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**ON THE DYNAMIC OPTIMIZATION OF
CONTINUOUS COVER TROPICAL FOREST
MANAGEMENT**

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CONTENTS

ON THE DYNAMIC OPTIMIZATION OF CONTINUOUS COVER TROPICAL FOREST MANAGEMENT	0
ACKNOWLEDGEMENTS	2
ABSTRACT.....	3
1. INTRODUCTION.....	4
2. CONTINUOUS COVER FORESTRY IN THE TROPICAL FOREST	6
2.1. Forest management approaches	6
2.2. Defining CCF	8
3. ECONOMIC-ECOLOGICAL MODELLING & OPTIMIZATION FRAMEWORK.....	11
3.1. Economic objective function.....	11
3.2. Growth models in the economic-ecological optimization	12
3.3. Optimization constraints.....	15
4. LITERATURE REVIEW ON THE METHODOLOGY OF OPTIMIZATION	18
4.1. Optimization choices.....	19
4.2. Transition matrix growth model	20
5. THE OPTIMIZATION MODEL	23
5.1. The model.....	23
5.1.1. Growth model	23
5.1.2. Economic objective function.....	25
5.1.3. The optimization problem.....	25
5.2. The parameter values	27
5.2.1. Forest growth data	27
5.2.2. Economic data	29
6. OPTIMIZATION RESULTS WITH THE RUNNING HORIZON ALGORITHM.....	31
6.1. NPV & DISCOUNTED CASH FLOWS	31
6.2. STEADY STATE STRUCTURE	31
6.3. THE CONTINUOUS COVER.....	33
6.4. REGULATED CASE ANALYSIS.....	35
6.5. SENSITIVITY ANALYSIS.....	35
7. DISCUSSION.....	36
8. CONCLUSIONS	38
REFERENCES	40
APPENDIX.....	44

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ABSTRACT

Continuous Cover Forestry (CCF) management is a common silvicultural approach in the tropical forests. However, it is mostly considered as either regulated Reduced Impact Logging (RIL) or unregulated ad-hoc Conventional Logging (CL) regime. The study builds a CCF economic-ecological optimization model without a commitment to either of these approaches and solves it with previously unemployed dynamic optimization methods.

The model maximizes a Net Present Value (NPV) function that describes net timber benefits to the forest owner. The growth model is a linear transition matrix model with non-linear stand basal area dependent ingrowth function. The damage model reflects the total harvest effect on the smallest size class residual trees.

Given 70-year cycle it was found that the NPV is 8,430.98\$ per stand. The steady state, reached by year 210, shows that a stand after harvests retains a continuous cover. It was found that at the steady state 33.60 m³ of dipterocarps and 29.78 m³ non-dipterocarps are harvested. This is a cash flow of 2,457.79\$ per stand per cycle. Residual trees are represented by all species, but strongly dominated by the non-commercials: dipterocarps 1.52 m³, non-dipterocarps 3.00 m³, and non-commercials 184.17 m³.

The non-commercial species group is not harvested, neither in the transition nor at the steady state. This may be because there is a marginal cost associated with their harvest. Furthermore, they suffer unproportionally larger harvest damages to the smallest size class by other species felling as indicated by damage matrix coefficients. It seems that these damages are enough to regulate the non-commercial species abundance at no cost. Furthermore, the ingrowth function while dependent on the basal area is not strongly influenced by the value of the stand basal area.

Since the carbon in the literature is priced regardless of the species of the tree, the volume of non-commercials remaining after each cycle has good potential for carbon sequestration benefits. There is also potential for artificial regeneration. The results suggest potential for mixed species and sizes forests existing without regulation.

1. INTRODUCTION

Globally, up to 25% of annual greenhouse gas emissions come from deforestation related activities (Smith et al., 2014). One of the main causes for this is land conversion from forestry to agricultural purposes (FAO & UNEP, 2020). On the one hand, forests are vital for human survival. They provide food, fuel wood for domestic use, materials and support large timber industries (FAO & UNEP, 2020). On the other hand, human intervention threatens habitat availability to 60% of the world's plant species and integrity of 10 of the 36 biodiversity hotspots (FAO & UNEP, 2020). Continuous cover forestry (CCF) is a forest management regime that aims to balance human needs with biodiversity protection by employing a selective harvesting approach (Maennicke & Griess, 2019).

This thesis is the first to apply the most general form of dynamic optimization methods in the context of tropical forest and, thus, provides new results on optimal unregulated harvesting schemes.

CCF management optimization has been studied with static optimization methods much more extensively (Indrajaya, van der Werf, Weikard, Mohren, & van Ierland (2016), Macpherson, Carter, Schulze, Vidal, & Lentini (2012)). Static optimization relies on an assumption that the steady state is reached within the first harvest. Dynamic optimization, however, allows flexibility for the steady state to appear in the further future opening a wider range of solutions.

In tropical forests, dynamic optimization studies are only a few and they have some major simplifications. Boscolo, Buongiorno, and Panayotou (1997) do not consider harvest damages to the residual stand in the growth function and apply harvest constraints. Meanwhile Boscolo and Vincent (2000) and Boscolo and Vincent (2003) included only a 60 year planning horizon without providing any analysis on the found optimal states.

Harvest constraints are very common in tropical optimization literature. This thesis argues, however, that the optimal choice of forest management is a decision that ideally should be endogenously decided (Tahvonen, 2008). This means that the quantity, timing of the harvest and forest management approach are optimal when they are the solution to the general optimization model. Thus, the model in this thesis does not restrict the area, volume, size or units of trees that can be harvested.

Removing the harvesting constraints means that a complete harvest can indeed be the optimal solution. Since the harvest problem in its most general form has not yet been solved, it is not known how private forest owner optimum compares to the regulatory agenda. Unconstrained optimization modelling has potential to show the real incentives or lack of incentives to carry ecologically sustainable forestry. Since institutional insecurities in some contexts mean that

strong institutional control is not always possible (Brown, Brown, & Brown, 2016) this is potentially important knowledge which we do not currently have.

The thesis aims to highlight the current development of the methodology in optimization literature in the tropical context, to form a dynamic economic-ecological optimization model and to, thus, find the optimal set of decision variables that provide the maximum benefits to the forest owner.

The main research question, therefore, is:

What is the dynamically optimal steady state of a forest stand in a tropical Malaysian forest managed under general CCF approach that maximizes the income to the forest owner?

In the subsequent chapters the research question is approached as follows. Chapter 2 expands on forest management approaches with emphasis on CCF. Chapter 3 describes the framework of this thesis, namely, the rich research available in the methods of setting economic-ecological dynamic optimization models. Chapter 4 is an extensive literature review of similar optimization models that identifies the current development of forest management optimization in the tropical forests. Chapter 5 introduces the dynamic economic-ecological model and the numerical values that are used. Chapter 6 provides the results and their analysis. Chapter 7 provides the discussion on the results and limitations of this study. Lastly, Chapter 8 closes with conclusions and suggestions for future research.

2. CONTINUOUS COVER FORESTRY IN THE TROPICAL FOREST

2.1. Forest management approaches

Most of the Earth's forests are affected by humans (FAO & UNEP, 2020, p. XVII). Throughout millennia forests have been crucial for human material welfare (FAO & UNEP, 2020, p. XIX) and played an important role in human spiritual tradition (Smith et al., 2014). While human intervention to ecosystems remains a central issue in climate change and biodiversity loss topics, economic considerations are also critical as many human lives depend on forest resources.

There are multiple management approaches available that offer different level of potential to balance human economic needs and wellbeing of ecological systems. Forest management approaches fall into two broad categories: rotation forestry management (RFM) and continuous cover forest management (CCF) (see Table 1) (Schütz, Pukkala, Donoso, & von Gadow, 2012).

On the one hand, rotation forestry management (RFM) is a traditional industrial approach and is well-studied all over the world. The forests under RFM are also called plantations as monoculture seedlings are manually planted after a clear-cut harvest (Schütz et al., 2012). To this day, RFM is still preferred for its simplicity and ability to supply good quality timber (Schütz et al., 2012) or grow crop trees in the tropics. RFM is managed over a rotation period which starts with establishing young trees manually and ends with a full removal of the tree cover (Schütz et al., 2012). Rotations are usually long and last several decades. Trees under RFM are somewhat uniform in size and have a monotonous look.

Rotation forest management (RFM)	Continuous cover forestry (CCF)
The trees are of uniform size and of the same species. Thinning was carried and the soil is cleared of shrubs.	The trees are of different maturity and species. The setting allows for ecosystem variety in tree and other flora as wells as fauna abundance.

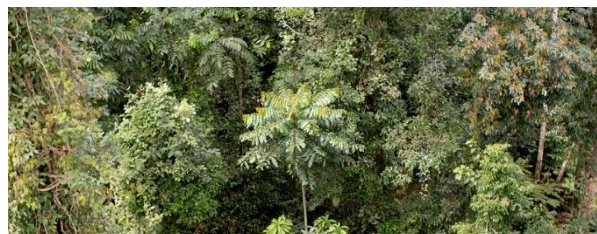
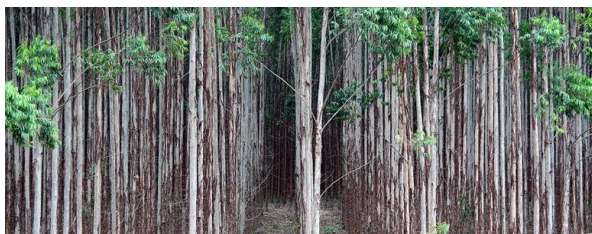


Table 1 Visual representation of RFM and CCF. (Rescue, 2014; Stammers, 2021)

On the other hand, CCF harvesting is selective: single trees or small groups of trees are chosen for removal and the soil never gets fully exposed (Seydack, 2002). This results in

forests that are diverse in tree ages and, if managed for species diversity, species distributions (Pukkala & von Gadow, 2012). The periods between harvests are called *cycles* avoiding confusion with RFM term *rotation* (Buongiorno & Lu, 1990). CCF has been historically practiced in China, Chile, Mexico and other countries, and is still practiced today, however, the scientific community started taking interest in CCF only some 100 years ago (Schütz et al., 2012).

CCF reduces some of the risks associated with forest management, the main ones being:

- CCF mimics natural processes which in turn results in a more ecologically sound forest (Schütz et al., 2012). For example, CCF has a stronger positive effect on long-term biodiversity which comes about from lesser ecosystem disturbance and higher residual cover (Edwards et al., 2012).
- CCF secures the land from full exposure preventing the transition to agriculture. Agriculture, forestry and other land use account for almost a quarter of the greenhouse gases emissions annually of which most are from forest degradation, forest fires and agriculture related fires (Smith et al., 2014).
- Furthermore, CCF reduces the risk of soil erosion which is quicker in tropical climate zones. Erosion mainly happens when bare soil is exposed, for example, as roads for logging purposes, or when land is in transition to cropland (Labrière, Locatelli, Laumonier, Freycon, & Bernoux, 2015). CCF secures the soil without large long-term exposure.
- As Schütz et al. (2012) argued, younger trees have a higher marginal growth and, therefore, have a higher marginal increase in value. Since selective CCF harvesting allows to remove some trees, as opposed to clearfelling, only the trees which have high opportunity cost but smaller marginal return can be removed. This helps to maximize economic return on the stand.
- Mixed species forests show a reduced economic risk due its ability to adapt to the economic fluctuations (Schütz et al., 2012), ecologic disturbance such as pests (Maennicke & Griess, 2019).
- Selective harvesting affects soil temperature insignificantly and the soil returns to pre-harvest temperature within 3 to 5 years (Mollinari, Peres, & Edwards, 2019). This could be very important from the climate change perspective.

There are areas, however, that CCF does not have significant effect on:

- In tropical forest countries, such as Malaysia, the state owns most of the forest and only provides harvest rights to the loggers (Boscolo & Vincent, 2000). This fuels a

short-sightedness problem while making harvesting decisions (Boscolo & Vincent, 2000).

- Forestry is not necessarily the most economically valuable option as opposed to land conversion to agriculture (Günter, 2011). Exogenous influences, such as increasing demand in the food market, for example, palm oil, can make forestry a less profitable option (Sultan, 2016).

It is generally accepted to regard CCF as a more costly management approach than RFM. For one, CCF requires more specialised forest treatment. For example, the number of workers needed who possess the required skills is higher, adapted machinery is needed to reduce damage to the residuals and sometimes labour intensive manual felling is needed (Maennicke & Griess, 2019). However, CCF is usually coupled with natural regeneration and it is a cost-effective option to increase the density of a stand (Seydack, 2002). If managed correctly, trees can do self-thinning and self-pruning which in turn may also increase the value of timber (Maennicke & Griess, 2019). Therefore, in total, CCF is not necessarily more expensive than RFM.

2.2. Defining CCF

In the literature one comes across various understandings of what CCF is. While a clear-cut is the biggest difference between RFM and CCF regimes, there are management options that fall in between (see Table 2) (Seydack, 2002).

The monocyclic harvest systems consist of the uniform and the shelterwood systems. The first is the purest RFM form; the trees are planted and harvested at the same time. The second approach employs near full harvest, only leaving some mature trees for seed dispersal. Once the seedlings establish, the mature trees are removed, and the remaining stand is even aged.

<i>Full clear-cut</i>	←—————→	<i>Sparse selective harvesting</i>
<hr/>		
<i>Monocyclic systems:</i>	<i>Polycyclic systems:</i>	
— <i>Uniform systems (RFM)</i>	— <i>High intensity selection cutting systems</i>	— <i>Moderate intensity selection cutting systems</i>
— <i>Shelterwood</i>		— <i>Naturalistic selection harvesting systems</i>

Table 2 An overview of forest management approaches with respect to a harvest method (Seydack, 2002)

Selective harvesting systems range from high intensity selection harvesting to very low intensity harvests that mimic natural processes (Seydack, 2002). Selective harvesting can be done in patches. Literature suggests that the size of a patch can be at most two heights of an average mature tree wide to still be considered CCF (Mason, Kerr, & Simpson, 1999). From

the ecological point of view, the specific size of the patch depends on the context and regeneration goals, and it is a balancing act. Light requiring tree species will be able to regenerate in larger patches and shade-tolerant species can establish in smaller patches (Mason et al., 1999). Some authors argue that to maximize biodiversity benefits the openings should be kept as small as possible (Maennicke & Griess, 2019). The single tree removal method is the closest to natural selection as taking away mature trees simulates natural mortality in undisturbed forests (Maennicke & Griess, 2019). Single tree removal as selective harvesting level is commonly found in optimization literature. Therefore, when selective harvesting is mentioned, it is meant as a single tree removal from now on.

Since CCF is a much more flexible term than RFM, many more terms arise to describe it too. In the literature, CCF is also referred to as close-to-nature (Maennicke & Griess, 2019; Mason et al., 1999), near-natural forestry, selection forestry (Schütz et al., 2012), mixed-species and mixed-sizes or mixed-ages forestry (Atta-Boateng & Moser Jr, 1998) and size-structured (Rämö & Tahvonen, 2015). CCF applied in monoculture forests may also be called uneven-aged forestry signifying that the only non-conformity is the age of trees.

In the tropical forests, the following two terms are of an additional interest: reduced impact logging (RIL) and conventional logging (CL). They both rely on the selective harvesting, however, they are additionally limited by timber harvest constraints (Heinrich, 1995). The harvest threshold is described with a minimum diameter at breast height (dbh) which means that trees that are larger than the set threshold cannot be harvested (Jerome K. Vanclay, 1995). Dbh is a diameter of a tree trunk at breast height and traditionally it is at 1.3m from the soil level (Paul et al., 2017). For the trees that have a buttress, some authors take a dbh measurement at 20 cm above where the buttress ends (Krisnawati, Suhendang, & Parthama, 2008).

Additional to RIL, other regulatory requirements include cutting of woody lianas in preparation for harvest, planning of roads, felling directions and skidding trails, inventory of trees prior and after harvests (Tay, Healey, & Price, 2002). In hilly areas, following RIL regimes, the controlled CCF management approach, means that almost 50% of forests are not harvestable (Tay et al., 2002). RIL does not permit to carry harvesting activities close to water springs, lakes, nature reserves and rivers (Heinrich, 1995). CL logging, however, is signified by its complete lack of control for technical considerations (Heinrich, 1995). This results in much larger damages to the residual trees than RIL (Tay et al., 2002).

What RIL makes up in costs in the planning, it returns in the reduced damages, higher yields in the next cycle, less waste and higher timber quality (Heinrich, 1995; Priyadi et al., 2007).

Since this thesis is a general optimization study, the CCF definition is also a general form of CCF. We define CCF as every management of mixed species and uneven-aged forests which avoids clear-cuts and artificial regeneration (Knoke, 2011).

3. ECONOMIC-ECOLOGICAL MODELLING & OPTIMIZATION FRAMEWORK

This thesis uses an economic-ecological dynamic optimization modelling framework to describe a landowner's management problem (Hyytiäinen & Haight, 2012).

Economic-ecological models consist of an economic objective function that is maximized subject to a forest growth model constraint and other optimization constraints. Each section of this chapter introduces a component of the model.

3.1. Economic objective function

The framework is founded on an assumption that the sole objective of a forest owner is to maximize the profit realised from their forest (Hyytiäinen & Haight, 2012). The function that describes the economic benefits flow to the forest owner is called an economic objective function. Such functions include many sources of income as long as they can be evaluated in monetary terms. The economic functions are built by considering multiple criteria (Table 3).

Economic objective function	— Timber/ Non-timber benefits
	— Deterministic/Stochastic
	— LEV/NPV
	— Discrete/Continuous time

Table 3 Considerations in the development of the economic objective function

In forestry management, the income sources are usually referred to as timber and non-timber benefits. The timber benefits can be described on a different level of detail. Indrajaya et al. (2016); Ingram and Buongiorno (1996) price the timber per cubic meter ($\$/m^3$) while Boscolo and Vincent (2000) price the timber per cubic meter depending on the dbh of the tree trunk. It can be described per type of product, for example pulp and sawlog, separately (Rämö & Tahvonen, 2014) or even multiple types of sawlog and pulp, and wood residue used for bioenergy (Sampo Pihlainen, Tahvonen, & Niinimäki, 2014). Ultimately, the higher the detail of economic pricing, the more accurate the cash flow approximation in the model. In building the pricing for the timber benefits, generally, the larger dependence is on the biological data availability as market prices are much more widely available.

The possibilities to obtain non-timber economic benefits from forests are numerous. The most important ecosystem service that has been analysed in the optimization literature is carbon sequestration. In the tropics, such studies are given by Indrajaya et al. (2016), Boscolo and Buongiorno (1997). Importantly, it is assumed that neither negative, e.g. loss of biodiversity, nor positive, e.g. carbon sequestration, externalities in forest owner centred studies are

considered unless they can be evaluated in monetary terms and there is a willingness to pay for it from exogenous parties.

The economic-ecological models can be deterministic or stochastic. The first only considers exogenously fixed prices which are assumed to remain over the planning horizon (Favrichon, 1998). The latter describes prices with a price path as well as allows for uncertainty in interest rates and ecological conditions. Stochastic models also include considerations for economic risks.

The economic functions differ on how they portray time. It is common to use Net Present Value (NPV) functions in discrete time as they sum cash flows over discrete time periods. NPVs are commonly used for finite planning horizon analysis. Infinite horizon studies include many static optimization studies that use Land Expectation Value (LEV) an economic function that considers residual stand as an investment for future income from harvests (Haight, 1985). It has been extensively criticised by Haight (1985) and Tahvonen, Pukkala, Laiho, Lähde, and Niinimäki (2010). Further discussion can be found in Rämö and Tahvonen (2015).

3.2. Growth models in the economic-ecological optimization

A growth model is a set of equations that describes the natural forest growth phenomena (J. K. Vanclay, 1994, p. 4). It approximates real life with mathematical expressions which in turn is useful in quantitative analysis.

Growth model	<ul style="list-style-type: none"> — Stand/forest level — Stand level growth models single tree/class/whole stand — Empirical-statistical/ process-based
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Table 4 The growth modelling considerations

The most common approach to forest management is to carry analysis on a stand level and then scale it to the size of the forest (Table 4). A stand is a 1 ha plot that represents the forest. While it is known that forests behave differently when bordering with a water body or a road (Bollandsås, Buongiorno, & Gobakken, 2008), it is commonly accepted as a good enough approximation for an analysis.

The tree growth describing functions can be based on three levels: whole stand, class and single tree (Hyytiäinen & Haight, 2012). Whole stand models are based on basal area or trees/ha and are generally not very detailed or useful even for RFM forests (Jerome K. Vanclay, 1995). Class level models consider the stand in subgroups distinguished by age in

the same species plantations and by age and species in mixed-species uneven-aged stands (Buongiorno, Peyron, Houllier, & Bruciamacchie, 1995). Lastly, single tree models are more detailed as they describe each tree in the stand by individual characteristics such as dbh, height and crown size (Hyytiäinen & Haight, 2012). The latter are not easily attained for uneven-aged mixed species forests in the tropics. For one, this is because of the species abundance. Indonesian Kalimantan forest has around 4000 species of which only 287 are classified as economically valuable (Conrad, Gillis, & Mercer, 2005 quoting Sedjo (1987)).

Regardless of the level chosen for the analysis, the growth models differ by the number of endogenous and exogenous variables they include (see Table 5).

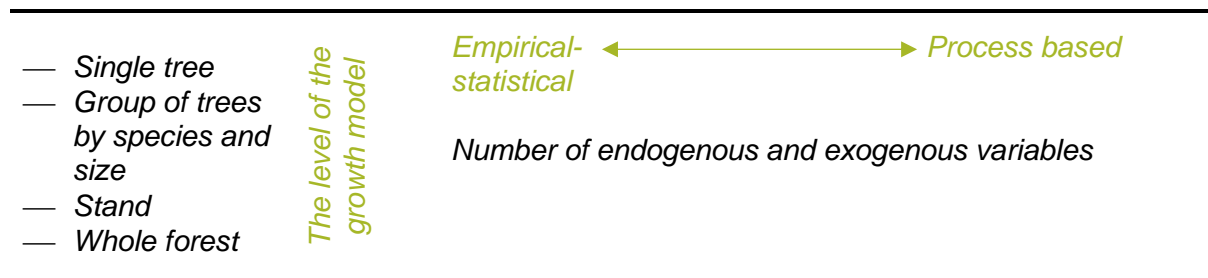


Table 5 Growth models overview

The empirical-statistical models use observations to endogenous variables such as stand density, dbh and calibrate these to simulate the forest growth (Jerome K. Vanclay, 1995). These models provide statistical correlations between the observations of specific trees and they are very specific to the context, thus, application to other forests can be troublesome (S. Pihlainen, Tahvonen, & Niinimaki, 2014).

The process-based growth models are much more advanced. These are the models that can describe forest growth as a result of several endogenous and exogenous variables such as water and sun availability, temperature or soil quality (J. K. Vanclay, 1994, p. 6). As a result, it not only describes the growth of trees at the initial climate condition but is also able to show how changes in the environment affect the growth. This is particularly important in the context of climate change when the climatic changes are occurring. Process-based models have been used in economic-ecological optimization in boreal forests in RFM, for example, by S. Pihlainen et al. (2014), but we did not find literature that applies this in CCF.

As it was mentioned earlier, RFM stands are manually established, therefore, all seedlings are of the same age and the stand is monotonous. Thus, RFM growth models describe the growth rate over time that applies to the whole stand. Contrary, CCF stand is more complex as the trees have different maturity at each snapshot of time. CCF growth models describe the trees in their distinct stages of lifetime: establishment of the youngest seedlings, growth transition, mortality (Figure 1). Therefore, it is common to employ class level model where the trees are

grouped not only by their species but also their maturity. These class level models are called transition matrix models as it describes the transition of the full forest system over time with help from a matrix, called a transition matrix.

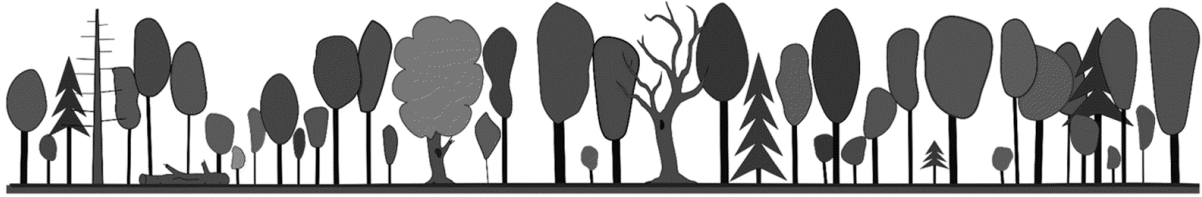


Figure 1 The CCF structure of a forest. There are distinct groups of trees in the different stages. Some trees are only establishing, some are steadily growing, some trees die (Gustafsson et al., 2020).

Under a transition matrix model a forest stand is distributed into groups by dbh and species called classes. The transition growth matrix is given in much more detail in chapter 5.

The stand structure at time is commonly denoted as x_t where each entry x_{ist} refers to a *number* of individual trees in the size s and species i group for $i = 1, 2, \dots, m$ and $s = 1, 2, \dots, n$ (Bollandsås et al., 2008). A transition matrix G has entries that are the proportions of each tree class advancing one size class up, that is growing, or staying in the same class over a growth period (Lu & Buongiorno, 1993). Formally

$$x_{t+1} = Gx_t + c_t \quad (1)$$

where G is a transition matrix, x_t is a stand composition at time t for $t = 0, 1, \dots$, and c is the ingrowth. The ingrowth is the addition of new trees to the smallest size class over a growth period.

The growth function used for economic optimization also considers a harvest vector h_t . Each entry h_{ist} refers to the *number* of individual trees in the size s and species i group for $i = 1, 2, \dots, m$ and $s = 1, 2, \dots, n$ that are harvested at time t . Formally

$$x_{t+1} = G(x_t - h_t) + c_t \quad (2)$$

The function describes the harvests in the beginning of the growth period, however, it is also common to model the harvest to occur in the end of the period (Rämö & Tahvonen, 2015).

Matrix growth models are somewhat easy to build (Boscolo et al., 1997; Buongiorno & Mitchie, 1980). The simplicity of the measurements means that they are also relatively cheap (Bollandsås et al., 2008). It requires to measure all trees in a stand a minimum of two times over a time period which is also called a growth period. As a result, the growth matrix models are in discrete time. The two or more measurements then describe how the whole stand transitions over the growth period and this aids in drawing the long-term predictions of the forest growth (Ralston, Buongiorno, Schulte, & Fried, 2003). The growth period is chosen

depending on the forest ecological context and statistical considerations (Buongiorno & Mitchie, 1980) and can be 5 years (Bollandsås et al., 2008), 2 years (Krisnawati et al., 2008) or 1 year (Boscolo et al., 1997). Importantly, the harvest cycle length is a multiple of the growth periods.

Transition matrices come in 2 types: state independent/linear or state dependent/non-linear (Bollandsås et al., 2008; Spathelf & Durlo, 2001). In the first case, the parameters are constants and in the latter case the parameters are recalculated for each stand structure at time t (Bollandsås et al., 2008). It is intuitive to think about a linear growth matrix as populated with constants and a non-linear growth matrix being populated with empirical-statistical functions that estimate each class (i, s) state at t given stand structure at $t - 1$. This can be done if growth, ingrowth and mortality functions for specific forest context are known (Bollandsås et al., 2008). In some growth models, especially in the tropics, it is common to find the transition matrix being linear but ingrowth being dependent on stand density and composition (Boscolo et al., 1997). Such models are linear in their growth but non-linear in their ingrowth.

3.3. Optimization constraints

Knoke (2011) identifies 3 major themes of economic-ecological modelling within CCF literature:

- Studies that analyse long-term results of a predefined management regime or compares several predefined management regimes.
- Static optimization studies.
- Dynamic optimization studies.

The studies under the first theme merely show the long-term trend of set conditions. In this thesis, the attention is paid to the studies in the second and third groups, namely, static and dynamic optimization problems of which objective is to find the best set of decision variables such that the objective is maximized. The biggest difference between the latter two is that the static optimization is restricted to achieving optimal forest stand structure within the first harvest cycle (Haight, 1985). Formally, static optimization adds the constraint $x_t = x_{t+1}$. On the contrary, the dynamic optimization does not have this constraint. This flexibility means that the optimal steady state is allowed to be reached further than one cycle into the future but it can default to steady state from the first cycle. The period between $t = 0$ and the steady state is called the transition period. For this reason, dynamic optimization is considered as one of the most sophisticated approaches in CCF economic research (Knoke, 2011). While static models can work better if the forest is already in or near climax state (Sianturi, 1993), Haight

(1985) theorised that, first, the steady states under static and dynamic optimization are different, and second, that dynamic optimal states provide higher harvest volumes. Furthermore, solutions of static problems are strictly included in the corresponding dynamic problem optimization solution set (Haight, 1985). This is an important premise to study optimization in its dynamic form.

Regardless of whether the static or dynamic optimization methodology is used, the steady state, also called the optimal solution, needs to be achieved within the model's timeframe. The planning horizon is thus an important consideration. Finite planning horizon studies are a few in the tropical forests (Boscolo & Vincent, 2000; 2003). These studies consider specific Malaysian context where the forest largely is owned by the state and the state provides logging rights for 60 years.

Infinite planning horizon studies while are modelled for infinity rather choose a very large timespan that adequately approximates infinity, for example, 200 years (Boscolo et al., 1997) or 750 (Rämö & Tahvonen, 2015). Given optimization software, long timeframes are not difficult to calculate and in economic terms the discounted cash flows in that far future are negligible, thus, the timeframe is considered as infinite.

Optimization constraints	<ul style="list-style-type: none"> — Steady state/dynamic optimization constraints — Planning horizon — Specific forest management requirements & RIL/CL — Non-timber constraints — Non-negativity constraints
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Table 6 The optimization constraints

The other group is the timber harvest constraints. The most commonly found is a minimum dbh constraint which means that only larger trees than the directed dbh can be harvested (Priyadi et al., 2007). This ensures that the stand is never clear-cut in the smallest size classes. In Nigerian forests, minimum dbh requirement means that the policy barely allows for full depletion of the larger size trees and is found to severely degrade the forests (J. S. A. Osho, 1995) regardless of the cycle length (Osho & Akinsammi, 1991). Meanwhile in Indonesia, under Indonesian Selective Cutting (TPI) policy, a study carried without economic consideration to the economics showed that the policy setup with min dbh harvest requirement and 35 year cycle could not ensure ecologically sustainable yields anyway already after the 2nd harvest (Mendoza & Setyarso, 1986).

In optimization studies that consider harvest constraints such as Boscolo et al. (1997) the steady state forest structure of a stand is optimal not because that it is the optimal

management outcome to the forest owner, but rather an optimal forest structure that fits into the policy context (Mendoza & Setyarso, 1986).

Other ecology related constraints are the non-timber constraints. Ecoservices are often handled as an ecological constraint as opposed to a benefit in the economic function. This is a useful technique when the ecoservice cannot be monetarily evaluated or is not a human benefit-oriented constraint. Illustrative examples can be found in Rämö, Assmuth, and Tahvonen (2020) which considers a constraint on deadwood and Mendoza, Önal, and Soetjijpto (2000) that determines a biodiversity goal and carries optimization constrained by it.

Lastly, one could consider the choice between RIL and CL regimes as limiting in the setup of the optimization model. As introduced in Chapter 2.2, the RIL regime has many more requirements in the planning stages and harvesting techniques. Ultimately, this affects the costs of harvesting operations. While we suppose that the landowner has a sole objective of maximizing the outcome of their land it seems counterintuitive to restrict their option to one or the other management technique. Carrying research on the premise that the optimal management approaches should be decided endogenously (Tahvonen, 2008), the choice between the two sets of requirements should also, thus, be decided endogenously. Therefore, the owner would be motivated to produce less damage to the residual trees to have better regeneration if enrichment is expensive. Alternatively, if the price for cleaner machinery is expensive then the owner would argue that larger damages can rather be dealt with artificial regeneration or less frequent harvesting. In either way, there is no reason, in non-regulated optimization as is being considered in this thesis, why there should be only two options. There may be other management decisions to be made in between that would not classify as either. For this reason, this thesis aims to build a model that does not limit itself to CL or RIL, but rather solely CCF – mixed species and ages management model. Ideally, cost functions would be built for each part of treatment which would allow to find the optimal set of the treatments to determine if CL or RIL or an option in between would be optimal. This is not in the scope of this thesis, however.

Lastly, mathematical constraints ensure that the model is logical: some of the variables take real non-negative values and no more trees are harvested than there are available.

4. LITERATURE REVIEW ON THE METHODOLOGY OF OPTIMIZATION

The following chapter identifies the advancements of the optimization modelling and the most influential literature.

In the data collection stage, a systemic literature review was carried in databases available at WUR: Scopus, Web of Science, CAB and EBSCO Host. Furthermore, key articles' citations were checked. The key articles in this case were identified as Boscolo et al. (1997), Boscolo and Vincent (2003), Buongiorno et al. (1995), Krisnawati et al. (2008) and Macpherson, Schulze, Carter, and Vidal (2010). To the best of the author's knowledge, all dynamic CCF optimization studies in the tropical context are shown. However, it is important to note that only literature in English was reviewed.

The review includes articles that are set in tropical forest context, have a CCF transition matrix growth model, and use optimization methods. The table does not include articles that solely build and optimize transition matrix growth models without any economic analysis nor economic modelling that cannot be understood as an optimization problem. The optimization studies found in the literature review were from Indonesia, Nigeria, Brazil, and Malaysia. The results are presented in the Table 7 and discussed in the rest of the chapter.

Author	Function type	Harvest constraint	Model builds on	Ingrowth	Damage	Static/dynamic
van der Werf, Indrajaya, Mohren, and van Ierland (2019) Indonesia	LEV	>40 cm	Indrajaya et al. (2016)	Non-linear; basal area dependent	All size effect on all sizes of trees; extended to suppose prolonged mortality process	Static
Indrajaya et al. (2016) Indonesia	LEV	>50 cm	Krisnawati et al. (2008) Macpherson et al. (2010)	Non-linear; basal area dependent	All size effect on all sizes of residuals	Static
Macpherson et al. (2012) Brazil	NPV Finite from 60 to 120; 2 harvest contracts.	>50cm; intensity	Macpherson et al. (2010)	A function of stand density, species group, and treatment. Poisson regression.	All size effect on all sizes of residuals	Static
Boscolo and Vincent (2003) Malaysia	NPV Finite 60y	>30, 40, 50, 60, 70 cm; or no logging at all	Boscolo et al. (1997)	Non-linear	Matrix that shows all trees logging effect on the smallest size class for each species group	An unconstrained dynamic result among many other simulated cases

Boscolo and Vincent (2000) Malaysia	NPV Finite 60y	>30cm	Boscolo et al. (1997)	Non-linear; basal area dependent	Matrix that shows all trees logging effect on the smallest size class for each species group	An unconstrained dynamic result among many other simulated cases.
Mendoza et al. (2000) Indonesia	LEV and NPV	>50cm	Buongiorno and Mitchie (1980)	Constant	Constant ratio	Static
Boscolo and Buongiorno (1997) Malaysia	LEV	-	Boscolo et al. (1997)	Non-linear; basal area dependent	Matrix that shows all trees logging effect on the smallest size class for each species group	Static
Boscolo et al. (1997) Malaysia	NPV Finite 200y	>30, 40 50, 60 cm	Buongiorno and Mitchie (1980); Buongiorno et al. (1995)	Non-linear; basal area dependent	-	Constrained dynamic optimization
Ingram and Buongiorno (1996) Malaysia	LEV	Yes; minimum number of trees also		Non-linear; basal area dependent	-	Static
Sianturi (1993) Indonesia	NPV	>50cm		Constant	Constant ratio	Static

Table 7 The literature review table

4.1. Optimization choices

Only three papers rely their methods on dynamic optimization methods. All three papers use the same Boscolo et al. (1997) growth model used in this thesis. These dynamic optimization studies, however, have some shortcomings that make it difficult to see the full potential of dynamic optimization.

Boscolo et al. (1997), for example, optimization model is bounded by harvest constraints. Meanwhile, the planning horizon is chosen to be 200 years. Boscolo and Vincent (2000) and Boscolo and Vincent (2003) have applied dynamic optimization methods and carry analysis for a case, out of many simulated constrained scenarios, that is not constrained by harvest thresholds. However, the planning horizon is 60 years. Only two harvests are allowed which is compliant with Malaysian forestry regulation. They do not provide any analysis of the transition phase nor the steady state.

All three studies also are restricted to the analysis of CL and RIL.

4.2. Transition matrix growth model

Overall, all reviewed papers had linear transition matrices and were empirical-statistical growth models. They have different number of size classes, 13 in Krisnawati et al. (2008) and 7 in Boscolo et al. (1997) and use different timber volume functions.

It is interesting to expand on how the same transition matrix models employ different formulations of the damage and ingrowth functions. Also, there are two predominant ways how the plentiful of tropical forest species are grouped for modelling.

The most dominant growth models used in optimization are Indonesian Krisnawati et al. (2008), Malaysian Boscolo et al. (1997) with additional damage in Boscolo & Vincent (1997) and Brazilian Macpherson et al. (2010).

4.2.1. Ingrowth

The ingrowth function for a single species uneven stand for the transition growth models was first introduced by Adams and Ek (1974). Lu and Buongiorno (1993) and Buongiorno et al. (1995) later re-introduced this formulation for multiple species.

Buongiorno et al. (1995) model for French Jura forest management is widely taken as the framework for building growth models in the tropics (Boscolo et al., 1997; Krisnawati et al., 2008) and is the most sophisticated ingrowth function formulation quoted in tropical forest optimization:

$$I_{it} = \gamma_i + \sum_{k=1}^m \delta_{ik} \sum_{s=1}^n B_s x_{ist} + \rho_i \sum_{s=1}^n x_{ist}$$

where B_s is the basal area of an individual tree in size class $s, s = 1, 2, \dots, n$, and $\gamma_i, \delta_{ik}, \rho_i$ are constants obtained from linear regression. Some ingrowth happens because of bird/animal/wind seed dispersal from neighbouring stands which is reflected with constants $\gamma_i \geq 0$. The part of equation with the basal area term shows species $i, i = 1, 2, \dots, m$, ingrowth relation to the total basal area of the stand at time t . Each δ_{ik} is expected to be negative as the more crowded the stand the less likely it is for a new species i seedling to establish (Lin, Buongiorno, & Vasievich, 1996). Buongiorno et al. (1995) allows for each species k to influence species i seedling to a different extent (Buongiorno et al., 1995). The ingrowth of species i , is positively related to abundance of the same species trees on the stand, $\rho_i > 0$, as the only regeneration considered is natural regeneration.

Neither of the growth models reviewed had full application of this ingrowth function in their growth models. Boscolo et al. (1997), for example, later introduced ingrowth where the basal area in its totality influences the ingrowth, but not the specific species basal area:

$$I_{it} = \gamma_i + \delta_i \sum_{i=1}^m \sum_{s=1}^n B_s(x_{ist}) + \rho_i \sum_{s=1}^n (x_{ist})$$

Originally, it was planned to use Krisnawati et al. (2008) growth model in this thesis. However, Krisnawati et al. (2008) references to a single species uneven-aged forest study by Buongiorno (1980). The regression coefficients results published reflect the single species ingrowth function. Indrajaya et al. (2016) use this model in its linear form (see Buongiorno et al. (1995) for the notation). Krisnawati et al. (2008) publish these matrices **A** and **R** which are used as given in Indrajaya et al. (2016). As the ingrowth is incorporated into the matrix **R** it is difficult to determine whether the single species ingrowth function is a typo or a mistake that is carried through to the transition matrix results. In conclusion it was decided to use the Malaysian Boscolo et al. (1997) growth model as the wrong ingrowth function notation and reported ingrowth regression coefficients gave low confidence in the Krisnawati et al. (2008) growth model.

Entirely different approach was used by Macpherson et al. (2010) that employ Poisson regression to estimate the ingrowth.

4.2.2. Damage

The damage is commonly used in the more recent literature. It was not mentioned at all in the early articles (Ingram & Buongiorno, 1996) and was introduced as a part of the costs rather than growth function by Boscolo et al. (1997).

A handful of studies treat damage as a constant fraction of harvest. These studies usually have a different damage constant for RIL and CL harvests (Mendoza et al., 2000; Sianturi, 1993).

Boscolo and Buongiorno (1997) studied harvest damage only to the smallest class trees by harvesting all size classes. The damage coefficients differ by the species affected. All of the subsequent articles that build on Boscolo and Buongiorno (1997) consider this damage formulation (Boscolo & Vincent, 2000; 2003).

The most sophisticated damage function was introduced by Macpherson et al. (2010) for Brazilian. The authors develop a model that reflects the damage to all size residual trees caused by all size classes harvested trees. The economic-ecological optimization studies that used this approach are Indrajaya et al. (2016), Macpherson et al. (2012) and van der Werf et al. (2019). However, this has not been yet applied to a Malaysian context, therefore, it was unavailable for this thesis.

All of the above studies assume that a damaged trees instantly dies. van der Werf et al. (2019) study a few scenarios that relax this assumption.

Special attention needs to be paid in unconstrained optimization to how the damage models are calibrated. Indrajaya et al. (2016), Macpherson et al. (2012) and van der Werf et al. (2019) use a model that was calibrated to fit the 50 cm minimum harvest constraint. Originally Boscolo and Buongiorno (1997) included damage that was related to CL regimes. The RIL damages are then multiplied by a constant to suppose lesser damage if RIL is used. The damage model was calibrated to reflect that half of the smallest size trees would die given full cut of trees above 60 cm dbh. The discussion is continued in chapter 7.

4.2.3. Species grouping

The major difference between the optimization methods in boreal forests and tropical forests is, perhaps, how the species diversity is dealt with. In boreal forests, the species are fewer. Bollandsås et al. (2008) transition matrix growth model was established with 3 species, Norway Spruce, Scots Pine and birch, and 1 broadleaves species group that has 10 species matrix model (Bollandsås et al., 2008). Tropical forests have thousands of species, so they are usually put to groups containing large number of species. Two ways of species grouping were encountered. The first one is largely biological and the second one largely economic.

Macpherson et al. (2010) for example, develop a transition matrix growth model for an unevenly managed Brazilian Amazon Forest where the groups are defined as: pioneers, light-demanding, intermediate light requiring, shade-tolerant and light-demanding emergent groups. The groups in this case are rather based on: “ecological traits, such as seed size, seedling shade tolerance, growth potential, wood density, and maximum adult size” (Macpherson et al., 2010). These groups then are assigned a ratio to show proportion of trees that are commercial in the group. Another example with this species grouping was developed for French Guiana forests by Favrichon (1998).

Otherwise, it is common to separate the trees into three large groups of species by pricing category (Boscolo et al., 1997; Buongiorno et al., 1995): dipterocarps, non-dipterocarps and non-commercial. The first one consists of the most valuable trees for timber. The second group includes still commercial trees, however, their price is significantly lower. Lastly, the trees that do not have a market price are called non-commercial trees. Boscolo et al. (1997) argued that this grouping is legitimate as dipterocarp species seem to have similar higher growth rates than other species groups.

5. THE OPTIMIZATION MODEL

5.1. The model

5.1.1. Growth model

The growth model is based on Boscolo et al. (1997) model of Malaysian forests. The authors present a transition matrix growth model that is non-linear in its ingrowth function but linear in the transition matrix. The forest plot is located in a never harvested forest, Pasoh Forest Reserve (Boscolo & Buongiorno, 1997). The model is an application of Buongiorno et al. (1995) model which describes French Jura forests under CCF management.

The addition of damage in the growth function appears in the follow-up study (Boscolo & Buongiorno, 1997) where the harvest damage is introduced as impact of the total harvest to the smallest size class residual trees.

Let $\mathbf{x}_t = [x_{1t} \ x_{2t} \ \dots \ x_{mt}]$ be a column vector of column vectors x_{it} for each species i , $i = 1, 2, \dots, m$. The latter vectors are of the form $x_{it} = [x_{i1t} \ x_{i2t} \ \dots \ x_{int}]$ where x_{ist} is a *number* of trees in a class of species i and size s , $s = 1, 2, \dots, n$, at time t . The row notation is used for convenience. The reader can suppose that all vectors introduced in the model are column vectors unless otherwise specified. Let \mathbf{h}_t be a harvest column vector at time t , $\mathbf{h}_t = [h_{1t} \ h_{2t} \ \dots \ h_{mt}]$ where vector $h_{it} = [h_{i1t} \ h_{i2t} \ \dots \ h_{int}]$ and h_{ist} is a *number* of trees in a class of species i and size s at time t . The vectors \mathbf{x}_t and \mathbf{h}_t are of size nm . The number of size classes and the width of the size class interval are fixed.

The matrix growth model then is

$$\mathbf{x}_{t+\theta} = \mathbf{G}\mathbf{x}_t + \mathbf{c}_t(\mathbf{B}_t) - \mathbf{h}_t - \mathbf{d}_t. \quad (1)$$

Here θ is a growth period, \mathbf{G} is a transition matrix of size $nm \times nm$, \mathbf{x}_t and \mathbf{h}_t are as defined earlier, \mathbf{d}_t is a damage vector of size nm and \mathbf{c}_t is a vector of ingrowth of size nm . Basal area, \mathbf{B}_t , is defined as a total sum of cross-sectional area of the tree trunk at breast height. Observe that the harvest is carried out in the end of the growth period. The harvest that is carried out in the beginning of the growth period, formally is noted as:

$$\mathbf{x}_{t+\theta} = \mathbf{G}(\mathbf{x}_t - \mathbf{h}_t - \mathbf{d}_t) + \mathbf{c}_t. \quad (2)$$

The remainder of the subchapter is dedicated to explaining the growth model in detail.

Let \mathbf{G} be a diagonal $nm \times nm$ upgrowth matrix that consists of matrices \mathbf{G}_i of size $n \times n$:

$$\mathbf{G} = \begin{bmatrix} \mathbf{G}_1 & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{G}_2 & \cdots & \vdots \\ \vdots & \vdots & \ddots & \mathbf{0} \\ \mathbf{0} & \cdots & \mathbf{0} & \mathbf{G}_m \end{bmatrix} \text{ and } \mathbf{G}_i = \begin{bmatrix} \alpha_{i1} & \cdots & \cdots & 0 \\ \beta_{i2} & \alpha_{i2} & \cdots & \cdots \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \vdots & \beta_{in} & \alpha_{in} \end{bmatrix}$$

where α_{is} is a fraction of trees staying in the same size class s over a growth period θ , β_{is} is a fraction of trees moving from s size class to $s + 1$ over time θ . The coefficients α_{is} and β_{is} in each \mathbf{G}_i are related in such a way that $\alpha_{is} = 1 - \beta_{is} - \mu_{is}$ where μ_{is} is a fraction of trees that die over time θ for all $s < n$. For $s = n$, $\alpha_{is} = 1 - \mu_{is}$ which means that trees stay in the size class n until they are harvested or die (Boscolo et al., 1997; Lu & Buongiorno, 1993). Furthermore, α_{is} , β_{is} and $\mu_{is} \in [0,1]$. Observe, that μ_{is} is a fraction of trees that die due to natural causes in each growth period.

The ingrowth is an addition of trees to the smallest size class of each species in the beginning of the growth period θ . The ingrowth is measured in units of trees and is dependent on the stand structure and its basal area.

The ingrowth function is given by Boscolo et al. (1997):

$$I_{it} = \gamma_i + \delta_i \sum_{s=1}^m \sum_{s=1}^n B_s x_{ist} + \rho_i \sum_{s=1}^n x_{ist} \quad (3)$$

where B_s is the basal area of an individual tree in size class s and $\gamma_i, \delta_i, \rho_i$ are constants obtained from linear regression. Some ingrowth happens because of bird/animal/wind seed dispersal from neighbouring stands reflected with constants $\gamma_i \geq 0$ (Buongiorno et al., 1995). The part of equation with the basal area term B_s shows species i ingrowth relation to the total basal area of the stand at time t . Each δ_i is expected to be negative as the more crowded the stand the less likely it is for a new species i seedling to establish (Lin, Buongiorno, & Vasievich, 1996) The ingrowth of species i , is positively related to abundance of the same species trees on the stand, $\rho_i > 0$, as the only regeneration considered is natural regeneration. Mathematically, the ingrowth column vector in eq. 1 is denoted $\mathbf{c}_t = [c_{1t} \ c_{2t} \ \cdots \ c_{nt}]$ of length nm where $\mathbf{c}_{it} = [I_{it} \ 0 \ \cdots \ 0]$ for each species n .

Lastly, the damage term \mathbf{d}_t has zeroes everywhere except the first column entry in each species vector. Namely,

$$d_{i1t} = \frac{2}{3} \sum_{s=1}^m D_{i,s} (h_{1st} + h_{2st} + \cdots + h_{nst}) \text{ and } d_{ist} = 0 \text{ for } s \neq 1. \quad (4)$$

The matrix \mathbf{D} is $n \times m$ size matrix of which each row holds coefficients for the proportion on how much of species i smallest size class trees die as a result of each size class tree being

harvested. Thus, for each species i damage term, i^{th} row of \mathbf{D} is picked, that is $D_{i,s}$. The constant $2/3$ reflects that the harvesting methods are RIL (Boscolo & Vincent, 2000).

For programming purposes, it is useful to rewrite the model into a form that each size and species class can be represented separately with its own equation:

$$x_{i,1,t+\theta} = I_{it} + \alpha_{i1}x_{i1t} - h_{i1t} - d_{i1t} \text{ for } s = 1 \quad (5)$$

$$x_{i,s+1,t+\theta} = \beta_{is}x_{ist} + \alpha_{is+1}x_{is+1t} - h_{is+1t} - d_{is+1t} \text{ for } s = 1, 2, \dots, n-2 \quad (6)$$

$$x_{i,n,t+\theta} = \beta_{in}x_{in-1t} + (1 - \mu_{in})x_{int} - h_{int} - d_{int} \text{ for } s = n \quad (7)$$

The notations in eq. 3-6 of the damage term and the incorporation of damage in the stand equations are novel to the literature.

5.1.2. Economic objective function

Let ω_{is} denote the volume (m^3) of merchantable timber for one tree in a species i and size class s . Let p_{is} denote the $\$/m^3$ net price of timber of species i per size class s .

The revenue is then

$$Q_t = \sum_{i=1}^n \sum_{s=1}^m h_{ist} \omega_{is} p_{is} \quad (8)$$

The economic function is (Tahvonen, 2008) (Rämö & Tahvonen, 2015):

$$\max NPV_{[h_{ist}]} = \sum_{t=0}^{\infty} (Q_t - \tau F_c) b^{\theta t} \quad (9)$$

where F_c is the fixed cost of harvesting, τ is 1 at each cycle that facilitates harvesting and zero otherwise, and $b = \frac{1}{1+r}$ is a discount factor. The economic function only reflects timber benefits and assumes that the timber is solely sold as saw wood.

The setup of the economic function has been widely used in the past in the boreal forests.

5.1.3. The optimization problem

The model is thus

$$\max NPV_{h_{ist}} = \sum_{t=0}^{\infty} (Q_t - \tau F_c) b^{\theta t} \quad (8)$$

Subject to:

x_0 the initial state

Revenue eq. 7

The growth eq. 4-6

The damage term eq. 3

$h_{ist} = 0$ for $t \neq \varphi k$ where $k = 0,1,2,3 \dots$ and φ is a length of a cycle.

$$h_{ist}, x_{ist}, d_{ist} \geq 0$$

$$h_{ist} + d_{ist} \leq x_{ist}$$

for $t = 0,1,2 \dots$, $i = 1, 2, \dots m$ and $s = 1, 2, \dots n$.

The objective economic function is maximized over infinite time horizon. The model is described in AMPL, algebraic programming language, and solved numerically with the KNITRO solver. The optimization tool is used widely in boreal forest optimization studies (Assmuth, Rämö, & Tahvonen, 2021; Rämö & Tahvonen, 2014) but is a novelty for tropical forest context. The software uses gradient, interior point algorithm (Tahvonen, 2008).

The code in this thesis draws inspiration from AMPL code used in Rämö and Tahvonen (2015) dynamic optimization study for boreal mixed species, size-structured forests.

Sensitivity analysis is carried out to ensure the steady state is a global maximum (Rämö & Tahvonen, 2015). This is performed to see how small changes in price and interest rate change the equilibrium state.

AMPL compares to spreadsheet solvers as a faster performer (AMPL, 2021). The benefits increase together with increase in the number of variables used in the model. It is said to be a language that makes it easier to control the model, especially, when there are more than two subscripts to a variable, just as in this model. It uses rather natural algebraic expression.

The income in the economic function is discounted. As it is mentioned in all the optimization studies that study longer planning horizons, the discount factor effect is very large in optimization modelling. This is because large interest rates start to become very small very quickly. There is an algorithm, running horizon algorithm, that was previously unpublished but used in multiple studies in the boreal forests (Rämö & Tahvonen, 2015) that deals with this discounting problem. The algorithm includes redefining the initial state of the forest to the next cycle's stand structure prior to harvest.

1. The initial stand is given, x_0
2. The optimization model is run with the initial stand structure.

3. The harvest data at $t = 0$ is collected.
4. The stand state at the end of the first cycle is taken and reassigned as initial state for the next cycle. The stand state here is prior harvests occur.
5. The process is repeated until the stand state converges. That is $x_t = x_{t+\theta}$ where θ is cycle length.

Each subsequent cycle harvests are then multiplied by appropriate volume figures and prices per size class. The cash flow then can be discounted to the start of the planning horizon. The powers used in the discount rate are at cycle interval.

It has been tested in this thesis that with an 4.8% interest rate the code without this abovementioned algorithm starts to misbehave at year 210 when the cycle length is 70 years.

5.2. The parameter values

This thesis only considers timber benefits in the economic objective function due to its scope. A choice was made to consider pricing, costs and damage function as for RIL management. This model cannot be called RIL optimization, however. As it was discussed in subchapter 2.2, the RIL regime also constricts the harvest volumes and other constraints that are in the regulation set.

5.2.1. Forest growth data

The model uses empirical growth data by Boscolo et al. (1997). The growth model used is taken as given and it has been calibrated and tested by the authors. The transition matrix as well as the ingrowth regression coefficients are supplied in their article and clearly presented.

Important to note, that the regeneration of the stand is solely natural. An example of a study that uses manual enrichment is Tahvonen (2008) that was set in a boreal forest context.

5.2.1.1. *Species groups*

The species are grouped into dipterocarps ($i = 1$) denoted D, non-dipterocarps ($i = 2$), denoted ND, and non-commercial ($i = 3$), NC, species groups. The first one includes the most valuable trees for timber. The non-dipterocarps are still commercial trees, but their price is significantly lower. The species are grouped like this for simplicity of pricing but also because their growth rate is somewhat similar (Boscolo et al., 1997).

5.2.1.2. Size classes

The growth model has 7 size classes of 10 cm width where $s = 1$ is 10 – 20 cm in dbh up to $s = 7$ which includes all trees with dbh that is larger than 70 cm (Boscolo et al., 1997).

The model supposes that growth in a diameter of any size class tree is less than the width of the class to ensure that trees can only move one size class per cycle (Buongiorno & Mitchie, 1980). Additionally, it is supposed that the trees are uniformly distributed in the classes (Bollandsås et al., 2008).

5.2.1.3. Damage parameters

The damage parameters for the smallest class of all species is provided in Boscolo and Buongiorno (1997). The matrix is not so clearly presented, therefore, it is noted here. The first row represents smallest class of dipterocarps tree units that are damaged as a result of harvest of each size class trees. The second row represents non-dipterocarps and lastly, the third row are the non-commercial trees.

$$D = \begin{bmatrix} 0.1 & 0.13 & 0.25 & 0.35 & 0.48 & 1.05 & 1.45 \\ 0.2 & 0.26 & 0.5 & 0.71 & 0.96 & 2.12 & 2.91 \\ 0.85 & 1.13 & 2.12 & 3.02 & 4.11 & 9.05 & 12.42 \end{bmatrix}$$

5.2.1.4. Transition matrix, ingrowth parameters

The matrix G is taken as is in Boscolo et al. (1997). The regression coefficients for ingrowth can also be found in this paper.

5.2.1.5. Basal area & volume of timber

The basal area is given for each size class average tree by formula $B_j = \pi r^2 = 3.14 * (dbh/2)^2$ (Tahvonen, 2008).

The volume is given by Boscolo et al. (1997) using volume formulas for different size class trees. They are not species dependent. The formulas are as follows:

$$V = 0.3211 - 0.002175DBH + 0.0003521DBH^2 \text{ for } 10 \leq DBH < 30 \text{ cm}$$

$$V = 0.1991 + 0.006148DBH + 0.0004081DBH^2 \text{ for } 30 \leq DBH < 60 \text{ cm}$$

$$V = 0.8602 - 0.3872DBH + 0.0013164DBH^2 \text{ for } DBH \geq 60 \text{ cm.}$$

The total basal area at the climax forest state is 24.2 m² and the total volume is 427.8 m³ as reported by Boscolo et al. (1997).

5.2.1.6. Initial state

The initial state is given by Boscolo et al. (1997).

5.2.2. Economic data

5.2.2.1. The planning horizon

Infinite horizon studies usually approximate the infinity with a large enough number of years, for example, 750 years (Rämö & Tahvonen, 2015). Following this logic, the planning horizon is also set to 750 years.

5.2.2.2. The harvest cycle

Harvest is done in the end of the growth period. Cycle length was chosen after initial runs of the model without the running horizon algorithm. In addition, this cycle length has been used by Boscolo and Vincent (2003) as a possible cycle length. Lastly, the algorithm required manual effort, thus, practical reasoning. The cycle is the same in the transition as well as at the steady state.

5.2.2.3. Prices

The optimization model is deterministic. The price does not change over time nor is it given any variance. The timber net prices, that is, roadside prices, are taken from Boscolo and Buongiorno (1997) as they were the most comprehensive and had dependence on the size of the dbh. The variable cost for harvesting trees with a market value was given as 28.3\$ per m³ and the variable cost for non-merchantable trees was estimated at 2\$ per m³. Adjusting for inflation gives \$48.68 and \$3.44 respectively. The prices are given in the Table 8 The pricing table with extrapolated values for size classes 1 and 2 (Table 8). D, ND, and NC are abbreviations for dipterocarps, non-dipterocarps, and non-commercial species groups. An added assumption is that there exists a market for the smallest size trees. The prices for size class 1 and 2 are linearly extrapolated.

Size class	Price per cubic meter 1997			CPI 1997	Inflation adjusted			Inflation adjusted extrapolated smallest size classes		
	D	ND	NC		D	ND	NC	D	ND	NC
1	-2.00	-2.00	-2.00	1.72	-3.44	-3.44	-3.44	14.57	2.00	-3.44
2	-2.00	-2.00	-2.00	1.72	-3.44	-3.44	-3.44	38.33	15.22	-3.44
3	36.11	18.60	-2.00	1.72	62.10	31.99	-3.44	62.10	31.99	-3.44
4	49.92	29.19	-2.00	1.72	85.87	50.20	-3.44	85.87	50.20	-3.44
5	63.77	38.94	-2.00	1.72	109.68	66.98	-3.44	109.68	66.98	-3.44
6	63.51	39.18	-2.00	1.72	109.23	67.39	-3.44	109.23	67.39	-3.44
7	63.42	39.17	-2.00	1.72	109.08	67.38	-3.44	109.08	67.38	-3.44

Table 8 The pricing table with extrapolated values for size classes 1 and 2

The fixed cost for RIL harvesting was reported as 935 \$ per ha (Boscolo & Vincent, 2000) adjusted for inflation it is \$1,515.31.

The Consumer Price Index (CPI) was taken from the U.S Bureau of Labor Statistics (CPI).

5.2.2.4. Interest rate

The interest rate was taken from the World Bank database (Worldbank, 25/09/2021). It is reported to be 4.8%. This is the base for analysis. The rate seems to compare well with other studies in the Malaysian context that used 6% interest rate (Boscolo & Buongiorno, 1997; Boscolo et al., 1997). Others analysed 2% and 10% (Boscolo & Vincent, 2003). The comparison between the results is given in Chapter 6.

6. OPTIMIZATION RESULTS WITH THE RUNNING HORIZON ALGORITHM

6.1. NPV & DISCOUNTED CASH FLOWS

The 70-year cycle, the interest rate 4.8% and the 1,515.31\$ fixed cost parameters provide a discounted NPV 8430.94\$ (Table 9 The cash flow in the transition and the discounted present value).

At year 350 the discount rate is essentially zero, therefore, the analysis of cash flow is appropriately ended there. It is observed that the undiscounted cash flow has some variance after year 210. However, since the stand becomes stable at year 210 in the units of trees with 1 decimal accuracy, that is $x_{210} = x_{280}$ and so on, the discrepancies in the cash flows are probably in the neighbourhood of a computational error.

YEAR	UNDISCOUNTED CASH FLOW	DISCOUNT FACTOR	DISCOUNTED
0	8320.392	1	8320.392
70	2843.333	0.037559	106.7918
140	2597.459	0.001411	3.664116
210	2457.784	5.3E-05	0.130219
280	2423.192	1.99E-06	0.004822
350	2408.951	7.47E-08	0.00018
			8430.984

Table 9 The cash flow in the transition and the discounted present value with 4.8%

Most of the income comes from the first harvest in the transition phase. This has been observed before and is expected (Boscolo and Vincent, 2003).

At the steady state the undiscounted income is 2,457\$ (Table 9).

6.2. STEADY STATE STRUCTURE

The stand reaches a dynamic steady state at year 210. The size structure of the stand at the steady state has an inverted J shape as expected (Figure 2) same as the stand structure considered in volume of timber (Figure 4).

The harvests at the steady state are in dipterocarps and non-dipterocarps (Figure 3 and Figure 6). Non-commercials are barely harvested if at all, the very small fractions in volume really mean no trees are harvested as the growth model is not an integer model. The non-commercials are affected by damages which are disproportionally larger to the non-commercials according to the damage matrix. This seems to be enough to regulate the species group.

PRIOR TO HARVESTS

THE HARVEST

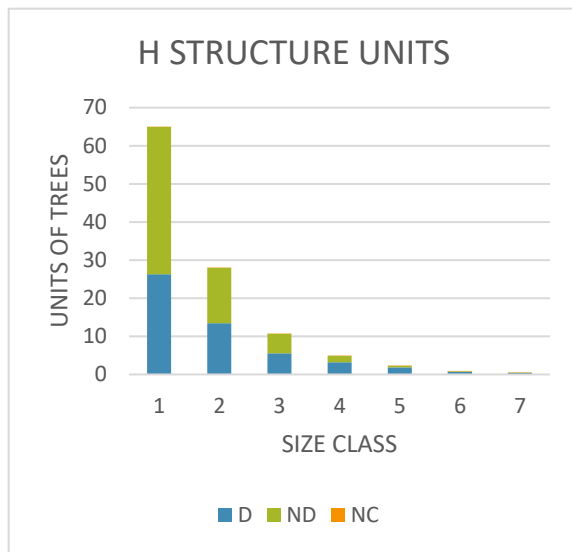
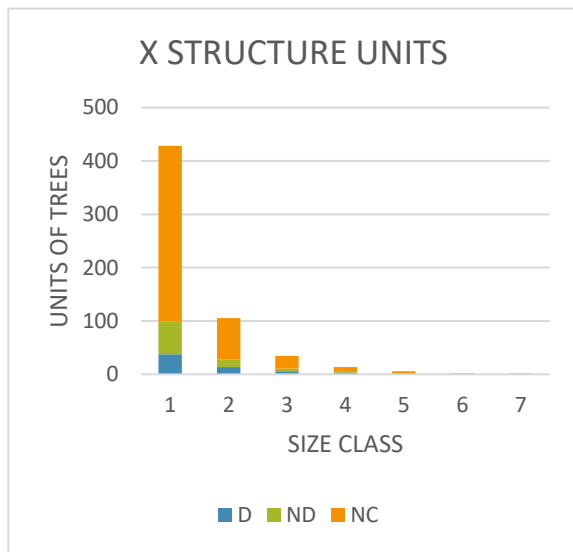


Figure 2 Stand structure at the steady state by tree units, t=210

Figure 3 Harvest at the steady state by tree units, t=210

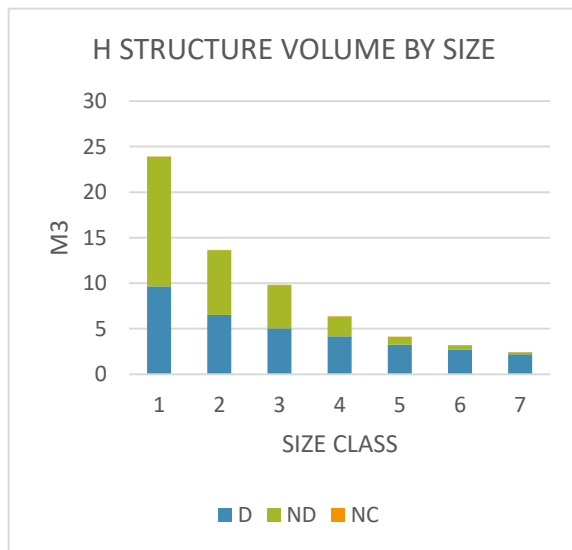
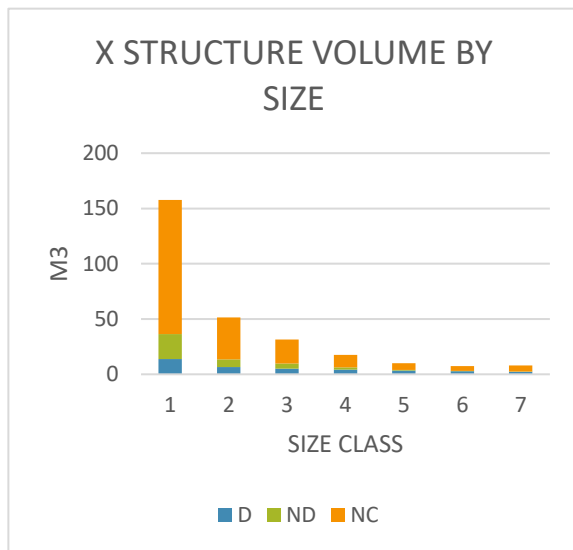


Figure 4 Stand structure at the steady state by each species volume per size class, t=210

Figure 5 Harvest at the steady state by each species volume per size class, t=210

Per cycle, in the steady state the harvests are 33.60 m³ of dipterocarps and 29.78 m³ non-dipterocarps (Figure 5). This totals to 2,457.79 \$ in undiscounted cash flow per harvest once the steady state is reached.

The steady state forest is much more abundant in the non-commercial trees (Figure 6). Observe that the Figure 7 does not include damage volumes.

PRIOR TO HARVESTS

THE HARVEST

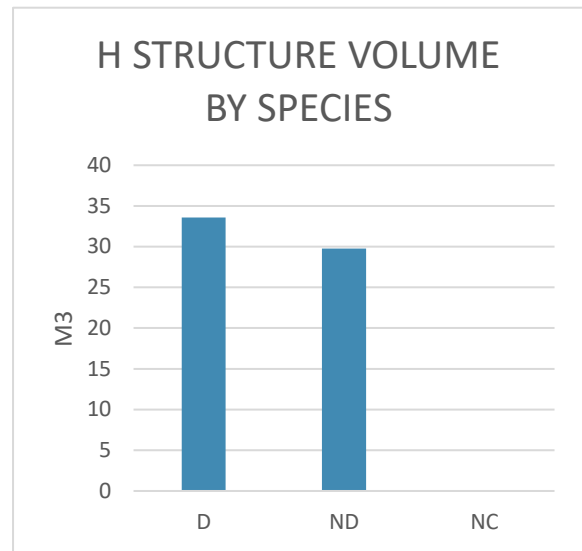
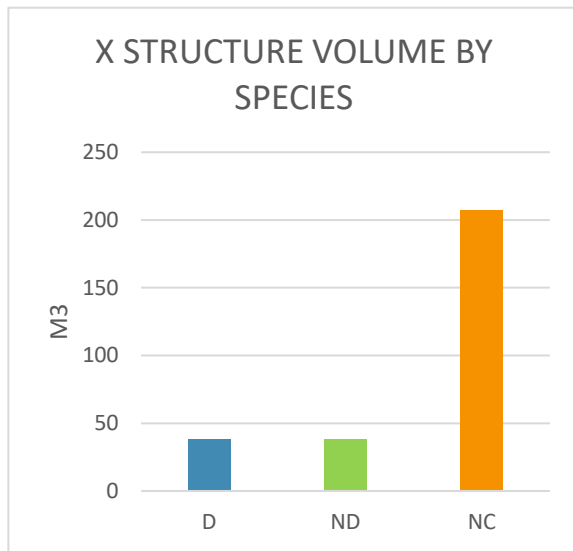


Figure 6 Stand volume by species at the steady state, t=210

Figure 7 Harvest volume by species at the steady state, t=210

6.3. THE CONTINUOUS COVER

Importantly, it was found that the stand remains CCF throughout the transition period and at the steady state (Figure 8). The volume of the whole stand fluctuates from ~160 m³ and ~270 m³. This is interesting to observe that the stand volume prior to harvests at the steady state is close to initial state's volume. Recall that the initial state was taken from a never harvested forest near the climax state.

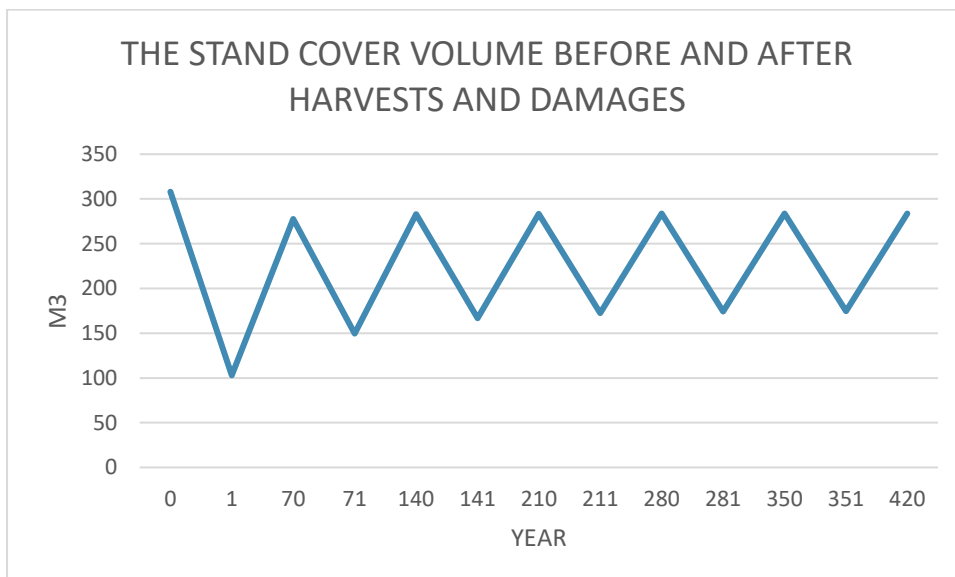


Figure 8 The stand total volume overtime. Total stand volume - harvest volume - harvest damages. Note somewhat unconventional notation of the horizontal axis. The graph shows the volume available at each beginning of the cycle and the harvest that happens in the end of the first year of each cycle. This is an illustration of the volume in residual trees.

By species, at the steady state, there remains 1.52 m³ dipterocarps, 3.00 m³ non-dipterocarps, and 184.17 m³ of non-commercial in the residuals (Figure 9).

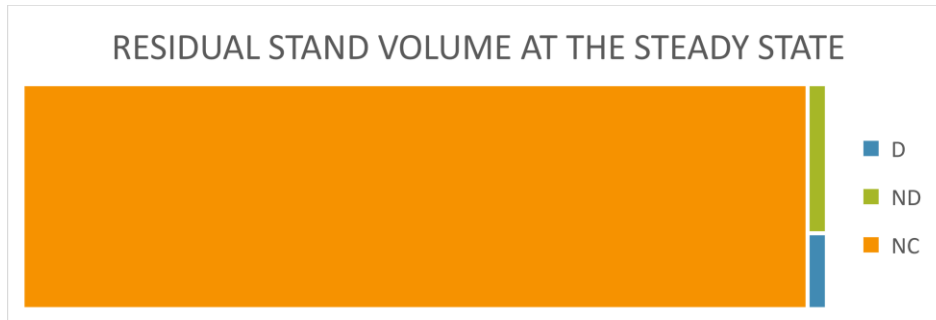


Figure 9 The residual tree volume by species of the steady state. Stand volume by species - harvest volume by species - harvest damages by species

The residual stand structure in non-commercial trees abundance is proportional to the initial stand structure in its size classes (Figure 9Figure 10). However, in absolute terms, the non-commercial are more abundant in the steady state by around 20%. This is interesting because it seems to confirm that the damages to the smallest trees that non-commercial species suffer is enough to regulate their growth and it converges to the stand as in Figure 10. Since the NPV is maximized in this model, it seems that the non-commercial overtaking the stand results in higher income than harvesting them.

Observe that the dipterocarps and non-dipterocarps volumes reflected in Figure 9 are in the first size class (Figure 10).

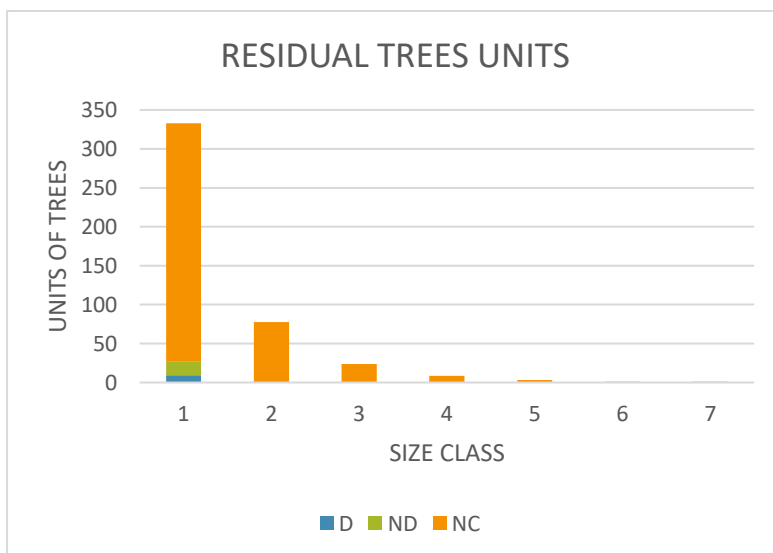


Figure 10 Residuals in tree units after harvest and damages are subtracted

6.4. REGULATED CASE ANALYSIS

A regulated case was also analysed. The model with 4.8% interest rate and 70-year cycle, found that NPV is 6,768\$ when minimum dbh harvest threshold, >50 cm, was enforced. Essentially, the difference between the regulated and unregulated cases when all other parameters are fixed means a 25% loss of NPV.

6.5. SENSITIVITY ANALYSIS

Two parameters were tested for sensitivity: net timber prices and the interest rate. Recall that baseline NPV was 8,430.98\$.

Prices were reduced by 15% which resulted in reduction in NPV by 1,264\$.

Increased interest rate, 10% interest rate, resulted in decrease in NPV by 1 %, that is 8,324\$.

It was found that the undiscounted cash flows remain the same with 10% (Table 10). This is argued to be the case because when the running-horizon algorithm was applied for 4.8%, the valuable trees were almost clear cut, with 10% there is no room to increase the harvests. It is generally accepted that with higher interest rates harvest volumes are larger. Furthermore, the biggest income is from the first harvest. The discount rates with 4.8% and 10% at year 70 are very small already. Therefore, NPVs are so very similar.

YEAR	UNDISCOUNTED CASH FLOW	DISCOUNT FACTOR	DISCOUNTED
0	8320.39	1.000000	8320.39
70	2843.33	0.0012662	3.60031
140	2597.46	0.0000016	0.00416
210	1463.63	0.0000000	0.00000
280	2423.19	0.0000000	0.00000
350	2408.95	0.0000000	0.00000
			8323.99

Table 10 The cash flow in the transition and the discounted present value with 10%

7. DISCUSSION

The steady state is reached in 210 years. This is further in the future than any other optimization study's planning horizon in the tropics. The steady state is reached after 3 cycles. This shows that the application of dynamic optimization method has an advantage for this growth model setup. There is a need, however, to rerun this model with static optimization methods to see how much of the difference in NPV the different methods produce.

The discounting is dealt with a creative running-horizon algorithm. It allows to run the optimization code without it being distracted by eventual multiplication by close-to-zero discount rate. This algorithm prevents the program from breaking while showing the physical development of the stand with given market conditions. While the most of the income comes from the initial harvests as expected, this algorithm continues to optimize the stand structure giving the position at which the physical stand structure stabilizes.

There is more work needed with running this code with shorter ad-hoc choices of cycles and smaller interest rates. The cycle length chosen is longer than current 30-year cycle recommendation in Malaysia. 70-year cycles have been studied before by Boscolo and Vincent (2003), however, largely the choice was based on the fact that this cycle was found to be optimal when optimization was run without the running-horizon algorithm. The harvest timings could be further optimized with simultaneous harvest timing and harvest quantity optimization methods.

Furthermore, the fixed cost used in this study is somewhat high. Indrajaya et al. (2016) reported RIL fixed cost at 389 \$ per ha for Indonesian context. These are very different fixed cost figures although the prices have been compiled around the same time. It is not clear how either of these fixed costs compare to the fixed costs that incur today. Technological development might have a strong role in this but remains not reflected in the figures.

Since the species in the tropical growth models are grouped, the pricing for each group is not easily accessible and, thus, are taken from 1997 adjusted for inflation. It is important to note that the net timber prices for smallest size classes are linearly interpolated from Boscolo and Vincent (2000). In addition, it is not clear if the species groups need to be redefined with time. Given technological advancements and potential of new applications of wood, what is not commercial now, does not have to remain not commercial in 20 years from now. Updated prices, rather than prices adjusted for inflation, should be considered in the future.

The case as described in chapter 6 was rerun with harvest constrain, a minimum dbh at 50cm. This resulted in 25% income for the forest owner. This is potentially important figure in policy making that relates to subsidies. Given that the prices used in this model are somewhat

outdated and that the non-timber benefits have not been applied the difference between regulated and non-regulated NPVs could be higher or smaller.

Potential pricing inaccuracies also arise from the way size classes are defined. The growth model used in this thesis includes all trees with dbh higher than 70 cm in the last size class. Grouping of trees like this can be problematic as the largest diameter trees can be up to 199.6 cm in dbh (Priyadi et al., 2007). Furthermore, the size classes are populated with non-negative real values, i.e. the model is not an integer model. While it has been accepted by multiple authors in the past it is somewhat odd given that the thesis models tree growth.

The growth model in this study has also raised some concerns. It seems that the damage matrix is not calibrated well to be applied in the unconstrained optimization. It has been used in Boscolo and Vincent (2003) that have run a dynamic unconstrained scenario, however, in the model in this thesis, it seemed to generate close to constant 75% total harvest volume damages to the residual trees. Given that this is supposed to reflect RIL damages, the percentage is very high. Also, the ingrowth function has a very low dependence on the total basal area. The ingrowth function produces largest impact from the constants that represent bird, animal, and/or wind seed dispersal from neighbouring stands, that is, impact from outside of the stand. This is probably one of the reasons why the non-commercial trees are not harvested.

Lastly, transition matrix models, generally, have limitations as they do not consider spatial distribution of trees which in turn can make management decisions difficult (Macpherson et al., 2012). Linear matrix growth models rely on an assumption that its probabilities remain the same over the whole planning horizon independent of the stand state at each time (Spathelf & Durlo, 2001). Additionally, it is unreasonable to expect that statistical-empirical models can adequately hold in the climate change context. Important work still needs to be done in ecological growth modelling for more accurate economic-ecological optimization research.

8. CONCLUSIONS

This thesis is the first to report on a general dynamic optimization method application in a tropical forest setting.

Given 70-year cycle it was found that the NPV is 8,430.98\$ per stand. The steady state is reached by year 210. The stand retains continuous cover throughout the transition period as well as at the steady state. This suggests potential for mixed species and sizes forests existing without regulation. The residual trees are represented by all three species groups, however, strongly dominated by the non-commercials (184.17 m³). Residual dipterocarps make 1.52 m³ and non-dipterocarps make 3.00 m³. Only the smallest size classes commercial trees are not fully harvested.

In ecological terms, the stand has potential to host all three species groups. The Indonesian Selective Cutting with Replanting System (TPTI), as the name suggests considers regulations on artificial regeneration (ITTO, 2006). However, there is no optimization literature that would include the artificial regeneration into the modelling even though the policy for its harvest threshold has been studied before (Indrajaya et al., 2016). Enrichment in valuable species could potentially form a species diverse forest that keeps a continuous cover.

The non-commercial species group is not harvested, neither in the transition nor at the steady state. This may be because there is a marginal cost assigned to harvest them. The ingrowth function together with damages that occur because of other species groups harvests seem to regulate the non-commercials at no cost. The non-commercials converge to a 20% larger than at the initial state size structure. Since the carbon in the literature is priced regardless of the species of the tree, the volume of non-commercials remaining after each cycle has good potential for carbon sequestration benefits.

The developed model is consistent in its results reflecting the usual dynamic optimization outcomes. Since the steady state is reached after 3 harvests, dynamic optimization theory is concluded to be relevant in this model. Unregulated dynamic optimization and unregulated static optimization models should be run and compared to see how different these equilibria are.

The most needed extension is analysing the carbon sequestration and what it does to the NPV and stand structure at the optimal state.

It would also be interesting to look deeper into the optimal choices between the forest treatments, namely the CL and RIL harvesting techniques. This could be achieved with a cost function where each regime is broken down by an activity and priced. The optimal set of these

activities could then determine the optimal choice between these two regimes or suggest an entirely different treatment combination. This may act as a strong policy argument.

To conclude, the thesis is largely an exploratory study that set a foundation for dynamic optimization research in the tropical forests. It is concluded that the model setup is compatible with dynamic optimization algorithms. The steady state showed that the forest is never fully harvested and with additional non-timber benefits and maybe artificial regeneration it has potential for unregulated tropical CCF.

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APPENDIX

.dat

```
param sc := 7;          #Number of size classes
param pl := 3;          #1= Dipt, 2= Non-dipt, 3=Non-c

param maxt := 750; #Length of time horizon
param r := 0.048;      #Interest rate
#param r := 0.005;

param FC = 1515.31;
#param FC =389;

param ps:              #timber prices that are dependent on the size class
  1      2      3 :=
1      14.57  2      -3.44
2      38.33 15.22 -3.44
3      62.10 31.99 -3.44
4      85.87 50.20 -3.44
5      109.68 66.98 -3.44
6      109.23 67.39 -3.44
7      109.08 67.38 -3.44
;

param PriceError:=     #Price multipliers for sensitivity analysis. Equal to
1 when not in use.
  1 1
  2 1
  3 1
;

#param ps: #timber price when the non-commercials have value
#
#1      1      2      3 :=
#1      14.57  2      2
#2      38.33  15.22 15.22
#3      62.10  31.99 31.99
#4      85.87  50.20 50.20
#5      109.68  66.98 66.98
#6      109.23  67.39 67.39
#7      109.08  67.38 67.38
#;

## Growth G matrix #columns refer to each species group

param a :
  1      2      3 :=
1      0.945 0.961 0.955
2      0.943 0.959 0.950
3      0.923 0.957 0.946
4      0.928 0.952 0.960
5      0.948 0.969 0.921
6      0.952 0.957 0.945
7      0.981 0.962 0.977
;
```

```

param b:
  1      2      3      :=
1  0.022 0.012 0.012
2  0.036 0.022 0.017
3  0.052 0.025 0.015
4  0.047 0.021 0.031
5  0.035 0.024 0.018
6  0.044 0.034 0.023
7  0      0      0
;

param m:
  1      2      3      :=
1  0.033 0.027 0.033
2  0.021 0.020 0.033
3  0.025 0.018 0.039
4  0.025 0.028 0.009
5  0.017 0.007 0.061
6  0.005 0.009 0.032
7  0.019 0.038 0.023
;

#Damage
param D:
  1      2      3      :=
1 0.1      0.2      0.85
2 0.13     0.26     1.13
3 0.25     0.50     2.12
4 0.35     0.71     3.02
5 0.48     0.96     4.11
6 1.05     2.12     9.05
7 1.45     2.91     12.42
;

# Ingrowth constants
param IngrowthConst :=
1 3.10
2 3.84
3 13.27
;

# Ingrowth basal area term coefficients
param IngrowthBCof :=
1 -0.10
2 -0.13
3 -0.30
;

# Ingrowth same species term coefficients
param IngrowthSSCof :=
1 0.017
2 0.017
3 0.017
;

#Basal area in m^2 per tree in each size class. mid-point
param BasArea:=

```

```

1 0.0177
2 0.0491
3 0.0962
4 0.1590
5 0.2375
6 0.3317
7 0.4416
;

#Volume of timber (m^3) in one tree in each size class. Same for all species.
param Vol:
    1      2      3      :=
1 0.368 0.368 0.368
2 0.487 0.487 0.487
3 0.914 0.914 0.914
4 1.302 1.302 1.302
5 1.772 1.772 1.772
6 3.905 3.905 3.905
7 5.361 5.361 5.361
;

## Initial stand 1= Dipt, 2= Non-dipt, 3=Non-c
param x0:
    1      2      3      :=
1 30.5 61.5 262.3
2 11.6 17.5 61.5
3 5.4 8.9 19.8
4 3.9 4.6 7.2
5 3.6 3.1 2.9
6 2.5 1.7 0.9
7 5.9 1.6 0.9
;

.run
reset;
model FINALCCF1mod;
data FINALCCF1dat;
option solver knitroampl;

option ampl_include 'C:\Program\Artelys\Knitro 12.4.0\ampl.mswin32';
option display_1col 10;
option knitro_options "maxit=2500 opttol=1.0e-5 ms_enable=1 ms_maxsolves=7
outlev=2 xtol=1.0e-50";
let k:=0;

repeat while k<=maxt {
    let Hbool[k] := 1;
    let k:=k+(70);
}

let k:=0;

solve;

display r, maxt,ps, objective;
close;

```

```

.mod

param maxt; #Length of the time horizon 500y
param pl; # Species 1=D 2=ND 3=NC
param sc; # Number of size classes
set T := 0..maxt;
set species:=1..pl; # setting a species set

#####Growth matrix related#####
param a {s in 1..sc, i in 1..pl}; # Recruit-function, probability
param b {s in 1..sc, i in 1..pl}; # Recruit-function parameters, conditional
param m {s in 1..sc, i in 1..pl}; # Mortality-function parameters
param D {s in 1..sc, i in 1..pl}; #Damage matrix entries

param PriceError {i in species}; #Price multipliers for sensitivity
analysis

##### ingrowth#####
param IngrowthConst {i in 1..pl}; # Ingrowth constants
param IngrowthBCof {i in 1..pl}; # Ingrowth basal area term coefficients
param IngrowthSSCof {i in 1..pl};# Ingrowth same species term coefficients

param x0 {s in 1..sc, i in species} default 0; #Initial stand, number of trees

param BasArea {s in 1..sc};

#####Econ parameters#####
param Vol {s in 1..sc, i in 1..pl};
param r; #Interest rate
param R := 1/(1+r); #Discount factor
param ps {s in 1..sc, i in 1..pl}; #Volume price
param FC;

param Hbool {t in T} default 0;

var x {t in T, s in 1..sc, i in species } >= 0; #stand development
var h {t in T, s in 1..sc, i in species} >= 0; #harvest
var d {t in T, j in 1..sc, i in species} =
    if j = 1 then sum {s in 1..7} 2/3 * D[s,i]* ( h[t,s,1] + h[t,s,2] +
    h[t,s,3] )
    else 0;

#Total basal area
var BasalTerm {t in T} =sum {i in species} sum {s in 1..7} BasArea[s] * x[t,s,i] ;
#the basal area at time t
var BasalAreabySpecies {t in T, i in species} = sum {s in 1..7} BasArea[s] *
x[t,s,i] ;
var Ingrowth {t in T, j in 1..sc, i in species} =
    if j = 1 then IngrowthConst [i]+ IngrowthBCof[i]*BasalTerm[t] +
IngrowthSSCof [i] * sum{s in 1..sc} x[t,s,i]
    else 0;

var hVolume {t in T} = sum {s in 1..sc} sum {i in species} Vol [s,i]*h[t,s,i];
var hVolumebySpecies {t in T, i in species} = sum {s in 1..sc} Vol
[s,i]*h[t,s,i];

```



```

var hVolumebySize {t in T, s in 1..sc} = sum {i in species} Vol [s,i]*h[t,s,i];

var xVolume {t in T} = sum {s in 1..sc} sum {i in species} Vol [s,i]*x[t,s,i];
var xVolumebySpecies {t in T, i in species} = sum {s in 1..sc} Vol
[s,i]*x[t,s,i];
var xVolumebySize {t in T, s in 1..sc} = sum {i in species} Vol [s,i]*x[t,s,i];

var dVolume {t in T} = sum {s in 1..sc} sum {i in species} Vol [s,i]*d[t,s,i];
var dVolumebySpecies {t in T, i in species} = sum {s in 1..sc} Vol [s,i]*d[t,s,i];
var IngVolume {t in T} = sum {s in 1..sc} sum {i in species} Vol
[s,i]*Ingrowth[t,s,i];

subject to initial_state {s in 1..sc, i in species}:
x[0,s,i] = x0[s,i];

### Stand structure at each time instance ### harvesting at end of period
subject to standstate_1sc {t in 0..maxt-1, i in species}:
x[t+1,1,i] = Ingrowth[t,1,i] + a[1,i] * x[t,1,i] - Hbool[t]*h[t,1,i] - d[t,1,i] ;
#first size class

subject to standstate_other {t in 0..maxt-1, s in 1..sc-2, i in species}:
x[t+1,s+1,i] = b[s,i]*x[t,s,i] + a[s+1,i]*x[t,s+1,i] - Hbool[t]*h[t,s+1,i] -
d[t,s+1,i]; #all size classes between 2 to 6.

subject to standstate_7sc {t in 0..maxt-1, i in species}:
x[t+1,sc,i] = b[sc-1,i]*x[t,sc-1,i] + (1-m[sc,i])*x[t,sc,i] -
Hbool[t]*h[t,sc,i] - d[t,sc,i]; #last size class

### Setting the boolean-matrix's effect on harvests
subject to harvests {t in T, s in 1..sc, i in species}:
h[t,s,i] = Hbool[t]*h[t,s,i];

#subject to harvestsMinDBHConstraint {t in T, s in 1..4, i in species}: # this is
the regulated scenario constraint min dbh 50cm
# h[t,s,i] = 0;

subject to HARVESTMAX {t in T, s in 1..sc, i in species}:
h[t,s,i] + d[t,s,i] <= x[t,s,i];

subject to xBasallimiter {t in T, s in 1..sc, i in species}: #limiting the total
basal area a stand can reach
BasalTerm [t] <= 25;

## **** The economic objective function ###

var Q {t in T} = sum {s in 1..sc} sum {i in species} h[t,s,i] * Vol[s,i]
*ps[s,i]*PriceError[i];

#the original
maximize objective:
sum {t in 0..maxt} (Q[t] - Hbool[t]*FC) *R^t ;

param k;

```