j^2} + \alpha_3 ln\overline{DBH_j^3} \qquad (3.10)$$

Where $\rho, \alpha_0, \alpha_1, \alpha_2, \alpha_3$ are parameters and $\overline{DBH_j}$ is the average diameter of the diameter class. The *agb*-values of the different tree species and diameter classes are given in chapter 4. Knowing the *agb*, the amount of $CO_2$ stored is calculated by (eq. 3.11):

$$\boldsymbol{\chi} = \frac{44}{12}\sigma \boldsymbol{AGB} \qquad (3.11)$$

Where $\boldsymbol{\chi}$ is the vector containing the average carbon storage per diameter class in tonnes of $CO_2$, $\sigma$ is the share of carbon stored in above ground tree biomass (which is estimated to be 0.47 by Indrajaya et al. (2016), following IPCC (2006)), and **AGB** is the vector containing all *agb* values of the different diameter classes. The term $\frac{44}{12}$ is used to express $\boldsymbol{\chi}$ in $CO_2$ instead of just carbon, as it is the ratio of the molecular mass of $CO_2$ to the atomic mass of carbon.

In Indrajaya et al. (2016), carbon remuneration for $CO_2$ storage above a certain baseline is rewarded every 2 years, and the present value of the carbon remuneration is added to the LEV. This remuneration comes in the form of temporary carbon credits. Indrajaya et al. (2016) give the following equation to give the relation between the permanent credits under the EU ETS program (which is also the price for emission allowances under the EU ETS) and temporary credits: $p_\infty = p\left((1+r)^\theta - 1\right)^{-1}$, where $p_\infty$ is the price of the permanent credit, p the price of the temporary credit and $\theta$ is the expiration period of the temporary credit. Under the 12% discount rate used in this thesis (see Chapter 4), a temporary carbon price of 1 USD is worth 3.93 USD of permanent credit.

Furthermore, the forest manager is obligated to use reduced impact logging (RIL) in order to be eligible to carbon remuneration. The usage of a baseline is necessary because the intention is only to reward additional carbon storage and not the full amount of carbon stored. Following this approach, in this model, forest managers are remunerated price $p$ for each tonne of $CO_2$ stored in the forest at every time period $t$ above a certain baseline. This baseline is determined by first calculating the optimal harvest strategy without carbon remuneration under conventional logging practices and determining the average amount of $CO_2$ stored. This average serves as the baseline and its calculation is shown in eq. 3.12.

$$baseline = \frac{\sum_{t=0}^{T} \boldsymbol{\chi y}_{t,CL}}{T} \qquad (3.12)$$

If the amount of $CO_2$ stored drops below this baseline, the returns will be negative and the carbon remuneration mechanism will serve as a carbon tax. Therefore, the remuneration is calculated by multiplying price $p$ with carbon storage vector $\boldsymbol{\chi}$ and forest stand vector $\boldsymbol{y_t}$ minus the baseline average carbon storage. This leads to the NPV-formula for carbon remuneration which is shown in eq. 3.13. Note that fixed costs are still imposed even if the manager chooses not to harvest the forest in order to enforce the cutting cycle length.

$$\max_{k,\boldsymbol{h_t}} NPV = \sum_{t=0}^{T} \frac{\boldsymbol{v_s h_t} + p(\boldsymbol{\chi y_t} - baseline) - F_{RIL,t}}{(1+r)^t} \qquad (3.13)$$

### *3.2.3 Carbon remuneration without harvesting*

If the carbon price is sufficiently high enough, it might be the best strategy to not harvest at all anymore. This will also be investigated. In this case, there will also be no more fixed costs. The NPV formula in this case will not have any choice variables and it is shown in eq. 3.14.

$$NPV = \sum_{t=0}^{T} \frac{p(\chi y_t - baseline)}{(1+r)^t} \tag{3.14}$$

# 4. Model calibration

In this chapter, the estimation of the model and its parameters is explained, thus answering subquestion c: *How are the model and its parameters estimated?* The data comes from two primary sources: Sheil et al. (2010) for the composition of the forest and data from Indrajaya et al. (2016) for the forest growth and economic parameters. The full list of parameters will be provided in an additional Excel-sheet; in this chapter, I will explain what parameters are present and where the data comes from.

## 4.1 Initial forest stand composition

The composition of the forest stand is based on Sheil et al. (2010), which investigated a one-hectare plot of land in East Kalimantan, Indonesia. The researchers made a distinction between dipterocarps, secondary commercial trees and others. This distinction suits the model well. They measured the trees in girth and calculated the diameter. For the composition of the forest in the matrix growth model, these diameters are divided into 13 5-centimeter diameter classes j, as was also the case in Indrajaya et al. (2016). This results in the forest composition given in Table 4.1.

*Table 4.1: Forest stand composition (from Sheil et al. 2010)*

| Diameter range (cm) | Diameter class (j) | Dipterocarp (i=1) | Non-dipterocarp (i=2) | Others (i=3) |
|---|---|---|---|---|
| **10-14** | 1 | 39 | 81 | 221 |
| **15-19** | 2 | 20 | 32 | 90 |
| **20-24** | 3 | 9 | 27 | 52 |
| **25-29** | 4 | 8 | 17 | 36 |
| **30-34** | 5 | 5 | 8 | 22 |
| **35-39** | 6 | 9 | 7 | 8 |
| **40-44** | 7 | 5 | 4 | 8 |
| **45-49** | 8 | 7 | 2 | 3 |
| **50-54** | 9 | 0 | 1 | 5 |
| **55-59** | 10 | 3 | 1 | 1 |
| **60-64** | 11 | 3 | 1 | 0 |
| **65-69** | 12 | 1 | 0 | 0 |
| **70+** | 13 | 8 | 0 | 3 |

## 4.2 Forest growth parameters

In section 2.2.3, the forest growth model is explained. I will use the same parameters as Indrajaya et al. (2016) where possible to ensure a good comparison between steady state and finite time horizon models is possible. Indrajaya et al. (2016) use growth periods of 2 years, because the growth matrix they use is developed by Krisnawati et al. (2008) which yielded more reliable results for 2-year growth periods. Therefore, in this model, the model will also use growth periods of 2 years. Furthermore, the same upgrowth matrices $A_i$, ingrowth matrices $R_{ik}$, ingrowth vectors $\mathbf{c}_i$ and damage matrices $\mathbf{E}_s$ are used as by Indrajaya et al. (2016).

Furthermore, average wood volume, basal area per diameter class per species, given by Indrajaya et al. (2016) (following Enggelina (1998)) are given in Table 4.2. Indrajaya et al. (2016) notes that there is no data on non-commercial species, which are assigned the same values as non-dipterocarp commercial species.

*Table 4.2: basal area, volume and amount of carbon in above ground biomass per diameter class of tree species*

| Species | Diameter class (j) | Basal area ($m^2$/tree) | Volume ($m^3$/tree) | Carbon storage ($tCO_2$/tree) |
|---|---|---|---|---|
| **Dipterocarp** | 1 | 0.012 | 0.17 | 0.142 |
| | 2 | 0.024 | 0.25 | 0.345 |
| | 3 | 0.040 | 0.41 | 0.669 |
| | 4 | 0.059 | 0.64 | 1.130 |
| | 5 | 0.083 | 0.96 | 1.738 |
| | 6 | 0.110 | 1.35 | 2.506 |
| | 7 | 0.142 | 1.82 | 3.439 |
| | 8 | 0.177 | 2.37 | 4.542 |
| | 9 | 0.216 | 3.00 | 5.821 |
| | 10 | 0.260 | 3.70 | 7.276 |
| | 11 | 0.307 | 4.49 | 8.911 |
| | 12 | 0.358 | 5.35 | 10.725 |
| | 13 | 0.413 | 6.29 | 12.718 |
| **Non-Dipterocarp and non-commercial** | 1 | 0.012 | 0.06 | 0.142 |
| | 2 | 0.024 | 0.13 | 0.345 |
| | 3 | 0.040 | 0.28 | 0.669 |
| | 4 | 0.059 | 0.49 | 1.130 |
| | 5 | 0.083 | 0.76 | 1.738 |
| | 6 | 0.110 | 1.11 | 2.506 |
| | 7 | 0.142 | 1.51 | 3.439 |
| | 8 | 0.177 | 1.99 | 4.542 |
| | 9 | 0.216 | 2.53 | 5.821 |
| | 10 | 0.260 | 3.13 | 7.276 |
| | 11 | 0.307 | 3.81 | 8.911 |
| | 12 | 0.358 | 4.54 | 10.725 |
| | 13 | 0.413 | 5.35 | 12.718 |

Table 4.3 shows the size of the initial forest stand in terms of basal area, volume and $CO_2$-storage, and compares this with the climax forest size, which is the final (steady) state of the forest as a result of the growth model without ever harvesting the forest. Values for the climax forest are taken from Indrajaya et al. (2016) and are also replicated with GAMS to show the growth model in GAMS functions as intended. The GAMS results are slightly different due to rounding differences.

Comparing the initial forest stand to the climax forest resulting from the forest growth model, it is safe to assume the initial forest stand provided from the Sheil et al. (2010) data is in a climax state, as it is slightly bigger in all forest characteristics than the climax forest resulting from the forest growth model.

*Table 4.3: Comparison of initial forest stand in model to climax forest of the growth model*

| Forest | Basal area ($m^2$/ha) | Volume ($m^3$/ha) | Carbon storage ($tCO^2$/ha) |
|---|---|---|---|
| **Initial forest stand** | 33.54 | 332.96 | 716.66 |
| **Climax forest (Indrajaya et al.)** | 26.41 | 329.98 | 660.80 |
| **Climax forest (GAMS)** | 26.40 | 329.72 | 660.30 |

## 4.3 Economic parameters

Again, the parameters from Indrajaya et al. (2016) will be used for the model. Specifically, the case for private forest management (where the forest is managed by a private party instead of the government) is regarded. There are a few key economic parameters which are summarized in Table 4.4. Furthermore, a time horizon of 120 years is chosen: this is sufficiently long to allow for multiple harvests of longer cutting cycles. For example, Boscolo et al. (1997) use the same argumentation for the 200-year time horizon in their model, where the discount rate is set to 6%. As this model uses a much higher discount rate of 12% to replicate the model of Indrajaya et al. (2016), this means that the discount factor for costs and benefits will be $\frac{1}{1.12^{120}} = \frac{1}{805680.26}$ which is low enough to assume the total NPV will not be affected significantly beyond 120 years. Even though not all cutting cycle lengths end at exactly 120 years (for example, an 18-year cutting cycle sees the last harvest at year 108), I assume that due to the discount factor at year 120, these endpoint issues do not affect results in a significant manner.

*Table 4.4: Economic parameters for privately managed forests (from Indrajaya et al. 2016)*

| Parameter | Value |
|---|---|
| **$FC_{CL}$ (US$/ha)** | 296.9 |
| **$FC_{RIL}$ (US$/ha)** | 388.9 |
| **Net price Dipterocarp CL (US$/$m^3$)** | 59.4 |
| **Net price non-Dipterocarp CL (US$/$m^3$)** | 32.0 |
| **Net price Dipterocarp RIL (US$/$m^3$)** | 61.0 |
| **Net price non-Dipterocarp RIL (US$/$m^3$)** | 33.6 |
| **Discount rate** | 12% |
| **Time horizon** | 120 years |

## 5. Model results

In this chapter, results from running the model in GAMS are shared and its interpretations are given. The chapter starts by investigating the case of private forest management without carbon remuneration and conventional logging harvesting practices, in order to establish a baseline amount of carbon storage. After this, a private forest managed with carbon remuneration and reduced impact logging is examined and a carbon supply curve for this case is constructed. Finally, the case of no harvest will be regarded, as a sufficiently high carbon price may lead to the situation where no harvesting is most profitable.

### 5.1 Conventional logging (CL) without carbon remuneration

Results from this base scenario are obtained by optimizing the NPV of each cutting cycle using conventional logging. The NPV optimization problem for this scenario is given in eq. 3.2. The optimal NPV's of each cutting cycle length are given in Table 5.1. Furthermore, additional data on average basal area, forest volume and carbon stored are given.

*Table 5.1: Conventional logging, no carbon remuneration, 12% discount rate.*

| Cutting cycle (years) | NPV (USD/ha) | Average basal area ($m^2$) | Average forest volume ($m^3$) | Average carbon stored ($tCO_2$) | Total volume harvested ($m^3$) |
|---|---|---|---|---|---|
| **6** | 2360.52 | 7.51 | 68.43 | 142.70 | 146.48 |
| **8** | **2377.80** | **7.80** | **71.40** | **149.02** | **145.37** |
| **10** | 2369.42 | 8.04 | 73.93 | 154.34 | 144.18 |
| **12** | 2355.99 | 8.15 | 75.12 | 156.79 | 140.93 |
| **14** | 2351.63 | 8.10 | 74.73 | 155.81 | 131.77 |
| **16** | 2346.37 | 8.30 | 76.87 | 160.31 | 130.96 |
| **18** | 2340.81 | 8.44 | 78.40 | 163.42 | 127.88 |
| **20** | 2335.12 | 8.69 | 81.08 | 168.96 | 134.93 |
| **22** | 2329.64 | 8.82 | 82.46 | 171.91 | 127.78 |
| **24** | 2324.60 | 9.10 | 85.47 | 178.08 | 133.45 |

The optimal cutting cycle length is only 8 years, which is rather short for forest management. Having a look at the discounted present values of the harvests shows an interesting result (Table 5.2). It appears that from the third harvest (at t=16 years) onward, subsequent harvests return negative values. However, because of the 12% annual discount rate, these values do not impact the total NPV that much. On the other hand, the added value of having the second harvest earlier easily compensates the negative returns of subsequent harvests.

*Table 5.2: Net present values of each harvest for a cutting cycle of 8 years.*

| t (years) | NPV (USD/ha) |
|---|---|
| 0 | 2206.657 |
| 8 | 193.128 |
| 16 | -9.326 |
| 24 | -8.187 |
| 32 | -2.923 |
| 40 | -1.000 |
| 48 | -0.345 |
| 56 | -0.123 |
| 64 | -0.046 |
| 72 | -0.018 |
| 80 | -0.007 |
| 88 | -0.003 |
| 96 | -0.001 |
| 104 | -0.000 |
| 112 | -0.000 |
| 120 | -0.000 |

Figure 5.1 shows the forest volume over time for a cutting cycle of 8 years. It shows that the first harvest and to a much lesser extent the second and third harvest extract the most forest volume. It also shows that the forest volume converges to an average of around 50m$^3$ per ha.

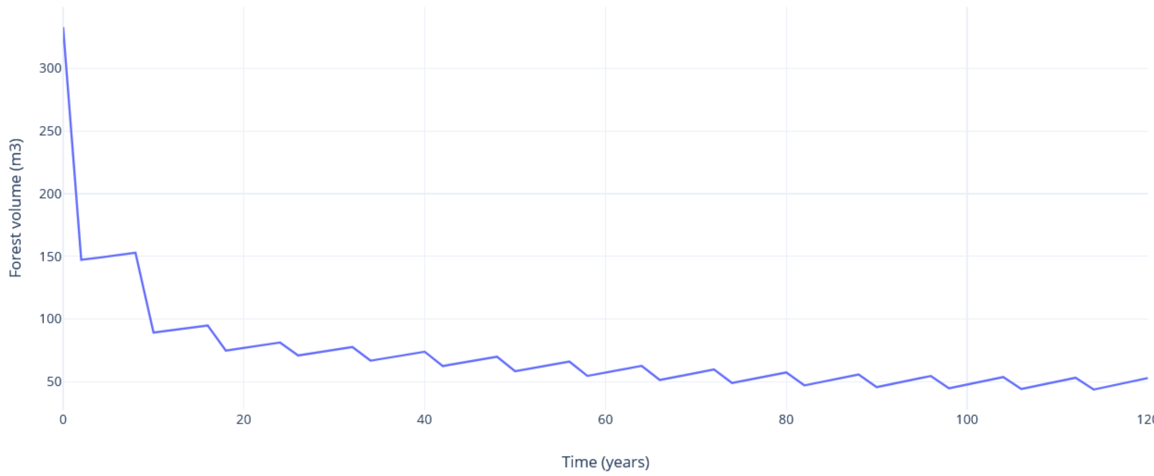


*Figure 5.1: forest volume over time (cutting cycle = 8 years)*

The effect of the high discount rate is further demonstrated in Table 5.3, which shows the results of the model where the discount rate has been set to 4%. Here a cutting cycle of 18 years returns the highest NPV.

*Table 5.3: Conventional logging, no carbon remuneration, 4% discount rate*

| Cutting cycle (years) | NPV (USD/ha) | Average basal area ($m^2$) | Average forest volume ($m^3$) | Average carbon stored ($tCO_2$) |
|---|---|---|---|---|
| **6** | 2190.42 | 7.74 | 70.77 | 147.79 |
| **8** | 2412.99 | 8.09 | 74.33 | 155.40 |
| **10** | 2521.04 | 8.37 | 77.19 | 161.46 |
| **12** | 2581.86 | 8.56 | 79.16 | 165.57 |
| **14** | 2614.19 | 8.68 | 80.49 | 168.34 |
| **16** | 2629.40 | 8.92 | 83.04 | 173.70 |
| **18** | **2633.22** | **9.15** | **85.50** | **178.88** |
| **20** | 2631.53 | 9.46 | 88.81 | 185.76 |
| **22** | 2623.03 | 9.94 | 93.83 | 196.53 |
| **24** | 2613.62 | 10.28 | 97.63 | 204.36 |

The aim of this section was to obtain a baseline for $CO_2$ stored in the forest. As the 8-year cutting cycle returns the highest NPV, the baseline $CO_2$-storage for carbon remuneration will be 149.02 $tCO_2$.

## 5.2 Reduced impact logging with carbon remuneration

Now that a baseline $CO_2$-storage has been established, the effect of a price on carbon storage can be investigated. Using the NPV-calculation in eq. 3.13, the model returns the maximal NPV's and their corresponding cutting cycles as shown in Table 5.4. Carbon prices are increased per 0.5 USD per $tCO_2$.

*Table 5.4: Reduced impact logging, carbon remuneration, harvesting allowed*

| Carbon price (USD per $tCO_2$) | NPV (USD/ha) | Cutting cycle (years) | Average basal area ($m^2$) | Average forest volume ($m^3$) | Average carbon stored ($tCO_2$) | Total volume harvested ($m^3$) |
|---|---|---|---|---|---|---|
| **0** | 2569.43 | 14 | 8.38 | 77.73 | 162.24 | 144.35 |
| **0.5** | 3120.79 | 14 | 8.94 | 83.32 | 174.48 | 148.87 |
| **1** | 3754.63 | 24 | 11.13 | 106.74 | 223.86 | 151.72 |
| **1.5** | 4480.45 | 36 | 14.78 | 149.34 | 311.66 | 147.94 |
| **2** | 5367.19 | 120 | 23.64 | 259.24 | 536.85 | 118.00 |
| **2.5** | 6578.92 | 120 | 29.76 | 332.31 | 689.95 | 83.52 |
| **3** | 7972.48 | 120 | 29.76 | 332.31 | 689.95 | 83.52 |

When RIL is applied and there is no remuneration from $CO_2$-storage, it appears that a cutting cycle of 14 years is optimal, rather than the 8 years for conventional logging. This practice also returns a higher NPV than conventional logging, which was not the case in Indrajaya et al. (2016). It can be explained by two factors. The first factor, explaining the longer cutting cycle, is the increased fixed costs for RIL. As is shown in Table 5.2, even the lower fixed costs of CL already returned negative NPV's from the third cutting cycle onward. Increasing these fixed costs makes harvesting even more expensive, and delaying these harvests decreases costs in the long run. The second factor, explaining the higher NPV, is the higher net price for wood harvested using RIL. Especially because the forest is already in a climax state at t=0, the revenues from the first harvest are significantly higher, easily compensating for the higher fixed costs.

As the carbon price increases, the length of the cutting cycle and average basal area, forest volume and carbon stored increase as well, which was to be expected. The biggest jump in average carbon stored is seen when increasing the carbon price from 1.5 USD/$tCO_2$ to 2 USD/$tCO_2$. At a price of 2 USD/$tCO_2$, the cutting cycle equals the time horizon of 120 years, only harvesting at t=0 and t=120. Increasing the price even further to 2.5 USD/$tCO_2$ leads to only harvesting at the end of the time horizon.

However, I argue that a baseline $CO_2$-storage that is based on conventional logging practices is not appropriate in this case, because Table 5.4 shows that even without carbon remuneration, reduced impact logging returns a higher NPV. Therefore, it makes more sense to use the average $CO_2$-storage under RIL with no carbon remuneration as this will be the decision a rational forest manager takes. Table 5.5 shows the results of optimal management for different carbon prices with a baseline $CO_2$-storage of 162.24 $tCO_2$, which is the average carbon storage using RIL with no carbon remuneration.

*Table 5.5: Reduced impact logging, carbon remuneration, higher average carbon stored baseline*

| Carbon price (USD per $tCO_2$) | NPV (USD/ha) | Cutting cycle (years) | Average basal area ($m^2$) | Average forest volume ($m^3$) | Average carbon stored ($tCO_2$) | Total volume harvested ($m^3$) |
|---|---|---|---|---|---|---|
| **0** | 2569.43 | 14 | 8.38 | 77.73 | 162.24 | 144.35 |
| **0.5** | 3088.19 | 14 | 8.94 | 83.32 | 174.48 | 148.87 |
| **1** | 3689.44 | 24 | 11.13 | 106.74 | 223.86 | 151.72 |
| **1.5** | 4382.68 | 36 | 14.78 | 149.34 | 311.66 | 147.94 |
| **2** | 5236.82 | 120 | 23.64 | 259.24 | 536.85 | 118.00 |
| **2.5** | 6415.96 | 120 | 29.76 | 332.31 | 689.95 | 83.52 |
| **3** | 7776.93 | 120 | 29.76 | 332.31 | 689.95 | 83.52 |

Only NPV's are impacted by this increase in baseline $CO_2$-storage. This can be explained through the remuneration mechanism: because storage below this baseline is taxed by the same amount as storage above this baseline is subsidized, the usage of a baseline $CO_2$-storage is essentially a lump sum tax. This means that the marginal benefit of storing an extra tonne of $CO_2$ is always equal to the carbon price, regardless of how high this baseline is and regardless of the current forest stand composition.

## 5.3 No harvesting with carbon remuneration

To conclude this chapter, the NPV is calculated for the case there is no harvesting at all. Two scenarios are investigated. The first scenario uses the assumption that the forest composition stays the same during the 120 year time horizon, as the forest is already in a climax state. The second scenario does use the forest growth model, in order to investigate if the growth model (which returns a smaller climax forest than the forest composition in t=0, see also Table 4.3) has any noticeable effect on the outcome. The baseline carbon storage is 162.24 $tCO_2$, the baseline determined from using RIL. The results are shown in Table 5.6.

*Table 5.6: No harvesting*

| Carbon price (USD per $tCO_2$) | NPV (USD/ha) (no growth model) | Average carbon stored ($tCO_2$) (no growth model) | NPV (USD/ha) (with growth model) | Average carbon stored ($tCO_2$) (with growth model) |
|---|---|---|---|---|
| **0** | 0 | 716.66 | 0 | 689.95 |
| **0.5** | 1366.86 | 716.66 | 1360.97 | 689.95 |
| **1** | 2733.72 | 716.66 | 2721.94 | 689.95 |
| **1.5** | 4100.58 | 716.66 | 4082.91 | 689.95 |
| **2** | 5467.44 | 716.66 | 5443.87 | 689.95 |
| **2.5** | 6834.29 | 716.66 | 6804.84 | 689.95 |
| **3** | 8201.15 | 716.66 | 8165.81 | 689.95 |

Comparing these results to the results shown in Table 5.4 and Table 5.5, the conclusion is that no harvesting returns a higher NPV from a carbon price of 2 USD per $tCO_2$ than allowing for harvests. This is due to the fixed costs imposed on harvesting in t=0 for the case where harvesting is allowed, even when the optimal strategy is to not harvest at t=0. Using the forest growth model or assuming the forest composition stays the same does not have a major impact on the NPV.

## 5.4 The carbon supply curve

Using the results presented in Tables 5.5 and 5.6, a carbon supply curve plotting average carbon stored under different carbon prices can be constructed. At carbon prices of 0 to 1.5 USD/$tCO_2$, the forest manager uses RIL, while at carbon prices of 2 USD/$tCO_2$ and above the forest manager will not harvest at all, as the NPV for no harvesting was higher with these carbon prices. In the case of no harvesting, the value of the amount of $CO_2$ stored for using no growth model is taken, as this seems more appropriate for a forest already in a climax state. This leads to Figure 5.2 showing the carbon supply curve for optimal management.

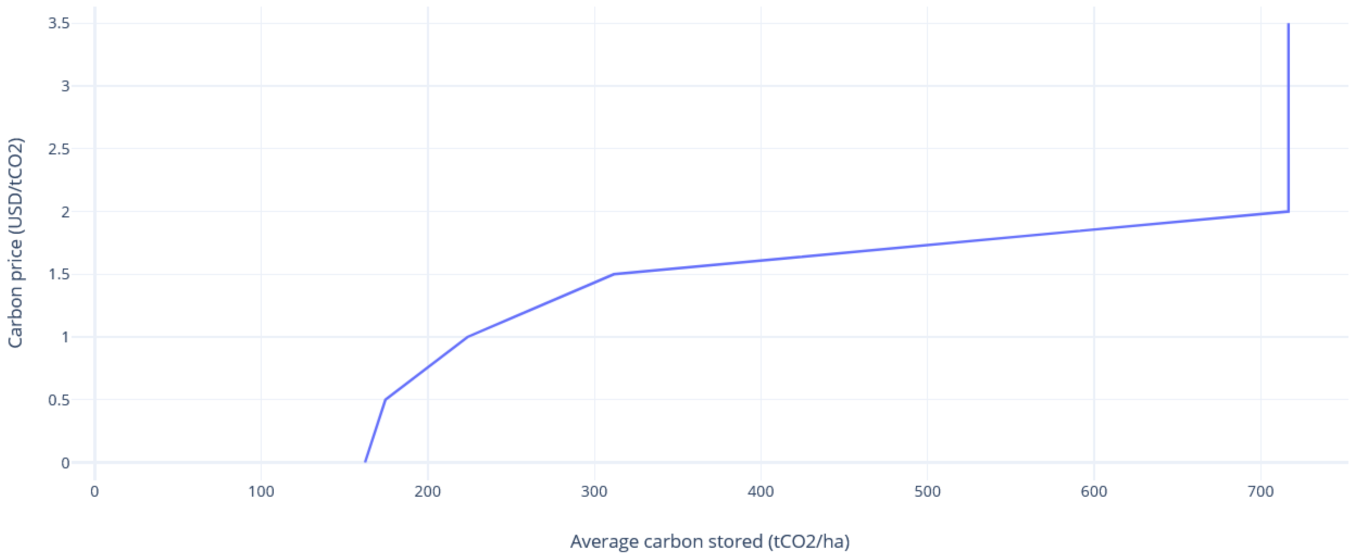


*Figure 5.2: Carbon supply curve*

# 6. Comparison with Indrajaya et al. (2016)

In this chapter, subquestion e: "How do the results of the new model compare to the results of the model used by Indrajaya et al. (2016)?" is answered. First, the results in the case of no carbon remuneration are compared to Indrajaya et al. (2016), after which the results for different carbon prices are compared. The results of the comparison are also discussed in this chapter, with the implications of these results for modelling with finite time horizon models and steady state models in general being discussed in Chapter 7.

## 6.1 Comparing results in the case of no carbon remuneration

Table 6.1 shows optimal harvesting under CL and RIL for both the finite time horizon model of this thesis and the steady state model used in Indrajaya et al. (2016). The finite time horizon model uses NPV, while the steady state model uses LEV. The steady state model results are taken from Indrajaya et al. (2016), Table 1 (p.4).

*Table 6.1 Comparison between finite time horizon and steady state model without carbon remuneration*

| | CL Finite time horizon | RIL Finite time horizon | CL Steady state (Indrajaya et al. 2016) | RIL Steady state (Indrajaya et al. 2016) |
|---|---|---|---|---|
| **NPV / LEV (USD/ha)** | 2378 | 2569 | 32 | 29 |
| **Cutting cycle (years)** | 8 | 14 | 18 | 20 |
| **Average basal area** | 7.80 | 8.38 | 5.65* | 6.00* |
| **Average carbon stored ($tCO_2$)** | 145.37 | 162.24 | 107.6 | 114.9 |

*Estimated average by taking the average of basal area before harvest and basal area after harvest

While NPV and LEV cannot directly be compared, it is interesting that for the finite time horizon model, using RIL returns a higher NPV than using CL. For the steady state model on the other hand, using CL is the optimal harvesting strategy. Furthermore, the steady state model returns longer cutting cycles. Finally, average carbon stored is higher in the finite time horizon model.

These results can be explained by looking at the initial forest stand of the finite time horizon model, which is in a climax state. As pointed out in Chapter 5, this makes RIL more profitable as the value of timber from RIL is higher than CL. Even though the fixed costs of RIL are higher, this is easily compensated for the large harvest in year 0. Also, a large forest in year 0 directly impacts the average carbon storage and basal area, but it also leaves the forest manager with the option of keeping a larger forest for a larger revenue in subsequent harvests, as the size of the forest also positively impacts tree growth.

## 6.2 Comparing results for carbon remuneration

For the case of carbon remuneration, Table 6.2 shows the results of Indrajaya et al. (2016) using a steady state model. Both results for harvesting and no harvest are given in this table. These results are taken from Indrajaya et al. (2016), Tables 2 and 6 (p.5, p.8).

*Table 6.2: Results of steady state model for different carbon prices, both harvesting and no harvesting (Indrajaya et al. 2016)*

| Carbon price (USD per $tCO_2$) | LEV harvesting (USD/ha) | Cutting cycle (years) | Average carbon stored ($tCO_2$) | LEV no harvest (USD/ha) |
|---|---|---|---|---|
| **0** | 29 | 20 | 115 | -11045 |
| **1** | 57 | 26 | 121 | -4682 |
| **2** | 135 | 26 | 137 | 1682 |
| **3** | 260 | 28 | 157 | 8046 |
| **4** | 690 | 30 | 302 | 14410 |
| **5** | 20774 | - | 661 | 20774 |

First the comparison of these results to the results of the finite time horizon model given in Table 5.5, which is the case of harvesting. The steady state model shares the similar result of increasing returns to carbon storage for increasing carbon prices. However, the increase of carbon storage when increasing the carbon price is lower for the steady state model than for the finite time horizon model. For example, in the finite time horizon model, a carbon price of 1.5 USD/t$CO_2$ already increases $CO_2$-storage to 311 t$CO_2$/ha, while for the steady state model a carbon price of 4 USD/t$CO_2$ is needed to return a similar results of 302 t$CO_2$/ha. Furthermore, for the finite time horizon model the average carbon storage does not increase anymore from 2 USD/t$CO_2$ onward, while the steady state model determines a carbon price of 5 USD/t$CO_2$ to return this result.

Comparing the case of no harvesting in the steady state model to the finite time horizon model, it is interesting that the results are quite similar. Both models conclude that from a carbon price of 2 USD/t$CO_2$ onwards, it is optimal to not harvest at all. The difference between the carbon price of 2 USD/t$CO_2$ for no harvesting allowed and the 5 USD/t$CO_2$ for allowed harvesting is explained by Indrajaya et al. (2016) by how they model the behaviour of the forest manager, where in the case of allowed harvesting the manager considers how marginal changes in the carbon price affects marginal changes in the harvesting strategy and forest stand, while in the case of no harvesting the initial forest stand is immediately in a steady (climax) state. Finally, the negative LEV's for lower carbon prices can be explained by the form that the steady state model takes, where the opportunity costs of not harvesting the forest (the term $\boldsymbol{v_s z_t}$ in eq. 2.45) leads to negative LEV's for lower carbon prices.

# 7. Discussion and conclusion

In this chapter, the findings of Chapters 5 and 6 are used to discuss some broader implications of these results. Then, some limitations of this research and recommendations for future research are discussed. Finally, this chapter ends with a conclusion answering the main research question: "*How does the model used by Indrajaya et al. (2016) for forest management in Kalimantan, Indonesia, perform when transformed to a model with a finite time horizon?*"

## 7.1 Implications of this thesis

In this section, implications of the model results and its comparison to Indrajaya et al. (2016) are discussed. These implications include the optimal cutting cycles, the carbon prices, the carbon supply curve and when it is appropriate to use either the steady state approach or the finite time horizon approach.

### *7.1.1 Optimal cutting cycles*

The finite time horizon model found significantly shorter cutting cycle lengths for carbon prices ranging from 0 to 1 USD/t$CO_2$, and returned longer cutting cycles from 1.5 USD/t$CO_2$ compared to the steady state model. However, as Table 5.2 showed, the shorter cutting cycle lengths for lower carbon prices might be due to a large bias towards early harvesting as the initial forest stand is large. Likewise, the higher cutting cycle lengths for higher carbon prices can also be attributed to the large forest stand, where benefits for carbon remuneration are relatively high compared to the steady state model. Furthermore, it appeared that when the initial forest stand is in a climax state and no carbon remuneration takes place, RIL harvesting practices are more profitable than CL harvesting, while also lengthening the optimal cutting cycle.

### *7.1.2 The effect of carbon prices*

This thesis supports the conclusion of Indrajaya et al. (2016) that for private forest managers, a carbon price of 2 USD/t$CO_2$ leads to a regime of no harvesting. However, the finite time horizon model returns significant increases in $CO_2$-storage for lower carbon prices, where these effects were very low for carbon prices below 4 USD/t$CO_2$ in the case of positive harvesting. This can be attributed to the initial forest stand being already in a climax state.

### *7.1.3 The carbon supply curve*

Comparing the carbon supply curve in Figure 5.1 to the carbon supply curves constructed in Indrajaya et al. (2016), the supply curve takes a similar form, where the carbon price has increasing returns to the average amount of $CO_2$ stored in the forest. As a forest manager can increase cutting cycle lengths and decrease the amount of trees harvested when the carbon price goes up, the concave carbon supply curves found in Indrajaya et al. (2016) also appear when using a finite time horizon model.

### *7.1.4 To choose the steady state approach or the finite time horizon approach?*

From these implications, it can be concluded that both these approaches seem to have their own merits. When investigating carbon prices for an area where forest management already takes place, the steady state model might be more appropriate as the forest stand will generally be within the range of the endogenous forest stands in a steady state model. Indrajaya et al. (2016) showed that forests For a finite time horizon model, specifically taking one hectare of land for researching the effect of carbon prices might be more problematic as results might be very specific for which plot of land is investigated. However, when the forest stand composition is known, the finite time horizon approach might more accurately reflect the effects of carbon prices on optimal forest management. In this thesis, it is shown that the steady state model overestimates carbon prices if the forest is in a climax state.

## 7.2 Limitations of this thesis and future research

There are two main limitations of this thesis: the fixed length of the cutting cycle and the size of the initial forest stand. Even though the forest manager may choose the optimal cutting cycle, the cutting cycle must always have a fixed length. Tables 5.1 and 5.2 show that a very short cutting cycle can be optimal, while returning negative NPV's for later harvests. It is unthinkable however that the forest manager will actually choose to keep these short cutting cycles after the second harvest has taken place. It might be interesting to investigate completely endogenous cutting cycles where the model determines optimal cutting moments which are not fixed to a particular cutting cycle length.

The size of the forest stand is also a limitation, as this is a forest in climax state. Therefore, only conclusions about optimal forest management under carbon remuneration programs can be drawn for forests which are in a climax state. This notion is further reinforced by the usage of a growth model that returns a slightly smaller climax forest than the size of the initial forest stand. Even though Table 5.6 showed that this does not have a big impact on results, it is still worth considering that the growth model under no harvesting reduces the size of the forest stand. In further research, it might be interesting to compare results of carbon prices on carbon storage for a range of initial forest stands. I would expect a convergence towards the results of the steady state models as the forest stands get smaller and smaller.

## 7.3 Conclusion

The main research question of this thesis was *"How do the results of the steady state model used by Indrajaya et al. (2016) for forest management in Kalimantan, Indonesia, change with regard to cutting cycle length and carbon storage when transformed to a model with a finite time horizon?".* First of all, it should be noted that applying this finite time horizon model to a forest in climax state returns short cutting cycles under optimal management. The optimal cutting cycle of 8 years for conventional logging in this model is much shorter than the optimal cutting cycle of 18 years in Indrajaya et al. (2016). When carbon prices are introduced, optimal cutting cycles get increasingly longer. It turns out that the finite time horizon model shows similarities in the shape of the carbon supply curve compared to Indrajaya et al. (2016). The finite time horizon model however returns higher carbon storage for the same carbon price compared to the steady state model. For example, where the steady state model Indrajaya et al. (2016) shows that a carbon price of 4 USD/t$CO_2$ returns an average carbon storage of 302 t$CO_2$, whereas the finite time horizon model gives an average carbon storage of 311 t$CO_2$ with a carbon price of only 1.5USD/t$CO_2$. For the case where no harvesting takes place, results of the two models are very similar. In terms of choosing which model to apply, the finite time horizon modelling approach may be more appropriate than steady state modelling when the forest stand composition is in a climax state, while steady state modelling may be more appropriate for forests which are already being managed.

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