Projecting growth and yield in mixed dipterocarp forest

Jannes van Hoeflaken

Van Hall-Larenstein University of Applied Sciences

Sarawak Forestry Corporation

Title:	Projecting growth and yield in mixed dipterocarp forests using a matrix model.
Subtitle:	A bachelor's thesis in which the potential of matrix models for growth projections in mixed dipterocarp forests of Sarawak, Malaysia is tested, using Permanent Sample Plot data.
Author:	Jannes van Hoeflaken
Student number:	000008278
Supervisors:	Peter van der Meer (VHL)
	Bibian Diway (SFC)
Hosting organization:	Sarawak Forestry Corporation (SFC)
University:	Van Hall-Larenstein University of Applied Sciences (VHL)
Study program:	Bachelor's in Forest and Nature Management
Major:	Tropical Forestry
Cover photo:	A tagged tree in a PSP plot, Jannes van Hoeflaken
Completion date:	October 2019

Acknowledgements

First and foremost, I would like to thank my supervisors, Peter van der Meer and Bibian Diway for their guiding help and effort.

I would specifically like to thank Rens Brouwer for his time and knowledge, helping me on many subjects. Also, thanks to Malcom Demies, who aided and guided me during my stay in Kuching. Furthermore, I would like to thank Jaap de Vletter for his feedback. Special thanks to Ling Chea Yiing for her help and knowledge. Also, I would like to thank Voon Mufeng and Wong Ong Cieh for their assistance in getting me around in Kuching.

Last but not least, I would like to thank the many SFC staff members that helped me in one way or another. I would like to thank the fieldwork crews, drivers and all others involved in the PSP project.

I would like to acknowledge the following institutions, for their willingness to share data or for their financial support, without which this report could not have been completed:

Sarawak Forestry Corporation
Ministry of Urban Development and Natural Resources of Sarawak
The establishment of the Permanent Sample Plot Project (a Sarawak Forestry Corporation project)
Ta Ann Holdings Bhd.
Zedtee Sdn. Bhd.

Abstract

Tropical forests are under serious pressure and deforestation and forest degradation are taking their toll. The mixed dipterocarp forests of Sarawak are no exception. The importance of sustainable forest management is evident and growth models are a convenient tool to help in determining sustainable exploitation rates.

A matrix model is constructed for mixed dipterocarp forest in Sarawak in order to determine the effect of differing logging intensities and logging cycle lengths. All trees in the database comprising of 11 permanent sample plots with a total of 6455 trees were divided into 3 timber groups: light, medium and heavy hardwoods. A separate model was constructed for each of the timber groups. Furthermore, a division was made based on forest age after logging, a separate matrix was made for the first 10 years after logging and one for more than 10 years after logging. 8 size classes were used. The matrix model was amended with a function for density-dependence. Four scenarios with logging intensities of 70% and 50%, and rotation cycles of 25 and 20 years were projected for 100 years and compared.

Population density increases after logging for all trees and trees of 50 cm or more. A difference in DBH increment between light, medium and heavy hardwoods was found, with LH growing 0.52 cm/yr, MH 0.37 cm/yr and HH 0.34 cm/yr. Matrices have been constructed and lambda values are 1.041 and 1.039 for LH, 1.019 and 1.022 for MH and 1.028 and 1.025 for HH. The stable stage distribution was calculated from the matrices and an elasticity analysis was conducted.

Projection outcomes showed an increase in total population but a decrease in trees of 50 cm or more for LH, a decrease or increase for both total population and trees of 50 cm or more for MH, depending on the scenario and a decrease for both total population and trees of 50 cm or more for HH. Scenario 3 was the best scenario. The LH group proved to be most resilient, the MH more sensitive and the HH showed a strong reduction in density for all scenarios. The model was evaluated, and recommendations are given.

Contents

List of tables and figures

Tables

Figures

List abbreviations

Abbreviation	Meaning
°C	Degrees Celsius
AAC	Annual Allowable Cut
AV	Average
BA	Basal Area
cm	Centimetre
DBH	Diameter at Breast Height
FDS	Forest Department Sarawak
FMU	Forest Management Unit
ha	Hectare
HCVF	High Conservation Value Forest
HH	Heavy Hardwood
HMDF	Hill Mixed Dipterocarp Forest
ITTO	International Tropical Timber Organization
LH	Light Hardwood
m3	Cubic metre
MDF	Mixed Dipterocarp Forest
MH	Medium Hardwood
mm	Millimetre
N/ha	Number per hectare
NC	Non-Commercial
PCT	Potential Crop Tree
PFE	Permanent Forest Estate
POM	Point Of Measurement
PSF	Peat Swamp Forest
PSP	Permanent Sample Plot
RIL	Reduced Impact Logging
Sdn. Bhd.	Sendirian Berhad (private limited company in Malaysia)
SFC	Sarawak Forestry Corporation
SFM	Sustainable Forest Management
TG	Timber group
TPA	Totally Protected Area
VHL	Van Hall- Larenstein University of Applied Sciences
VOL	Volume
yr	Year

1 Introduction

On a daily basis, we are confronted with news about forest destruction. As of September 2019, reports are circling the news about fires raging in the Amazon and the Siberian taiga, as well as a thick haze covering south-east Asia, and continuous forest dieback due to drought, disease and pollution in the Netherlands. The topic of sustainable forest management might be more relevant than ever before.

Tropical forests often suffer heavily from unsustainable practices. The main causes for deforestation and forest degradation are the clearance of forests for agriculture and logging (Zimmerman and Kormos 2012). The extraction of wood has been one of the most important functions of tropical forests throughout history. Many nations have relied on timber export as a source of income. In the past, forests where seen as a seemingly endless resource, but as cutting levels and population densities increased, it turned out that this resource was far from endless (Angelsen and Kaimowitz 2001). After a forest has been deprived of its valuable timbers, the threat of conversion to agricultural land is imminent.

The island of Borneo has been severely impacted by deforestation and forest degradation. The island has lost over 150.000 square kilometres of forest over the past five decades. Forest classified as intact covers less than 30% of the island and is mainly found in Kalimantan. In Sarawak most forest has been affected by logging activities, with only around 10%-15% of the land covered by intact forest (Gaveau et al. 2014).

Land clearance for shifting agriculture or palm oil plantations has reduced forest cover in Sarawak (Gunarso et al. 2013). Although a large proportion of the state is still under forest cover, most of this forest has been logged (Global Forest Watch 2019). Logging in Sarawak and in tropical forests in general is mainly done on a selection basis. Selective logging is seen as the most appropriate type of forest management for tropical rainforests.

The aim of this thesis is to contribute to managing tropical forests in a more sustainable way. The setup of this report starts with an overview of selection forest systems and the situation in Sarawak, and a short introduction to growth modelling, together leading to a problem statement. A set of research questions and sub-questions is formulated. The following chapter describes the methodology used, leading to results in chapter four. A conclusion of the results is given, and methodology and results are discussed in chapter five. Recommendations and an evaluation of the model are given in the last chapter.

1.1 Selective logging in tropical forests

As discussed before, logging in lowland tropical forests is often done on a selection basis. This is contrary to uniform silvicultural systems that are usual for temperate regions. Below an explanation of the concept of selection forestry and its application in tropical forests.

1.1.1 Definition of selective logging system

The predominance of selection systems in tropical forests can be attributed to the specific situation of these forests: soil types, species composition, forest structure, ecological functioning, commercial interests and maybe above all, sustainability (Lamprecht 1989). Selection systems can be further subdivided into group selection and single-tree selection systems (Skovsgaard 2018). In tropical forests, single tree selection is one the most commonly applied silvicultural systems (Lamprecht 1989). See figure 1 for a representation of a selection forest. A selection forest can be characterized by the following aspects:

- Irregular distribution of size classes (Lamprecht 1989; Matthews 1989; Skovsgaard 2018).
- For regeneration dependent on natural regeneration (Skovsgaard 2018).
- High diversity of tree species (in tropical forests) (Lamprecht 1989).
- Timber extraction at certain time intervals (logging cycle) (Lamprecht 1989; Vanclay 1995).
- Commercial interest is only focussed on suitable (i.e. commercial) species (Lamprecht 1989).
- Only trees that have reached or exceeded a minimum diameter are extracted. These diameter limits normally differ among species groups (Lamprecht 1989; Matthews 1989).

Figure 1: Representation of a selection system. Trees of all size are present. (Matthews 1989)

Generally speaking, selective logging is seen as a sustainable system, or at least more so than even-aged systems (Vanclay 1995). However, to be called sustainable, the amount of timber harvested at one operation shall not exceed the long-term growth (Vanclay 1996; Zimmerman and Kormos 2012). Another point of importance is the interval of logging, better known as the logging cycle or rotation. Research has shown that logging cycles are often too short for timber stocks to regrow (van Gardingen et al. 2006; Sist et al. 2003). Therefore, to achieve sustainability, yield regulation is of great importance.

1.1.2 Selection forestry in the Amazon and Borneo

Selection forestry is a broad concept. Many tropical regions have developed their own systems (Lamprecht 1989), and one could talk for a long time about these systems and their differences. Below a brief overview of logging intensities and rotation times in two different tropical regions is given, with reference to sustainability.

While forests in the Amazon basin are characterized by rather low standing volumes of commercial timber (van Gardingen, Valle, and Thompson 2006), the dipterocarp forests of south-east Asia generally have high standing volumes of commercial timber. Also, growth rates of commercial species are thought to be higher in south-east Asian forests (Forshed et al. 2008).

Looking at the forests of the Amazon basin, volumes of 20-35 m3 are extracted per hectare, on 30-year cycles. Diameter limits are often determined for species groups. The extraction rate is deemed too high to be sustainable. The assumed growth is a too high a estimation, and a growth rate of 0.33 m3 per hectare per year (10 m3/cycle) is seen as more realistic, or a prolongation of the cutting cycle is needed (van Gardingen et al 2006). Regrowth is often not satisfactory and mortality rates in the residual stand after logging can be higher than new growth (Higuchi et al. 2019).

When looking at the dipterocarp forests of Borneo, rotations are normally in the range of 25-35 years, and harvested volumes are between 20-100+ m3 per hectare. Diameter limits are determined for dipterocarps and non-dipterocarps. The high standing volume of commercial species in these forests (Appanah et al. 2015) leads to high extraction figures in the first rotation (i.e. in primary forest), with yields of over 100 m3 per hectare being recorded (Sist, Picard, and Gourlet-Fleury 2002). However, regrowth after such intensive logging is often not satisfactory and damage to the residual stand can be severe. This leads to low harvestable volumes in the next rotations and can be seen as a marked degradation of the forest (Forshed et al. 2007).

Guidelines for reduced impact logging of mixed dipterocarp forests have been developed by (Sist et al. 2015) for Indonesia. For Sarawak, silvicultural guidelines have been assessed by the ITTO mission of 1989-90 (ITTO 1990) and currently SFC has come up with thorough RIL guidelines (Sarawak Forestry Corporation 2018). Levels of sustainable yield have been appraised for peat swamp forests in Sarawak (Chai and LeMay 1993; Chiew 2004). In East Kalimantan a logging intensity of 1.6 m3 per hectare per year on 35 year rotations in lowland mixed dipterocarp forest was found to be sustainable (Sist et al. 2002). Also in Kalimantan, a thorough study of harvesting potential in MDF has been conducted by Favrichon et al. (2001). The result of these studies could be applied in Sarawak. However, comparatively few attempts to model forest growth have been made, leaving forest managers with little scientifically backed tools to conduct sustainable forestry. Currently, the FORMIND model is being promoted for use in Sarawak, and shows promise for future use (Fischer et al. 2016).

1.2 Forest sector in Sarawak

The forest sector has traditionally been a major component of Sarawak's economy. It is a multi-billion ringgit industry, employing over 80.000 people in 2008 (Forest Department Sarawak 2019b). The timber industry is dominated by the so called 'big six': Samling, Rimbunan Hijau, Shin Yang, Ta Ann, WTK and KTS. These companies together have a combined concession area of more than 3.7 million hectares in Sarawak (Tawie 2015), and are integrated companies, that besides actual log extraction also have saw- and plywood mills. The efficiency of the Sarawak timber industry is high because of this integration of up- and downstream operations (Mittelmeijer 2019).

The annual allowable cut (AAC) was previously based on an ITTO report dating back to 1990, which states 9.2 million m3 per year for the state of Sarawak (Fah 2007; ITTO 1990). More recently, the AAC is based on pre-felling inventories carried out by the FMU's themselves, and FDS states a total of no more than 170.000 hectares is to be logged each year in PFE classified forests (Forest Department Sarawak 2019b). The share of log production from planted forests is expected to increase the coming years, in order to maintain timber supplies.

In Sarawak, a cutting cycle of 25 years is generally used. In the past cutting cycles have been different, but for a concession to qualify as a forest management unit (FMU), the cutting cycle is set at 25 years (International Forest Management Consultants 2015). Minimum legal felling DBH is currently set at 45 cm for non-dipterocarp trees, and 50 cm for dipterocarps (Fah 2007). 7-12 trees are on average felled per hectare (Woon and Norini n.d.), but with the lower DBH limits currently used this figure can be higher. This normally translates to 0.8-2 m3 per hectare per year, or 20-50 m3 per 25-year logging cycle, and is conform with the statements of the FMU's (Pasin Sdn. Bhd. 2019; Raplex Sdn. Bhd. 2019; Ta Ann Holdings Berhad 2019; Zedtee Sdn. Bhd. 2019). Logging activities are concentrated in Mixed Dipterocarp Forests (MDF) of the state's interior.

1.3 Growth modelling

Growth models are frequently used in forest management to make projections of forest growth. They can be seen as an invaluable tool for successful forest management, since planning can be adjusted to modelling outcomes. Below a short explanation is given.

The history of growth models in their most basic form dates back to the 18th century, when the first yield tables were developed in both China and Germany (Vanclay 1994). Simple yield tables have been used ever since but were generally developed for even-aged stands. The first models based on equations were developed in the first half of the 20th century. It was not until computers came into use in the 1970s-1980s that growth models became more complex (Shifley et al. 2017).

Growth models essentially use three main parameters: increment, mortality and recruitment (see figure 2). However, many additional parameters can be added to increase accuracy. By using time steps, the change in vector (basal area, volume or population density (Sun et al. 2007)) over time can be projected. Every time step the vector is multiplied by the model parameters, and the vector changes. Projection time can be as long as desired, keeping in mind that making very long term projections might not be realistic (Vanclay and Skovsgaard 1997).

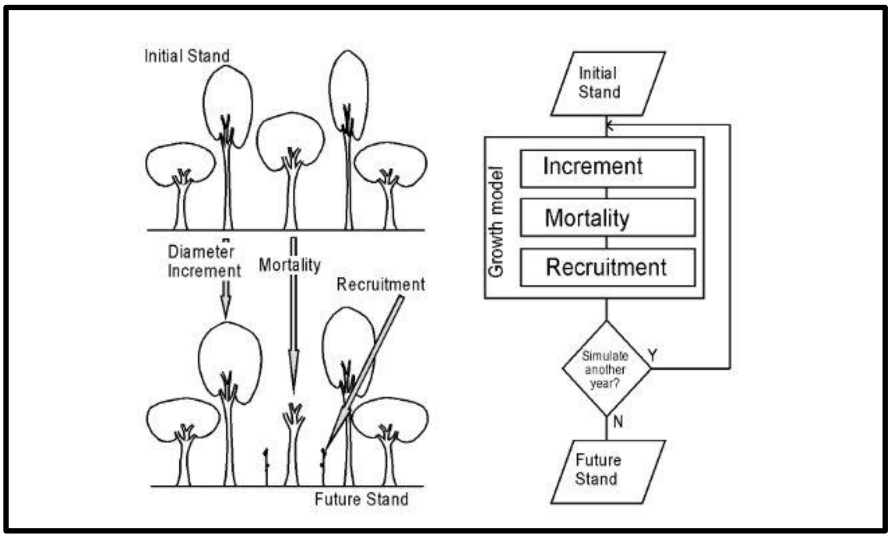


Figure 2: Schematic representation of a growth model (Vanclay 1994).

Three basic types of forest growth models can be discerned according to Vanclay (1994): whole stand models, size class models and single-tree models. In a whole stand model, no details of individual trees are present, and growth is projected as basal area, volume or stem number growth for the whole stand. Size class models do make differences between individual trees, albeit grouping them in predetermined size classes. Now growth can be projected per size class, making the model more detailed. Single-tree models are more detailed even then size class models. This type of model uses not a stand or size class as a basis but uses every individual tree from a database. These three classes respectively increase in complexity (Twery 2004; Vanclay 1994).

1.4 Problem statement

Looking at the logging sector in Sarawak, several issues restraining the sustainable exploitation of dipterocarp forests can be observed. The following issues are summed up below.

A cutting cycle of 25 years is used in Sarawak, and the AAC is set as a state-wide limit. But few regulations are formulated for volume extraction on a hectare basis (Woon and Norini n.d.), and the AAC per concession is based on a monthly production limit (Fah 2007). This can lead to overharvesting and damage to the residual stand when excessive amounts of timber are extracted at once on a hectare basis, while remaining below the monthly production limit for the entire concession.

One of the factors limiting sustainable exploitation is the legal DBH limit. Often high volumes are extracted because all (or nearly all) legally harvestable trees are harvested from a cut block. This means a significant basal area reduction (sometimes >60% reduction) (Sist et al. 2002) and strongly increased levels of light, which can lead to invasions of pioneer species and unsatisfactory recruitment of commercial species for the future generation (Huth and Köhler 2003; Lamprecht 1989).

Another factor contributing to low growth rates, tree mortality and general unsustainability of logging practices is the damage inflicted on the residual stand during logging. Especially the destruction of future crop trees and soil damage by skidding activities have a strong negative impact on the quality of the stand (Pinard et al., n.d.). However, applying Reduced Impact Logging (RIL) techniques can substantially reduce the damage (Marn and Jonker 1981; Pakhriazad et al. 2010).

The previous sections may give the impression that sustainable harvesting of timber from tropical selection forests is not possible. However, numerous research reports have shown that when regulated and carried out properly using RIL systems, selective logging can be done sustainably (Enters et al., 2001; Pinard et al., n.d.).

In the past several researchers have looked at growth rates. Species-specific or species group growth predictions have been made for several forest types in Sarawak (Kammesheidt et al., 2003; Yan Chiew, 1991), especially for peat swamp forests (Chai and LeMay 1993; Chiew 2004). Growth rates have been recorded in planted dipterocarp forests, but these might not be comparable to natural forests (Tan et al., 1987). Models made for mixed dipterocarp forest in Sabah and East Kalimantan (Forshed et al. 2007; Pinard and Cropper 2000; Sist et al. 2002), this could be applicable on dipterocarp forests in Sarawak.

Table 1: Log production in Sarawak for the period 2000-2018

Year	Log production in millions of m3
2000	14.3
2001	12.2
2002	11.9
2003	12.2
2004	12.1
2005	12.0
2006	11.9
2007	11.9
2008	11.3
2009	10.4
2010	10.2
2011	9.6
2012	9.6
2013	8.5
2014	9.2
2015	9.1
2016	8.7
2017	7.1
2018	6.4

As can be seen in table 1, log production has declined dramatically over the past two decades. Reasons for this are numerous and are beyond the scope of this report. However, with the Sarawak timber industry facing serious log shortages, a clear picture can be seen unfolding (J. Wong 2018). This is a problem that is also strongly impacting the state's economy. Maintaining a stable log supply is key for the timber industry.

To summarize the challenges regarding sustainable yield in the mixed dipterocarp forests of Sarawak:

- Overharvesting has been identified as the main problem (Bruenig 2006).
- The length of the logging cycle is often not appropriate with regard to the logging intensity.
- Legislation (sometimes) restricts sustainable harvest.
- Damage done during logging operations decreases stand quality.
- Although there is a lot of knowledge about sustainable forest management (Enters et al., 2001), this is often not put into practice.
- Too little research has been done to construct reliable growth projections/models specifically for Sarawak.
- Because of the high complexity of dipterocarp forests, sustainable exploitation is simply more difficult than in other forest types (Appanah and Turnbull 2015).

2 Objective and Research Questions

The objective of this thesis is to construct a matrix model as a tool to aid in determining a sustainable exploitation rate for Mixed Dipterocarp Forests (MDF) in Sarawak. The model output will be the projected population density in the next logging cycles, and it's change over time. Growth rates are based on Permanent Sample Plot (PSP) data. The following main research questions and sub questions have been set.

2.1 Aim of PSP project

SFC's PSP project started in 2016 with the aim of determining growth rates, standing stock, population density and species composition of the forests of Sarawak. The idea is that in the future this data can be used to construct equations and growth models to determine a sustainable state-wide AAC. For this, 23 one-hectare permanent sample plots were set up throughout Sarawak. The project is scheduled to finish in 2020.

2.2 Research questions and sub-questions

The setup of this thesis can roughly be divided in two parts. First, growth rates will be determined for mixed dipterocarp forest in Sarawak. The second part is about modelling this growth to make projections. Thus, the following two main questions and their sub-questions can be formulated:

1. What are growth rates for three timber groups in mixed dipterocarp forests in Sarawak?

    - Is there a difference in growth and if so, what is the difference in growth between light, medium and heavy hardwoods?

    - What are vital rates for the three timber groups?

2. What is a sustainable harvest level for three timber groups in mixed dipterocarp forest, and how can this be determined using a matrix model?

    - How can equations for matrix multiplication be formulated so that realistic projections of forest development can be made?

    - What is the difference in projected population density and growth, related to initial population structure and felling intensity?

    - What is a sustainable rate of exploitation for each of the timber groups?

    - How can recommendations for a sustainable yield and harvesting cycle, and for proper use of growth models, be formulated?

3 Methodology

To answer the research questions stated in the previous chapter, a projection will be made using a matrix model. The population of the tree species is divided into timber groups and in several diameter classes, and by using vital rates the development from one class to another is projected. Input for the model will be calculated from data gathered in 11 PSP plots in 4 logging concessions in central Sarawak. First the vital rates and model equations will be formulated, after which model construction can commence.

The most important factor altering forest development will be logging intensity. Once the core matrix with the vital rates has been constructed, one can run different scenarios with varying logging intensities and cycle lengths. This gives a forecast of how the forest could develop and what effect various measures have on forest development, making it a useful tool for forest managers.

3.1 Description of study area

The subject of this project is Sarawak's Mixed Dipterocarp Forest (MDF). Therefore, a brief overview of the geographical and biotic situation of Sarawak is given.

3.1.1 Geography of Sarawak

Sarawak is a state of Malaysia, covering a land surface of around 124.500 square kilometres and is located on the island of Borneo. The state has an elongated form and is situated just north of the equator, at a latitude of 0° to 5° north. Located on the west coast of Borneo, the state borders the south China sea to the west, the Indonesian provinces of West, East and North Kalimantan to the south and east and Brunei and the Malaysian state of Sabah to the north and northeast (Sarawak Government 2019b). See figure 3 and figure 4 for maps of the region.

Figure 3: Map of Sarawak and neighbouring regions (OpenStreetMap 2019)

According to the Population and Housing census, the population of Sarawak was 2.5 million in 2010 (Sarawak Government 2019a). The capital of Kuching is also the state's largest city, with Miri and Sibu being the second and third cities, respectively. Sarawak has the lowest population density of all of Malaysia's administrative districts, with around 20 people per square kilometre (Department of Statistics Malaysia 2011). Population is concentrated along the coast and rivers.

Figure 4: Map of Sarawak (OpenStreetMap 2019)

The landscape of Sarawak can be divided into three main geographical regions: alluvial plains and peat swamps along the coast, undulating and steep hilly terrain of medium elevations cover most of the interior, and a string of mountain ranges spreads along the eastern border with Indonesia. Sarawak's highest point at 2.424 metres is reached at the summit of Gunung Murud. The Rajang river is the largest river of both Sarawak and Malaysia and functions as the main gateway into the interior (Sarawak Government 2019b). The three most common soil types are lithosols, acrisols and histosols. These three soil types cover most of the state. Other soil types that are locally abundant include ferralsols, podzols, gleysols and rhegosols (Land and Survey Department Sarawak 1968).

Sarawak has a year-round hot equatorial climate, with some monsoon influence. Temperature typically ranges from around 23 °C at night to around 33 °C during the day, but colds nights may drop down to 20 °C, were as on hot afternoons temperature may hit 38 °C. More moderate temperatures are recorded in the montane areas along the border with Indonesia. Rainfall is high and no dry season is present. Most of Sarawak receives between 3000 and 5000 millimetres of rainfall annually. The monsoon effect can be seen in the period December-March, when rainfall is very high. During the period June-September, rainfall is more moderate. Humidity is typically high, with values of around 80% to 90% on most days (Sarawak Government 2019b). In the drier period of June through to September, a haze can be present because of slash and burn activities.

According to the Forest Department Sarawak (2019), more than 80% of the state was under forest cover in 2012, which includes planted forest and possibly palm oil plantations. The most common type of forest is Mixed Dipterocarp Forest (MDF), covering around 9.6 million hectares. Peat Swamp Forest (PSF) covers around 0.75 million hectares (Forest Department Sarawak 2019c). Forest can be classified as Permanent Forest Estate (PFE), Totally Protected Area (TPA) or Stateland Forest. Of the total forest land, around 4.3 million hectares is classified as PFE in 2017. In the same year around 0.7 million hectares is classified as TPA, and around 0.3 million hectares consist of planted forests (Forest Department Sarawak 2019a).

3.1.2 Biotic situation

Sarawak's forests boast high levels of biodiversity as is usual for tropical rainforests. Over 8.000 species of vascular plants have been described to science as of 2006. Furthermore, 185 species of mammals and 530 species of birds, as well as countless other animal species have been described in the same year (Sarawak Forestry Corporation 2006).

As noted in the previous section, the most common forest type of Sarawak is Mixed Dipterocarp Forest. Also, because the setting of the PSP-project is MDF, this forest type will be described in a bit more detail below. Other major forest types such as kerangas and peat swamp forest are beyond the scope of this thesis and will not be discussed.

MDF is dominated, as the name suggests, by species in the Dipterocarpaceae family. This is a family of trees with a pantropical distribution, although the highest diversity and abundance is found in southeast Asia. 15, 16 or 19 genera are present with 470 to more than 580 species. Dipterocarps are mostly large canopy trees growing in lower elevation tropical rainforest. Mast fruiting of dipterocarps is recorded and thought to be a regeneration strategy, but the phenomenon is not yet well understood (Appanah and Turnbull 2015).

Dipterocarps generally represent around 30-50% of the stand basal area, and around 20-30% of all trees in a stand (Lee et al. 2002). The genera *Shorea*, *Hopea*, *Dipterocarpus*, *Dryobalanops* and *Vatica* are most abundant in Sarawak. Well represented non-dipterocarp families include Euphorbiaceae, Myrtaceae, Burseraceae, Myristicaceae and Sapotaceae. Some notable non-dipterocarp genera found in MDF include *Macaranga, Syzygium, Saurauia, Pouteria, Pternandra, Diospyros* and *Elateriospermum* (C. Y. and S. 2012; Demies et al. 2019; Lee et al. 2002) (Data from database was also used).

Tree species diversity is high in Sarawak, even for tropical rainforests. Highest species diversity is found in Mixed Dipterocarp Forest. Over 2000 tree species are present in MDF, and frequently over 200 species are recorded per hectare. Many species have a scattered distribution and are present over large areas, but always in very low densities of not more than one mature tree per hectare (Demies et al. 2019; Imai et al. 2016; Jawa and Chai 2007).

Trees in the Dipterocarpaceae family are known for reaching exceptionally large dimensions. In virgin stands, basal area and commercial volume is often very high compared to other tropical forest formations, with many large diameter trees present (Appanah and Turnbull 2015). Tree height is normally substantial as well, with the emergent layer of trees (often dipterocarps or *Koompassia*) frequently exceeding 50 metres (Lamprecht 1989). Recently, the world's second tallest tree species and the tallest tropical tree, a dipterocarp (*Shorea faguetiana*), was discovered in Danum valley, Sabah, measuring 100.8 metres in height (Gagen 2019). The large dimensions and good structural properties of many timbers found in MDF has made these forests a prime target for the timber industry, with a large proportion of the world's tropical timber coming from dipterocarp forests.

3.1.3 Description of logging concessions

Out of the 23 permanent sample plots set up by SFC for the PSP-project, data from 11 plots was used in this project. The plots are divided into two databases, with 5 plots in Anap Muput database and 6 plots in Kapit database. Plots in Anap Muput database were established in 2018 remeasured in August 2019. The five plots are located in Anap Muput FMU, in Bintulu division.

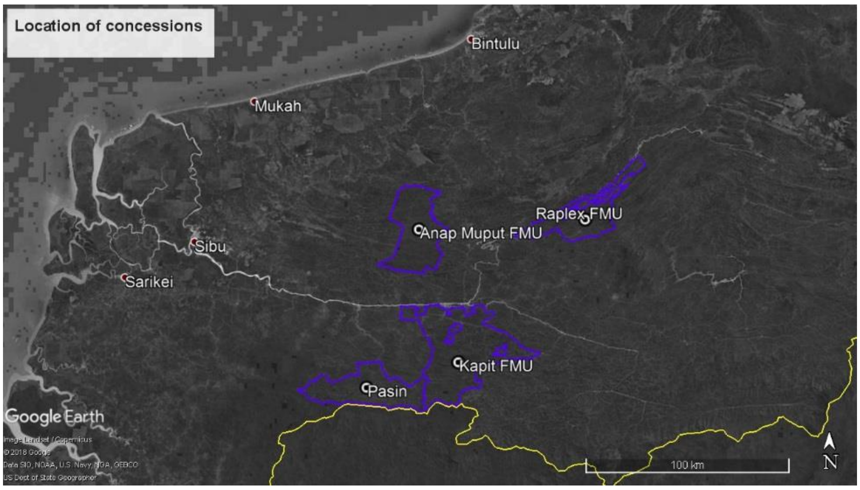


Figure 5: Map of logging concessions with PSP-plots

The six plots in the Kapit database were established in 2016 and remeasured in 2017 and 2018. The plots here are divided over three concessions, with each two plots: Raplex, Kapit and Pasin. These are all located in Kapit division. Three concessions (Anap Muput, Raplex and Kapit) are classified as Forest Management Unit (FMU), and Pasin concession aims to certify as FMU in 2020. Below a brief description of each concession. See figure 5 for a map of the logging concessions in Sarawak. In appendix 9 a map of the exact plot locations is included.

Anap Muput Forest Management Unit

Anap Muput FMU is situated in Tatau district, Bintulu division. The FMU covers 83.535 hectares of land and has 5 settlements inside the FMU area. The land is classified as Permanent Forest Estate. Most of the forest can be classified as mixed dipterocarp forest, and the terrain is generally hilly with steep slopes and elevation up to around 750 meters above sea level. Management is done by logging contractor Zedtee Sdn. Bhd. and the timber licence is issued to Shin Yang Trading Sdn. Bhd. The first logging operations started in 1977 and currently the harvesting of the second rotation is conducted, with the licence expiring in 2024. The monthly production limit was 7.000 m^3 for the period

2013/2014, on 25-year rotations. RIL techniques are used for timber extraction. Areas excluded from logging operations include HCVF and watershed protection areas, steep slopes (terrain class IV), community land (mainly shifting agriculture) and other protected areas. Anap Muput FMU works together with SFC, Sarawak Forest Department and several other institutions on research projects, mainly focussing on sustainable forest management. (Zedtee Sdn. Bhd. 2019)
Five PSP-plots have been set up in Anap Muput FMU.

Raplex Forest Management Unit
Raplex FMU is located in Kapit division in central Sarawak, the northern parts of the FMU bordering the Rajang river. FMU land totals 63.993 hectares and is licenced to Raplex Sdn. Bhd., a subsidiary company of Ta Ann Holdings Berhad. The logging contractor is Ironwall Sdn. Bhd. Five settlements are present within the FMU. Around 70% of the FMU is actively logged, the remainder being either protected or community land. The rotation cycle is 25 years and RIL is carried out, with logs extracted with excavator winching systems. The AAC is around 100.000 m^3, depending on the annual coup size. Total log harvest is lower at around 70.000 m^3 in 2018. Intensive enumeration of harvestable trees, PCT's and protected trees is conducted. An enrichment planting program is carried out. Furthermore, the FMU works together with SFC and other institutions on SFM, wildlife monitoring and social surveys. (Raplex Sdn. Bhd. 2019)
Two PSP-plots have been set up in Raplex FMU.

Kapit Forest Management Unit
Kapit FMU covers 149.756 hectares of land in the southern part of Kapit district in central Sarawak, bordering the Rajang river in the north, the boundary with Indonesia in the south and Pasin concession area to the west. Elevation in the FMU ranges from around 100 to 900 meters above sea level. Most of the forest is classified as hill mixed dipterocarp forest (HMDF). The timber licence is held by Tanjong Manis Holdings Sdn. Bhd. and the logging contractor is Hariwood Sdn. Bhd., both subsidiary companies of Ta Ann Holdings Berhad. In or bordering the FMU, 55 communities are present. Of the total area, 119.657 hectares are logged, the rest being either community land, grade IV terrain or is part of the international buffer zone at the border with Kalimantan. The AAC ranges from 77.000 to 93.000 m^3. Logging cycle is set at 25 years with an average coup size of around 4800 hectares. RIL techniques are used and detailed pre- and post-logging assessments are carried out. Also, an enrichment planting scheme is currently in use. Kapit FMU works together with SFC and several other organisations on research subjects including SFM, wildlife monitoring and social surveys. (Ta Ann Holdings Berhad 2019)
Two PSP-plots have been set up in Kapit FMU.

Pasin concession area
The licenced concession area covers 132.435 hectares and is scheduled to be certified as FMU in 2020. The concession is located in Song district in central Sarawak, bordering the Rajang river to the north, Indonesia in the south and Kapit FMU to the east. The timber licence is held by Pasin Sdn. Bhd. and the logging contractor is Hariwood Sdn. Bhd., both subsidiary companies of Ta Ann Holdings Berhad. Inside or directly adjacent to the concession area, 111 communities are present. Around 50% of the land is located in the Heart of Borneo conservation area. Of the total concession area, 90.280 hectares are operable, the remainder being either community land, buffer zones of grade IV terrain. The annual allowable cut is around 100.000 m^3 on 25-year logging cycles. RIL techniques are used and pre- and post-harvesting assessments are carried out. Pasin works together with SFC on two research projects. (Pasin Sdn. Bhd. 2019)
Two PSP-plots have been set up in Pasin.

3.2 Plot setup

The PSP-plots measure 1 hectare in size, with a square setup of 100x100 metres. Every plot is divided into 100 quadrats of 10x10 (100 m^2) metres. All trees with a DBH of 10 cm or more are recorded and tagged with aluminium tags bearing a unique number for each tree. New recruitment receives a new number, making sure old numbers are not used again. The point of measurement (POM) is normally breast height (1.3 metres), but when large buttresses are present is 20 cm above the buttress. A yellow stripe is painted at the POM and is repainted when needed at every reassessment. The plot setup (figure 6) is based on the recommendations for PSP-setup in *Permanent Sample Plot Techniques for Mixed Tropical Forest* (Alder and Synnott 1992).

The plots in Kapit division were established in 2016 and reassessed in 2017 and 2018. The plots in Anap Muput were established in 2018 and reassessed in 2019. At establishment the following was recorded:

- Tree vernacular name
- Botanical family
- Genus
- Species
- DBH
- Total height and merchantable bole height
- Tree condition (tree has broken top, climbers present, tree is leaning, or tree is forking)
- Remarks

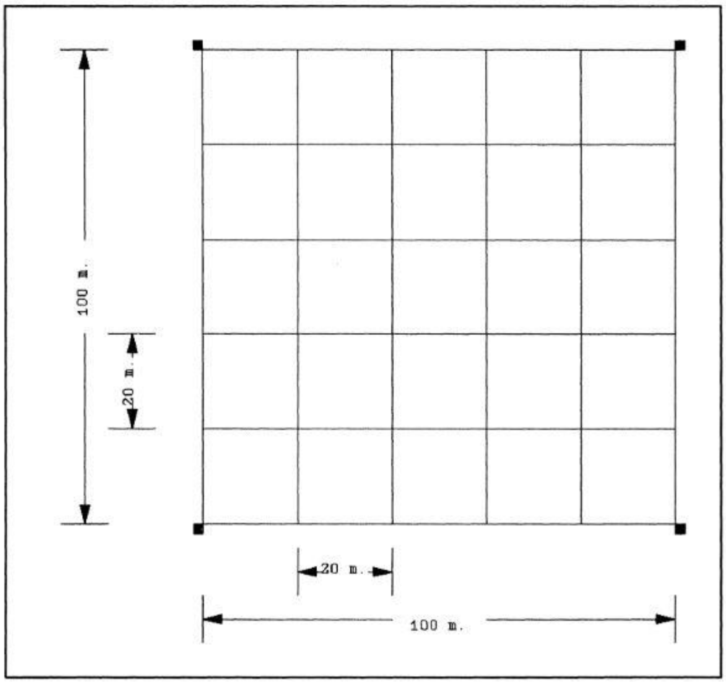


Figure 6: Standard PSP-setup described by Alder & Synnott (1992). The used plots differ slightly: instead of 20x20 metre quadrats, 10x10 metre quadrats were used.

During reassessment the DBH of all trees was remeasured to determine increment. Also, all newly recruited trees (i.e. all trees that grew to 10 cm or more between the previous and the current assessments) are recorded and tagged, and tree mortality is recorded. If changes in tree condition are noticed, this is also recorded. Species that at establishment could not be identified are determined. Tree density per hectare is also assessed by looking at the total population and at trees of 50 cm or more, as can be seen in table 2. For an overview of species present in the database, see table 3.

Table 2: Overview of plots

Plot	Age after logging at establishment	Density/ha	Trees 50 cm or more
AM16	15	629	50
AM17	Control	516	50
AM18	11	553	11
AM19	21	726	23
AM20	7	771	16
Kapit 1	1	392	5
Kapit 5	5	456	14
Kapit 10	10	584	8
Kapit 15	15	717	31
Kapit 20	20	584	24
Kapit UL	Control	589	25

Table 3: Overview of species composition for the two databases. [1] note that 90 entries in the Anap Muput database remain unidentified.

Database		Family/species	Entries in database
Kapit (6 plots)	Number of families	All	60
	Top 3 most common families	Dipterocarpaceae	774
		Euphorbiaceae	552
		Lauraceae	169
	Number of species	All	624
	Top 3 most common species	*Macaranga hosei*	164
		Shorea parvifolia ssp. parvifolia	155
		Saurauia pavonii	116
Anap Muput (5 plots)	Number of families	All	63
	Top 3 most common families	Dipterocarpaceae	858
		Euphorbiaceae	391
		Myristicaceae	135
	Number of species	All	663[1]
	Top 3 most common species	*Macaranga hosei*	132
		Saurauia glabra	119
		Shorea sagittata	95

3.3 Timber grouping

Because of the large amount of species present in the dataset, species were grouped. In the Malaysian timber industry, species are frequently grouped based on timber density (Wong et al. 2002). Four timber groups are discerned: light, medium and heavy hardwoods, and softwoods. All trees in the database (6622 individual trees, including several entries of <10 cm) were grouped when possible into timber groups. In table 4 an overview of the timber groups is shown. Table 5 represents the durability of the timber groups. Tables 4 and 5 are taken from *A Dictionary of Malaysian Timbers* (Wong et al. 2002).

Table 4: Timber classification according to the Malaysian Grading Rules. Wood density is at 15% moisture content.
[2] Softwoods are included in the timber grading classification but are not significant in the Malaysian timber industry since very few species are available commercially. An exception is the genus *Agathis*, which is highly valued timber.

Group	Wood density in kg/m^3
Light hardwoods	400-720
Medium hardwoods	720-880
Heavy hardwoods	800-1120
(Softwoods)	Conifers only[2]

As can be seen in table 4, the wood density of the medium and heavy hardwoods is overlapping. A timber with a density of 800-880 kg/m^3 is normally classified as heavy hardwood. However, when high natural durability is lacking (<10 years in ground contact, see table 5), the timber is classified as medium hardwood in spite of its high density (Wong et al. 2002).

Table 5: Classification of timber durability. Years of service before rotting for 5 cm thick square rods in ground contact, in a humid tropical climate. When used in temperate climates, durability is expected to be much higher.

Rating	Years of service
Non-durable	0-2
Moderately durable	2-5
Durable	5-10
Very durable	> 10

Trees were sorted primarily on their scientific names. The *Dictionary of Malaysian Timbers* (Wong et al. 2002) was used to determine the species' timber group. Additionally, the *New Checklist of the Trees of Sarawak* (Jawa and Chai 2007) was used, since this book has additional information regarding trees not listed in Malaysian timber dictionary. If species or timber group could not be found in both books, the online Global Wood Density Database (Harja et al. 2019) was used to determine the wood density per species.

In the timber dictionary, the Latin name often redirects to timber name, which is often the same for all species in a genus or even family. Some genera are grouped together under one timber name. The for the timber industry most important genera are often split into several different timbers (e.g. *Shorea*, which is grouped into 10 different timber categories).

Timber names are when possible given as Standard Malaysian Names in the timber dictionary. Sarawakan names are often different from Standard Malaysian names, but the dictionary states for most species which name they have in Peninsular Malaysia, Sabah and Sarawak. Furthermore the checklist of trees of Sarawak was used to identify the Sarawakan name, which are mostly of Iban origin (Jawa and Chai 2007). The checklist was also used to group species not listed in the timber dictionary. Species are allocated to the timber groups using the following strategy.

Timbers described under a Standard Malaysian Name (either species, genus or botanical family) often have a timber group allocation in the dictionary. The timber group as described is allocated to that species/genus/family. If no timber group is given, but the timber is classified under one name in the dictionary, an average of the lowest and highest wood density is taken in order to allocate it to a timber group. The timber groups listed in table 4 are used.

If a specific genus is not listed in the book but the family is listed as being of commercial interest, the species is allocated to the family timber group, unless stated otherwise. Often the dictionary states something as '*A large family producing a rather uniform timber (…). However, only some genera (…) can grow to timber size whereas others are either shrubs or small trees'* (Wong et al. 2002). In such a case, the genera that do grow to timber size are listed and grouped. If a specific species is not listed in the books but the genus is listed as being of commercial interest, the species is allocated to the genus' timber group, unless specifically stated otherwise. The same as applied to family/genus is true here; when a specific species is listed as being able to grow to timber size, this is grouped.

If only the vernacular name of a measured tree is known, this is used to allocate the species to a timber group. The vernacular name often redirects to a timber class, which in turn determines timber group. When only the Sarawakan name is known and the species does not occur in the Malaysian Timber Dictionary, the Check list of Trees of Sarawak is used to determine genus/species and timber class.

When a species or genus cannot be classified based on the information from the two books, the online Global Wood Density database (Harja et al. 2019) is used to determine average wood density and allocate it to a timber group. If a specific species is not present in the database, but other species of the genus are, an average of the other species' wood density is used to allocate the species to a timber group. When a species is not listed in this database as well, it is classified as non-commercial and is excluded for growth calculations. When information on both scientific and vernacular naming is lacking and the species cannot be classified whatsoever, the cell for timber group is left blank and it is excluded for growth calculations.

3.4 Matrix construction

In this thesis a size class model approach is used, more specifically an Usher (1966) type transition matrix model. The base input for such a matrix model is diameter increment, tree recruitment and mortality (see figure 7), and are expressed as probabilities. These probabilities are called *vital rates*, since they are essentially all you need to project growth (Hastings and Gross 2012). Vital rates are calculated per size class. This yields a table (matrix) in which all vital rates per size class are represented. To start projecting population development, an initial population number per size class, called a *vector,* is needed. A projection is then made using a set time interval. Often, and conveniently, such a time interval is set as equalling one year of forest development, however time steps may be any duration (Fujiwara and Diaz-Lopez 2017; Hastings and Gross 2012). In this thesis each time step represents one year.

Projecting growth will change the vector each time step. From the vital rates, the vector and its change over time, several values can be calculated. A short explanation of the three most important values and their meaning is given.

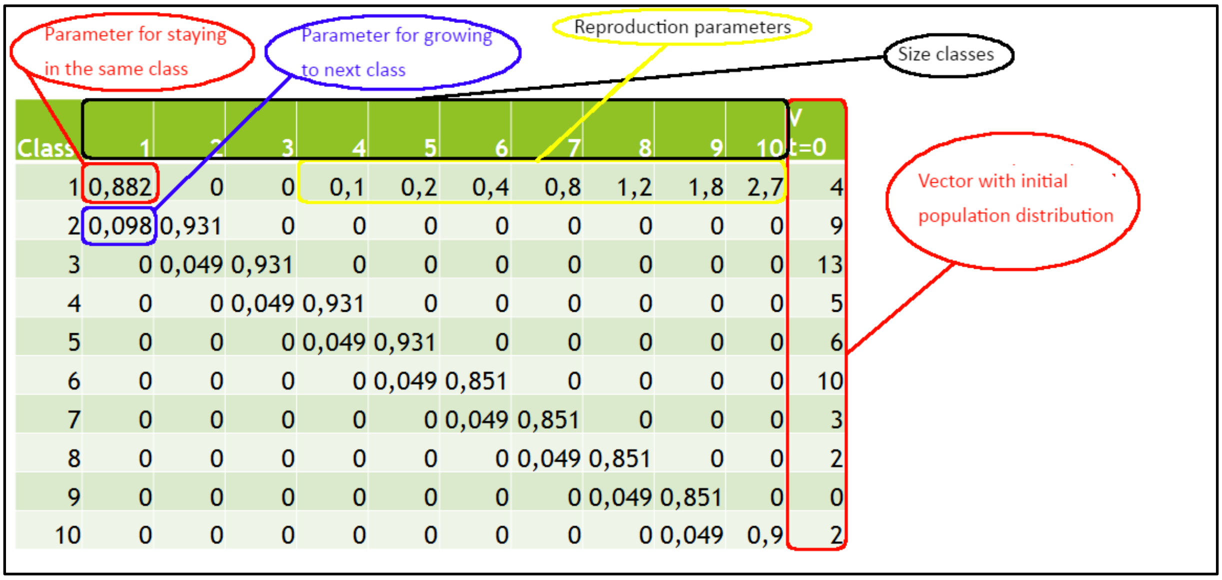
Dominant eigenvalue: Often expressed as λ, also called the finite rate of increase. It represents the asymptotic population growth rate. This is the population growth rate over an infinite number of time steps at unchanged vital rates (Hastings and Gross 2012; Vanclay 1994).

Stable stage distribution: The proportional distribution of individuals per size class with an unchanged initial vector after an infinite amount of time steps. The so-called *eigenvector* is the vector at the stable stage distribution. The vector will change every consecutive time step, but the proportional distribution will remain the same (Hastings and Gross 2012).

Matrix elasticity: The proportional change in projected population development when a parameter is changed. An elasticity analysis can be performed to find the model parameters that have the largest impact on population development (Hastings and Gross 2012).

A transition matrix as a tool to forecast forest growth is especially well suited to (tropical) selection forests. This is due to the intricate mix of species, age and size classes found in these forests, which makes it convenient to group into classes. An important thing to keep in mind is that a size class grouping per species can only be used for effective modelling if the sample size of the species is large enough (Vanclay 1989). To enlarge population data, species with similar growth characteristics are often grouped (Pinard and Cropper 2000; Sist et al. 2003). One should take into account that grouping does decrease accuracy since growth rates will most likely vary between species and tree sizes.

Size classes are normally based on DBH. However, for seedling and sapling classes, a class grouping based on height is often used since DBH is difficult to measure or non-existent in these classes (Huth and Köhler 2003; Verwer et al. 2008; Zuidema and Boot 2001). Because no data of trees <10 cm DBH was present, no such seedling and sapling classes are used.



Class	1	2	3	4	5	6	7	8	9	10	V t=0
1	0,882	0	0	0,1	0,2	0,4	0,8	1,2	1,8	2,7	4
2	0,098	0,931	0	0	0	0	0	0	0	0	9
3	0	0,049	0,931	0	0	0	0	0	0	0	13
4	0	0	0,049	0,931	0	0	0	0	0	0	5
5	0	0	0	0,049	0,931	0	0	0	0	0	6
6	0	0	0	0	0,049	0,851	0	0	0	0	10
7	0	0	0	0	0	0,049	0,851	0	0	0	3
8	0	0	0	0	0	0	0,049	0,851	0	0	2
9	0	0	0	0	0	0	0	0,049	0,851	0	0
10	0	0	0	0	0	0	0	0	0,049	0,9	2

Figure 7: Example matrix with explanation of contents. Own production.

3.4.1 Classification into age classes and size classes

The databases of Anap Muput and Kapit division were pooled together to create a larger database. The plots are split into 3 classes to take the effect of age after logging on tree growth into account. The control plots were not used in the calculation of the growth rates.

Table 6: Age classes

Class	Years after logging	No. of plots	Plot ID's
1	1-10	3	Anap Muput 20 Kapit 1, 5
2	More than 10	6	Anap Muput 16, 18, 19 Kapit 10, 15, 20
Control	Unlogged	2	Anap Muput 17 Kapit Unlogged

A difference in growth, mortality and regeneration between recently logged dipterocarp forests and 'older' forests in peninsular Malaysia was recorded (Ismail et al. 2010; Rahman and Rahim 2010; Yasin et al. 2010). Different growth rates in the first years after logging have also been recorded in the Amazon region (Figueira et al. 2008). In order to take this effect of logging into account, two matrices will be constructed for each timber group. The first matrix will have vital rates as calculated from class 1 (see table 6) plot data. This matrix will have different parameters and will be used to project growth for the first 10 years. It is assumed that the effect of logging wears off after 10 years (although it will most likely wear off over time to a point it will stabilize, but to include this in a matrix model a line must be drawn somewhere). The second matrix will contain the 'standard' vital rates. These are the vital rates as calculated for the six plots in class 2 (see table 6). This matrix is than applied on the projected vector after 10 years using the first age class matrix.

DBH classes

The tree population is grouped into size classes of 10 centimetres. Seven classes of 10 cm are used, up to 80 cm. One final class for all individuals 80 cm or more is made. Classes are made for each of the three timber groups. See table 7. Vital rates are calculated per class. If too few entries are recorded in the upper DBH classes, these are grouped together to calculate vital rates for a combined class. This will result in exactly similar vital rates for each of these classes, which most likely will decrease accuracy. However, it is seen as the best solution to solve a data-deficit in the upper classes.

Table 7: Size classes as used in matrix projections

Class	Range (cm)
1	10 to <20
2	20 to <30
3	30 to <40
4	40 to <50
5	50 to <60
6	60 to <70
7	70 to <80
8	>80

3.4.2 Dataset cleaning and calculation of vital rates

Diameter growth is calculated per size class. For each size class the average change in diameter between measurements is taken ($DBH\ increment = DBH\ year\ 1 - DBH\ year\ 0$). For Kapit database, two average increments are taken since three measurements have been recorded. Here growth is calculated for the period 2016-2017 and for 2017-2018. For the plots in Anap Muput FMU growth is calculated for the period 2018-2019. Furthermore, growth is determined per timber group and age class. In other words, the database is sorted on A) age of forest after logging B) timber group and C) size class (see previous sections). The output is diameter increment for each diameter class per timber group per age class.

In some entries, calculating diameter increment resulted in errors or unrealistically high or low figures. Also, natural mortality occurs, and entries are discontinued. Measurement errors most likely occurred, and the obvious are filtered out. Therefore, the following entries were excluded for growth calculations:

- Tree has died between two measurement (no data available to calculate growth). Records of trees that have died between two measurement can be used for calculating mortality rates.

- The tree has been labelled non-commercial or is of unknown species/genus. In this case no timber group could be assigned and thus the entry is excluded.

- Growth is 2.5 cm or more. When this occurs, the entry is excluded since such a high growth reading is most likely the result an error in measurement or data entry. Although for some fast-growing pioneer species it is possible to attain such increments, this is only expected to happen under ideal circumstances. Average growth rates have been recorded for 11 *Macaranga* species in a forest situation in Sarawak by Davies (2001), showing that growth rates for pioneer species typically range from 2 – 20 mm per years (Davies 2001).

- Growth is -1.0 cm or lower. As discussed in many papers, negative growth readings are possible because of changing moisture content of the wood (Pastur et al. 2007; Tian et al. 2019). Also, it is possible that a tree is damaged at the POM and therefore has a lower DBH in the next reading. However, negative changes in DBH are expected to be low, and readings equal or lower than -1 cm will generally be the result of measurement or data entry errors and are therefore excluded for growth calculations.

In order to determine the recruitment and mortality rates, the following strategy was used.

- A small database with trees of <10 cm was used to determine average growth of this class. The average increment was around 0.4 cm per year. (see appendix 8 for an overview of the database of trees <10 cm).

- Data on new recruitment required extensive filtering. Many records were unrealistically high, these most likely represent trees missed in the previous assessment. All trees with an average of 10 cm + the growth rate as recorded from the database with trees of <10 cm (0.4 cm/yr) were included as new recruitment. All others were excluded.

- Since this project takes all trees into account and groups them into timber groups, fecundity rates cannot be determined accurately. It is assumed that all trees of 30 cm and more are reproductive (Naito et al. 2008). Although this is a strong generalization, and few publications are available on reproductive size, this figure is used because no other information was found.

- The observation period for recording tree mortality was deemed not long enough to determine accurate tree mortality. Therefore, mortality rates were taken from literature. These were based on the reports of Ismail et al. (2010) and Rahman & Rahim (2010), which state growth, mortality and ingrowth rates for dipterocarp forests in peninsular Malaysia. the mortality was set at 3% for the first 10 years after logging, and at 2% for >10 years after logging for all classes (Ismail et al. 2010; Rahman and Rahim 2010).

3.4.3 Equations for matrix multiplication

Matrix multiplication was done in Excel using a standard matrix multiplication formula (for density-dependence function, see next paragraph). The Excel plug-in Poptools (Hood 2010) is used for calculating lambda values and for conducting an elasticity analysis.

The type of transition matrix used is an Usher (1966) type of matrix model. The equation was formulated as $N_{t+1} = MN_{t,}$ (Hartshorn 1975; Jensen 1993; Liang and Picard 2012; Usher 1966; Vanclay 1994).

Were:

N_{t+1}	Population at time + 1
M	Matrix with probability multipliers
N_t	Population at time = 0

A more thorough depiction of the matrix multiplication process can be seen in figure 8.

$$\begin{bmatrix} m_{1,1} & m_{1,2} & \cdots & m_{1,s} \\ m_{2,1} & m_{2,2} & \cdots & m_{2,s} \\ \vdots & \vdots & & \vdots \\ m_{s,1} & m_{s,2} & \cdots & m_{s,s} \end{bmatrix} \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_s \end{bmatrix}_t = \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_s \end{bmatrix}_{t+1}$$

Figure 8: Representation of matrix multiplication (Hartshorn 1975).

The finite rate of increase (λ) is calculated for the final matrices. An elasticity analysis is also carried out. Furthermore, the stable stage distribution of the three matrices for 10 or more years after logging is determined and compared with the stable stage distribution found in unlogged forest. All of the above is done in Excel using the Poptools (Hood 2010) program, which has detailed functions for these calculations.

3.4.4 Determining matrix probabilities

To construct the actual matrices, the vital rates must be expressed as matrix probabilities. For mortality a constant factor for all classes is used. Fecundity is also expressed as a constant factor, but only for reproductive trees. DBH increment and mortality is used to determine both the upgrowth and the probability of remaining in the same class. These probabilities are calculated as follows:

$$Growth\ to\ next\ class = \left[\frac{DBH\ increment}{Size\ class\ width}\right] \cdot Mortality\ factor$$

$$Remain\ in\ class\ = Mortality\ factor\ - Growth\ to\ next\ class$$

$$Mortality\ factor\ = 1 - \left[\frac{Number\ of\ trees\ that\ died\ in\ one\ time\ period}{Total\ number\ of\ trees\ in\ the\ same\ time\ period}\right]$$

$$Fecundity\ = \left[\frac{Number\ of\ new\ trees\ recruited\ to\ class\ 1}{Number\ of\ trees\ in\ reproductive\ classes}\right]$$

3.5 Function for density dependence

After initial test runs, the basic matrix showed highly unrealistic growth, adding a function of density dependence was deemed necessary. Due to the exponential nature of the matrix, multiplication results in uncontrolled growth. Projected densities quickly exceeded 1000 individuals after 100 years, for each of the timber groups. By including a growth-controlling function in the model equation, the projected population development is kept within realistic limits.

The chosen density dependence function is based on Jensen (1993), *Simple density dependent matrix model for population projection* (Jensen 1993) and Miller et al. (2001), *Density dependent matrix model for grey wolf population projection* (Miller et al. 2001). In these reports, the authors describe the following equation:

$$P_{t+1} = P_t + \left[\frac{K - p_t}{K}\right] \quad rP_t$$

Were *P* is population, *K* is carrying capacity (maximum tree density per hectare in this case) and *r* represents the matrix' finite rate of increase. This equation essentially lowers growth when population size increases, changing the model growth projection from exponential to logistic. Because the equation was primarily made for animal populations, some changes were made to make it applicable on tree populations.

Maximum population density was determined by determining the highest values recorded in the plot data (see appendix 6). Although these figures are most likely not the highest possible, there was no other data available to base the carrying capacity on. Densities are expressed as average number per hectare.

Jensen (1993) and Miller et al. (2001) used the carrying capacity for the whole population. Testing this with the PSP database resulted in a warped outcome. This was likely due to the maximum population in each class being lower than the total maximum population, resulting in highly unrealistic population growth, especially in the higher DBH classes. To remediate this, the carrying capacity was determined for each of the size classes, and the equation fitted for the respective class.

A minimum population was also determined for each size class. This was because when having no minimum, i.e. the minimum is 0, growth rates are reduced for each value higher than 0. Since the vital rates were determined using averages per class, growth projected with only a maximum density again resulted in unrealistic projections. The minimum density was also taken from the dataset (see appendix 6). By using the minimum and the maximum, the equation changes into:

$$P_{t+1} = P_t + \left[\frac{K - (p_t - Min)}{K}\right] \quad rP_t$$

were *Min* is the minimum density per class as recorded from the dataset. Furthermore, both the probability to grow from one class to the next and the probability to remain in the same class have to be adjusted with the density dependence function. To sum up in a final equation for matrix multiplication, the following is used:

$$N_{t+1} = G_{pc} \cdot \left[\frac{K_{cc} - (N_{cc} - Min_{cc})}{K_{cc}}\right] \cdot N_{pc} + M_{cc} - G_{cn} \cdot \left[\frac{K_{nc} - (N_{nc} - Min_{nc})}{K_{nc}}\right] \cdot N_{cc}$$

Were:

G_{pc}	Growth probability from previous to current class
K_{cc}	Carrying capacity for current class
N_{cc}	Number of individuals in current class
Min_{cc}	Minimum population for current class
N_{pc}	Number of individuals for previous class
M_{cc}	Mortality probability for current class
G_{cn}	Growth probability from current to next class
K_{nc}	Carrying capacity for next class
N_{nc}	Number of individuals in next class
Min_{nc}	Minimum population for next class

The equations for the first and the last size class are somewhat different than what is stated above. Growth into the first class occurs due to regeneration from higher classes, and this is calculated instead of the formula for upgrowth from a previous class. For the final size class (class 8), no next class is present, and no formula for upgrowth is used. Only the mortality factor determines the probability of 'leaving' this class.

3.6 Description of scenarios

To test the model, projections were made according to several sets of criteria, called scenarios. Four scenarios were made in order to compare projection outcomes. The criteria are logging intensity in percentage of total harvestable trees, logging cycle length in years and percentage of damage to the residual stand because of logging. Below a description.

Table 8: Scenarios

Criteria	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Logging intensity	70%	70%	50%	50%
Cycle length	25	20	25	20
Damage to residual stand	27%	27%	27%	27%

3.6.1 Criteria

Figures for logging intensity are not based on the actual situation. This is because it is very hard to address actual logging intensities, since this varies heavily between stands and data on this is kept confidential by logging contractors. Based on personal impressions from the fieldwork period, two logging intensities are compared. A high figure of 70% and a lower figure of 50% tree extraction of trees of harvestable size are used. Furthermore, harvestable sized trees are defined as all trees of 50 cm and more. The actual minimum DBH limits are 45 cm for non-dipterocarps and 50 cm for dipterocarps. Because 10 cm size classes are used, and sorting is not done for non-dipterocarps/dipterocarps, the 45 cm limit cannot be used and therefore the minimum felling DBH is set at 50 cm for this modelling application.

Two cycle lengths of 25 and 20 years are compared. A cycle length of 25 years is normal in Sarawak (Fah 2007; International Forest Management Consultants 2015), but in the past shorter rotations have been used. Currently, an interest in reducing the logging cycle was noted and therefore it was decided to compare population development using the normal cycle length and a reduced cycle length.

Figures for damage to residual stand are taken from Marn & Jonker (1981). In this report the difference in damage after logging is addressed for conventional logging methods and for a simple form of Reduced Impact Logging (RIL). The percentages of damage to the residual stand calculated from this report are 39% for conventional logging and 27% for RIL (Marn and Jonker 1981). Since the FMU's are obliged by law (Forest Department Sarawak 2019c) to use RIL techniques, only the low damage percentage has been chosen for the comparison of scenarios.

3.6.2 Initial population vector

To start projecting, an initial population vector is needed. Since no directly post-logging data was available to use as vector, logging was simulated. The population distribution per size class from plot Kapit Unlogged was used, and the percentages for logging intensity and damage to residual stand were used as described in the scenarios. This yields the following set of vectors.

Table 9: Initial population vectors per timber group and scenario.

TG	LH		MH		HH		Total	
Scenario	S1 and S2	S3 and S4	S1 and S2	S3 and S4	S1 and S2	S3 and S4	S1 and S2	S3 and S4
Class 1	186.2	186.2	48.9	48.9	24.8	24.8	259.9	259.9
Class 2	48.2	48.2	13.9	13.9	7.3	7.3	69.4	69.4
Class 3	33.6	33.6	10.2	10.2	5.1	5.1	48.9	48.9
Class 4	21.2	21.2	5.1	5.1	4.4	4.4	30.7	30.7
Class 5	1.3	2.2	0.4	0.7	0.2	0.4	2.0	3.3
Class 6	0.4	0.7	0.0	0.0	0.0	0.0	0.4	0.7
Class 7	0.7	1.1	0.0	0.0	0.0	0.0	0.7	1.1
Class 8	1.5	2.6	0.4	0.7	0.4	0.7	2.4	4.0
Total	293.0	295.7	79.0	79.6	42.3	42.7	414.3	417.9
>=50	3.9	6.6	0.9	1.5	0.7	1.1	5.5	9.1

4 Results

The results of this project are split into two parts. First input for matrix construction is determined, and three sets of transition matrices is constructed. Model testing can now commence, population development is projected in the second part. This part is subdivided into four sections. Projections are made for light, medium and heavy hardwoods, and these are summed up to determine total population development.

4.1 Input for growth models: Tree density, vital rates and stable stage distribution

Tree density per hectare was determined to check on the model, and maximum and minimum population density was used for the density-dependence function (see appendix 6 for the minimum and maximum values). Stable stage distribution was determined to check on the model. The vital rates were calculated and used for the construction of the transition matrices, which are included in appendix 1.

4.1.1 Tree densities and number per timber group

In figure 9 the density of the total population can be seen, plotted against the number of years after logging. Figure 10 represents the density of trees of more than 50 cm, also plotted against the years after logging. The value of 1000 years after logging represents infinity: these are the control plots that have not been logged before. A trend of increasing density with increasing age after logging can be detected.

A spike in the population of trees of more than 50 cm can be seen at an age after logging of 15 years. These two plots have a high stocking for their age, and the values of trees of 50 cm or more are actually similar to values found in the unlogged control plots.

For matrix construction it is essential to know what stocking can be seen as realistic. The aim of doing projections will also be to see if the model actually forecasts a population density as represented in the plots. Of course, the density will heavily depend on the initial population density, but the pattern that is to be projected should be similar to what has been recorded.

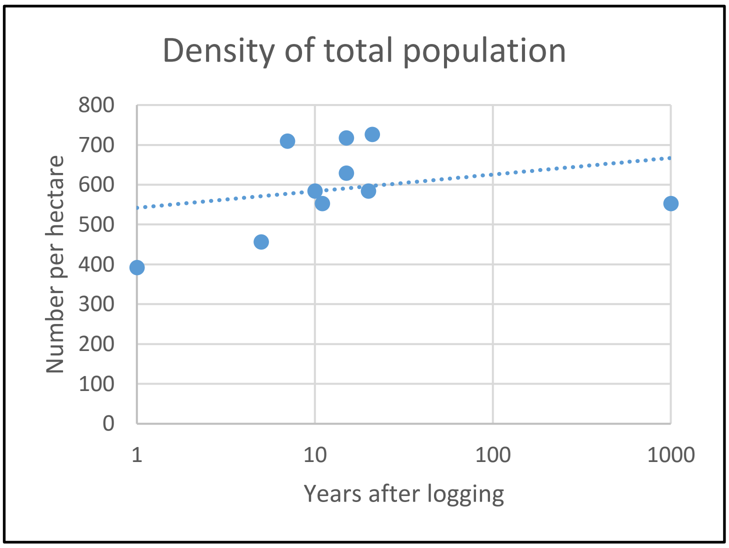


Figure 9: Density of total population related to age after logging.

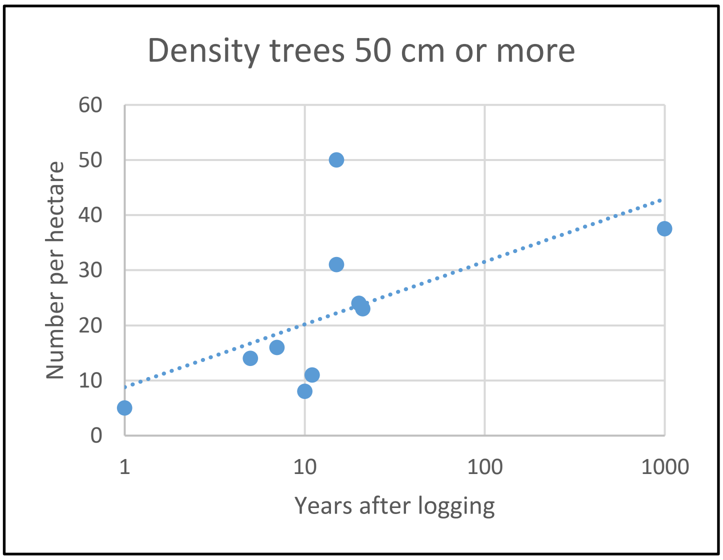


Figure 10: Density of trees of 50 cm or more related to age after logging.

The proportional distribution of timber groups is light hardwoods 67.0%; medium hardwoods 23.7%; heavy hardwoods 9.3% (see figure 11). Trees not classified into any of these timber groups were not taken into account for the proportional distribution. It is clear that the number of trees in the light hardwoods group is much higher than in the medium and heavy hardwood group. The medium hardwood group has in turn more entries that the heavy hardwood group.

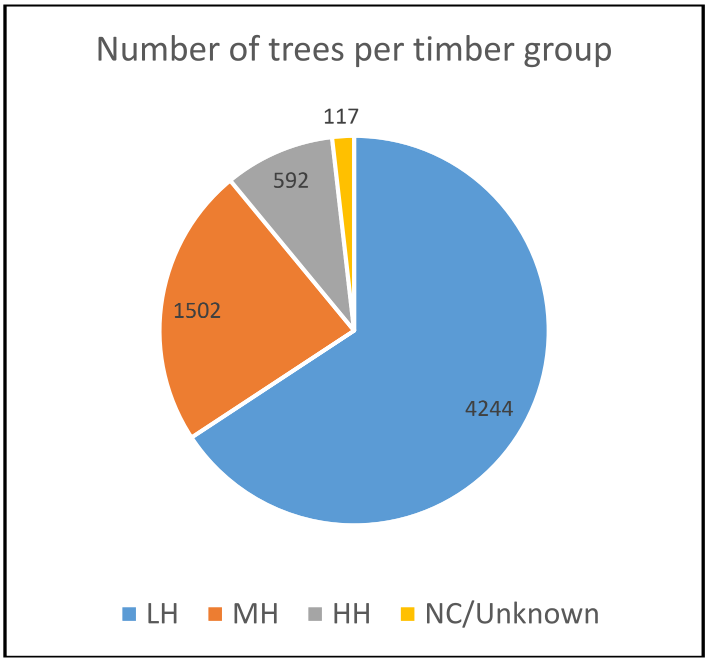


Figure 11: Total number of trees per timber group, including non-commercial and unknown trees, for all plots

4.1.2 Vital rates and lambda values

Determining DBH growth, mortality and ingrowth is the first step in the process of making transition matrices. In table 10 below a general overview of growth rates is given.

Table 10: Overview of population number and growth rates

Type	Number in database	Growth in cm per year
All trees (10 cm or more)	6455	0.47
Dipterocarps	1599	0.61
Non-Dipterocarps	4856	0.42
All trees of 50 cm or more	257	0.73
All trees smaller than 50 cm	6198	0.46

Average growth for each of the timber groups can be seen below in table 11. The control plots were excluded for growth calculations. Light hardwoods appear to grow faster than medium and heavy hardwoods, and the growth of medium and heavy hardwoods is rather similar. Around 5.8% of the total population of 5252 trees in the nine plots used for growth calculations was excluded because of irregularities in the growth records. In appendix 3 the growth rates per timber group, class and age class after logging can be seen, as used in calculating the transition probabilities.

Table 11: Average growth rates, sample size, total population and percentage of total population included in sample size, per timber group. Average growth in cm per year. 3 Softwoods are not present in the dataset.

Group	Abbreviation	Average growth	Sample size	Total population	% of total population is sample size	Standard deviation
Light Hardwoods	LH	0.52	3372	3592	93.9%	0.5204
Medium Hardwoods	MH	0.37	1137	1195	95.1%	0.4326
Heavy Hardwoods	HH	0.34	439	465	94.4%	0.3772
(Softwoods)[3]	-	-	-	-	-	-
Non-Commercial	NC	-	-	-	-	-

Fecundity rates are calculated per timber group and are used to calculated fecundity probabilities as used in matrix multiplication. See appendix 1 for the fecundity probabilities in the matrices. In table 12 the average annual number of recruited trees into class 1 is shown.

Table 12: Fecundity in number of trees recruited per year

Group	1-10 years	>=10 years
LH	20.03	17.22
MH	4.42	5.41
HH	2.01	2.19

Mortality rates were set for all trees at 3% (factor = 0.97) for the first 10 years after logging and at 2% (factor = 0.98) for 10 or more years after logging (see paragraph 3.4.2 in methodology). As mortality is used to calculate the upgrowth probability as well as the probability to remain in the same class, these figures can be seen in the matrices included in appendix 1.

All six matrices are included in appendix 1. The lambda values (λ) were calculated using the Poptools (Hood 2010) Excel plug-in function *Matrix tools > Finite rate of increase*. See table 13 below. For the light and heavy hardwoods, lambdas are slightly lower for the 10 or more years matrix, whereas for the medium hardwood group this is the other way around. Furthermore, light hardwoods have much higher values than medium and heavy hardwoods. Interestingly, medium hardwoods have lower lambda's than heavy hardwoods, although average DBH growth is higher for medium hardwoods.

Table 13: Asymptotic population growth rates for LH, MH and HH

LH		MH		HH	
First 10 years	10 or more years	First 10 years	10 or more years	First 10 years	10 or more years
$\lambda = 1.041$	$\lambda = 1.039$	$\lambda = 1.019$	$\lambda = 1.022$	$\lambda = 1.028$	$\lambda = 1.025$

4.1.3 Stable stage distribution

The stable stage distribution as found in the unlogged control plots was calculated. The distribution shows a distinctive diameter distribution curve, as can be seen in figure 12, were the stable stage distribution as calculated from the matrices is compared with the distribution as found in the control plots. See appendix 4 for a table with an overview of the control plot size distribution.

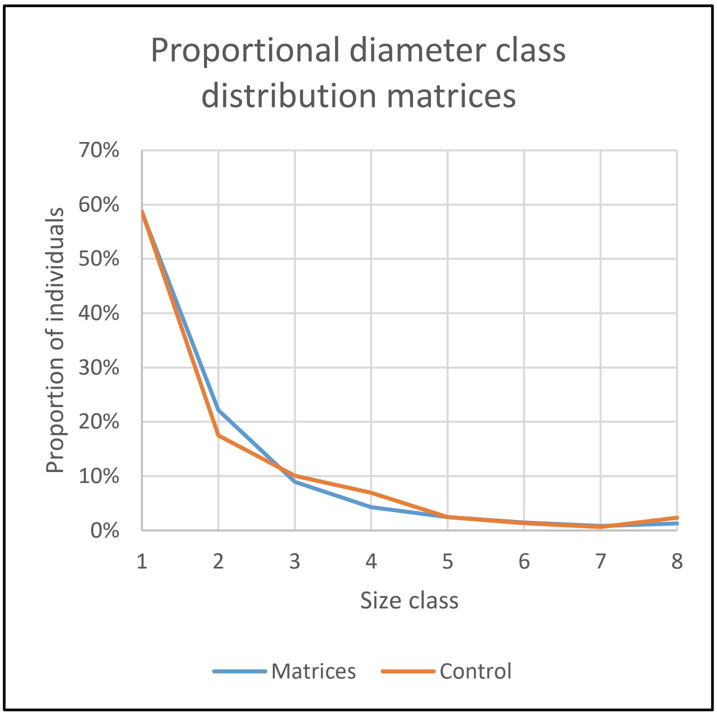


Figure 12: Proportional size class distribution as calculated from the matrices vs. that found in the control plots

Now comparing this with the stable stage distribution as calculated from the average stable stage distribution of each timber group, it can be seen that the stable stage distributions are rather similar. For the calculation of the matrices' stable stage distribution, only the matrices for 10 or more years after logging were used, since the year 0-10 after logging matrices are only to be used for the first 10 years after logging. A reverse J-curve pattern can also be clearly seen in the matrices' stable stage distribution, although the percentages differ slightly from the control plot distribution. The difference is rather large for class 8, in a stable stage this class has a higher population than in the projected population distribution. See figure 12. In appendix 5 a table with the stable stage distribution as calculated from the matrices is shown.

4.1.4 Matrix elasticity

An elasticity analysis was done for each of the transition matrices, using the Poptools function *Matrix tools > Age distribution*. The outcomes of this analysis can be found in appendix 2. It can clearly be seen that the growth rates in the lower size classes have most impact on population development, and that the probabilities for staying in the same class are of most importance on population development. Also, the influence of fecundity rates is rather limited for all timber groups. Furthermore, the influence of the larger size classes is higher in the 10 years or more matrix for each of the timber groups.

4.2 Projections

In the following sub-sections, the outcomes of the projections are discussed. Projection time is 100 years, which is 4 or 5 logging cycles, and four different scenarios have been projected. Population development for each of the timber groups is discussed, as well as the development of the total population. For the reason of simplicity, the change in population between year 0, directly after the first simulated harvesting, and year 100, directly after last simulated harvesting, was compared between scenarios. Also, the simulated harvest in number of trees of 50 cm or more is given for each projection scenario.

Before discussing the difference between projection scenarios, the model was first tested. This was done using a pre-set vector of 100 individuals per hectare in size class 1, distributed over the three timber groups as represented in the dataset (LH: 67.0%, MH: 23.7%, HH: 9.3%). Population development was projected for 500 years, as can be seen in figure 13, using the second matrix (10 or more years after logging) for each timber group. It can be seen that stabilization of the total population occurs after around 200 years of projection, reaching around 900 individuals. The difference between the timber groups is also evident: light hardwoods stabilize quickly after around 100 years, whereas medium and heavy hardwoods take 200-250 years to stabilize. Interestingly, the set maximum population is never reached for medium and heavy hardwoods (maximum population density set at 236 for MH and 100 for HH), which max out at around 206 and 81 trees per ha, respectively. Contrary to the former timber groups, population density per hectare overshoots for light hardwoods (maximum population density for LH set at 569), capping at 613 individuals per hectare. The reason for this is not exactly known, but it is likely that during matrix multiplication some values distort.

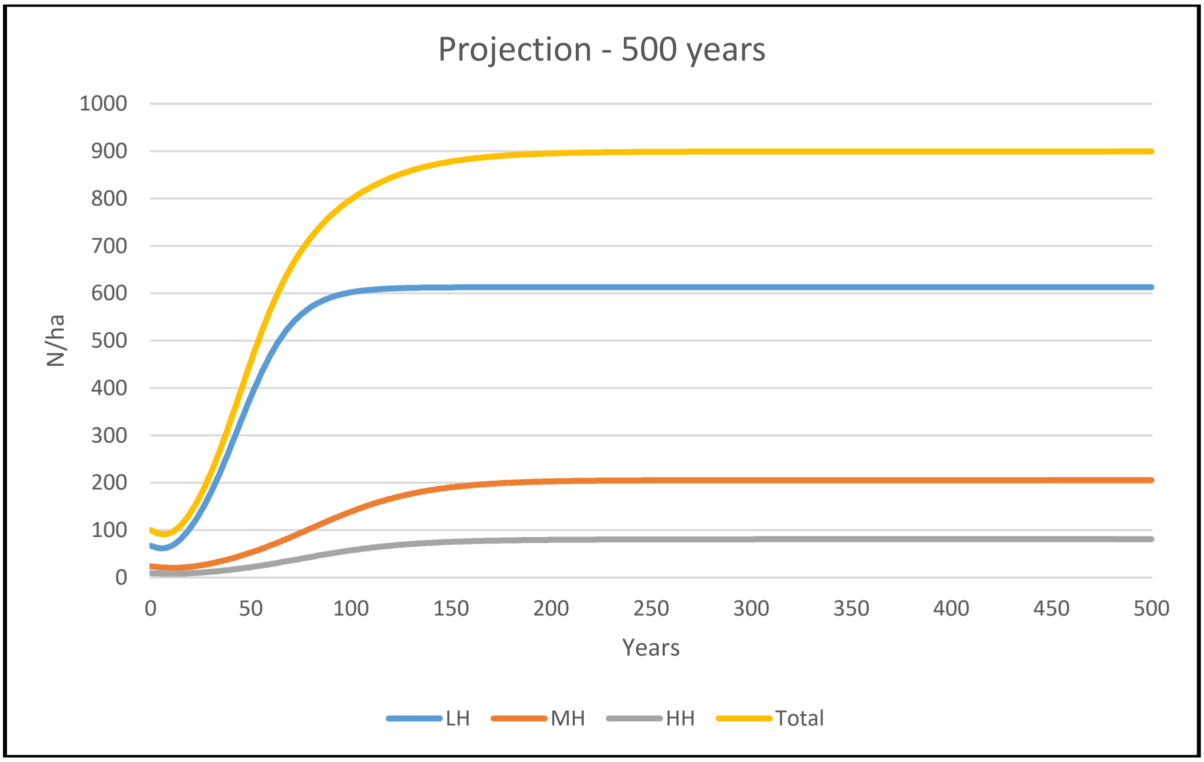


Figure 13: 500-year projection of the total tree population. Initial vectors are: LH=67, MH=23.7, HH=9.3.

4.2.1 Population development: light hardwoods

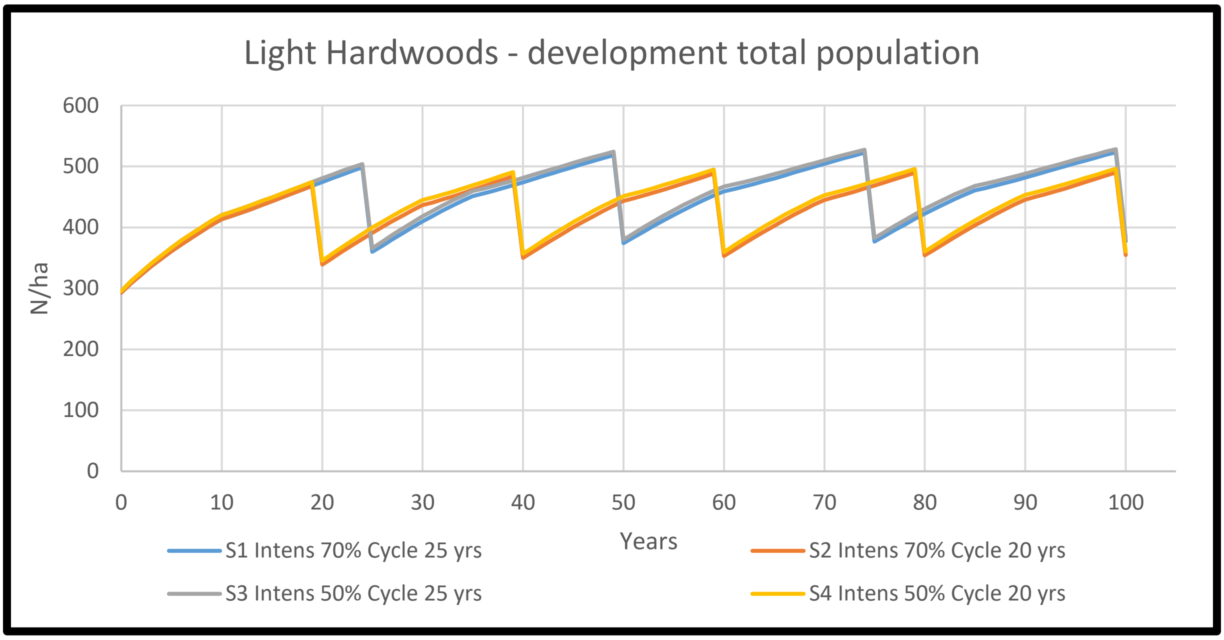


Figure 14: LH, projected development total population

Figure 15: LH, projected development trees 50 cm or more

Population development over 100 years for the light hardwoods group is positive for all scenarios looking at the total population development (see table 14). Negative development can be seen in table 14 for trees of 50 cm or more, implying a shift in proportional distribution towards a higher percentage in the lower size classes.

Table 144: LH, change in population after 100 years

Scenario	Total population	Trees 50 cm or more
1	28.7%	-13.9%
2	21.0%	-23.5%
3	29.5%	-11.3%
4	22.0%	-20.7%

Both the total and the population of 50 cm or more seem to stabilize rather quickly, after one rotation for 25-year logging cycles and after two rotations for 20-year logging cycles. Although a negative development is recorded for trees 50 cm or more, this happens mainly in the first rotation. The subsequent rotations seem to have reached a more the less stable stage. It is furthermore also evident that the population regenerates rapidly after logging, which is in accordance to the pioneer nature of many of the species included in this timber group. See figure 14 for total population development and figure 15 for the development of trees of 50 cm and more. The best scenario would be, unsurprisingly, scenario 3 (logging intensity 50%, cycle length 25 years, 27% damage to residual), with a population increase of 29.5% and a decrease of only 11.3% for trees 50 cm or more.

4.2.2 Population development: medium hardwoods

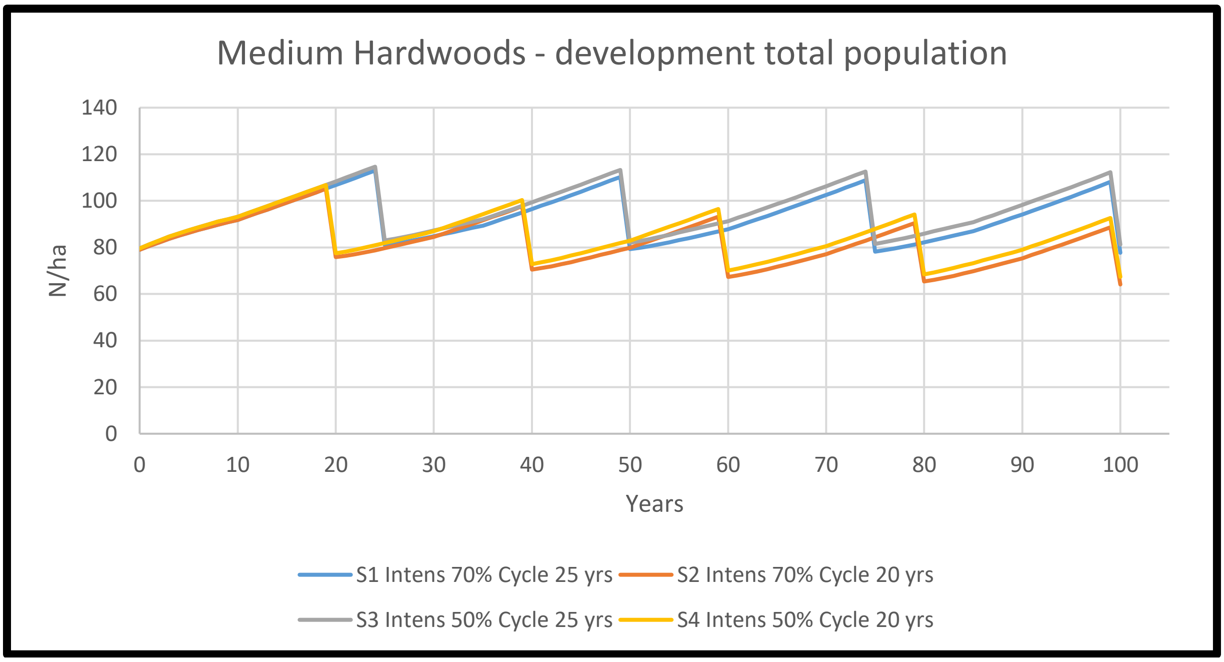


Figure 16: MH, projected development total population

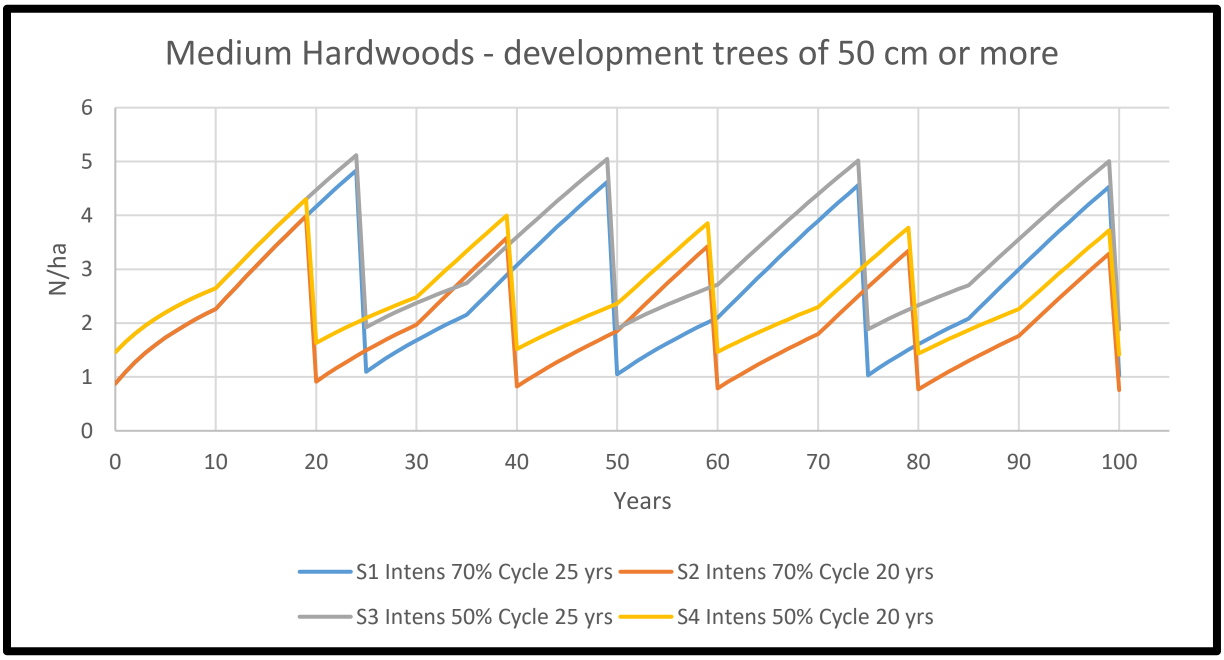


Figure 17: MH, projected development trees 50 cm or more

Population development over 100 years for the medium hardwood group shows a distinctive difference for rotation times of 25 or 20 years. For 25-year rotations, a positive trend can be detected, and for 20-year rotations a negative. However, the increase in the population of trees of 50 cm or more seen in S1 and S3 (in table 15) is misleading, since the starting density was rather low, and cycle 2, 3 and 4 actually have a slight negative trend. Tough it can be said that population for 25-year logging cycles shows a more the less stable development (see figure 16 and 17). Contrary to the pattern seen in the light hardwood group, a shift in proportional distribution towards a lower percentage in the lower size classes can be detected.

Table 155: MH, change in population after 100 years

Scenario	Total population	Trees 50 cm or more
1	-1.6%	17.3%
2	-18.9%	-13.7%
3	2.1%	28.8%
4	-15.4%	-3.1%

Population has not completely stabilized after 100 years of projection for all scenarios but is probably close to stabilizing. Population development for the shorter (20 year) rotation times is evidently negative. Regeneration of the population happens at a moderate rate, much slower than seen in the light hardwood group. Again, the best scenario would be scenario 3 (logging intensity 50%, cycle length 25 years, 27% damage to residual), with a total population increase of 2.1% and an increase of 28.8% for trees 50 cm or more. However, as said before, this strong increase in trees 50 cm or more is misleading since the starting density was low (1.46 trees/ha).

4.2.3 Population development: heavy hardwoods

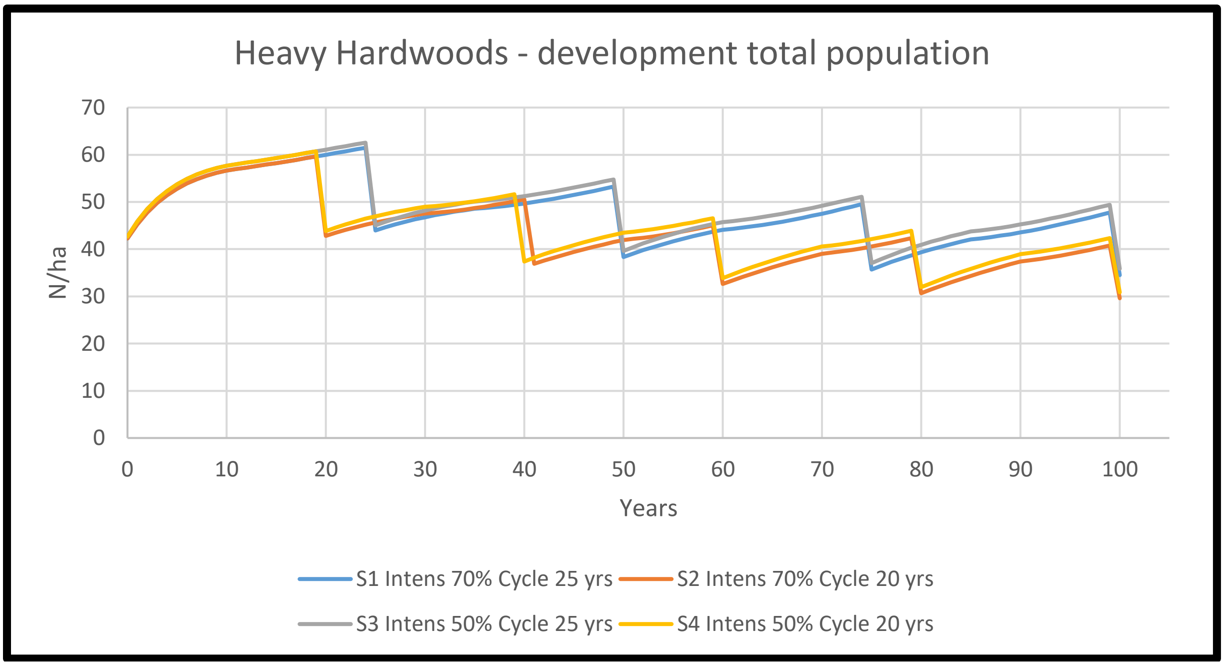


Figure 18: HH, projected development total population

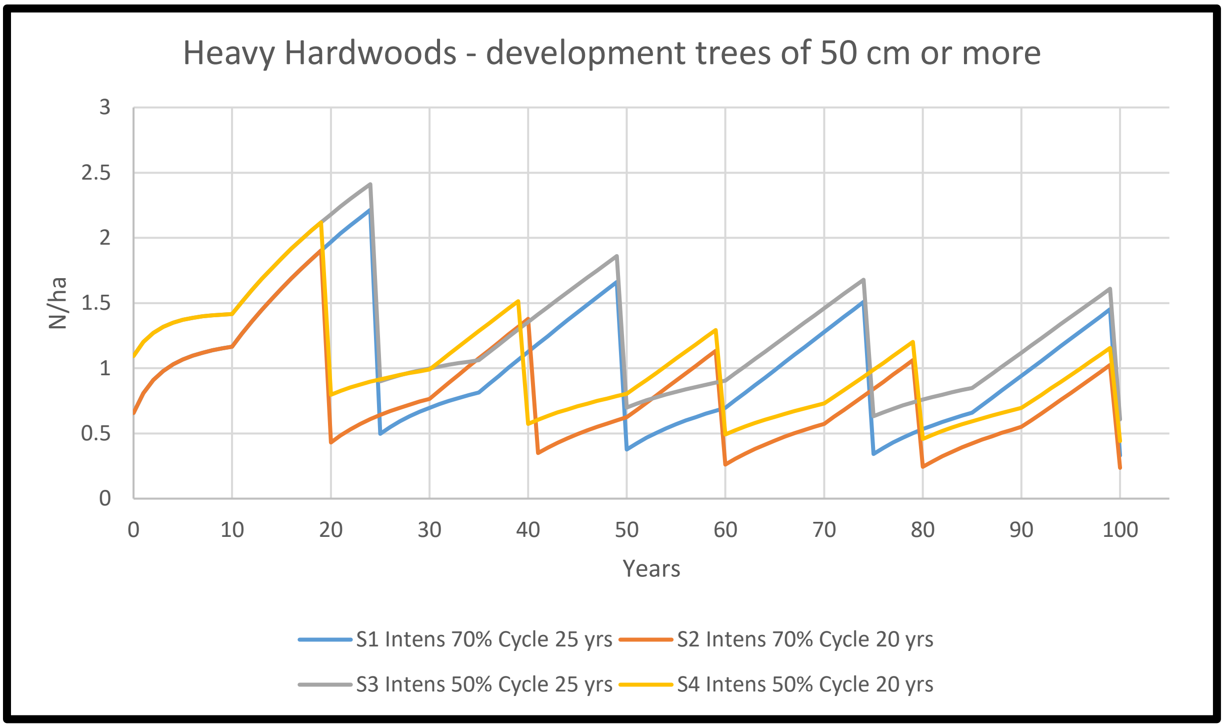


Figure 19: HH, projected development trees 50 cm or more

Looking at the heavy hardwood group, it is evident that population development is strongly negative. A decrease for both total population and for trees 50 cm or more is projected, with the latter showing a very strong decrease (nearly 60% in S4, see table 16). To nuance the decrease for trees 50 cm or more, the initial density was high compared to the set maximum values, which causes slow growth in the first rotation. As is the case for light hardwoods, a shift in proportional population distribution towards a higher percentage in the lower size classes can be seen.

Table 166: HH, change in population after 100 years

Scenario	Total population	Trees 50 cm or more
1	-18.4%	-49.7%
2	-30.0%	-64.1%
3	-16.0%	-44.5%
4	-27.7%	-59.7%

Stabilization of the population density has not occurred after 100 years of projection for all scenarios, and the population is still decreasing. Population development for 20-year rotation times shows a stronger negative development (see figures 18 and 19). Regeneration of the population is much slower than that of the light or medium hardwood group. The ‘best’ (or better: least negative) scenario would again be scenario 3 (logging intensity 50%, cycle length 25 years, 27% damage to residual), with a population change of -16.0% for the total population and -44.5% for trees 50 cm or more. The strong decrease in population compared to the development of the medium hardwood group is remarkable, since matrix lambda values for the heavy hardwood matrices are higher than those of the medium hardwoods. It could be due to the population density of the heavy hardwood group being lower than that of the medium hardwoods, implying that recovery after logging decreases with lower population densities (see discussion).

4.2.4 Total tree population development

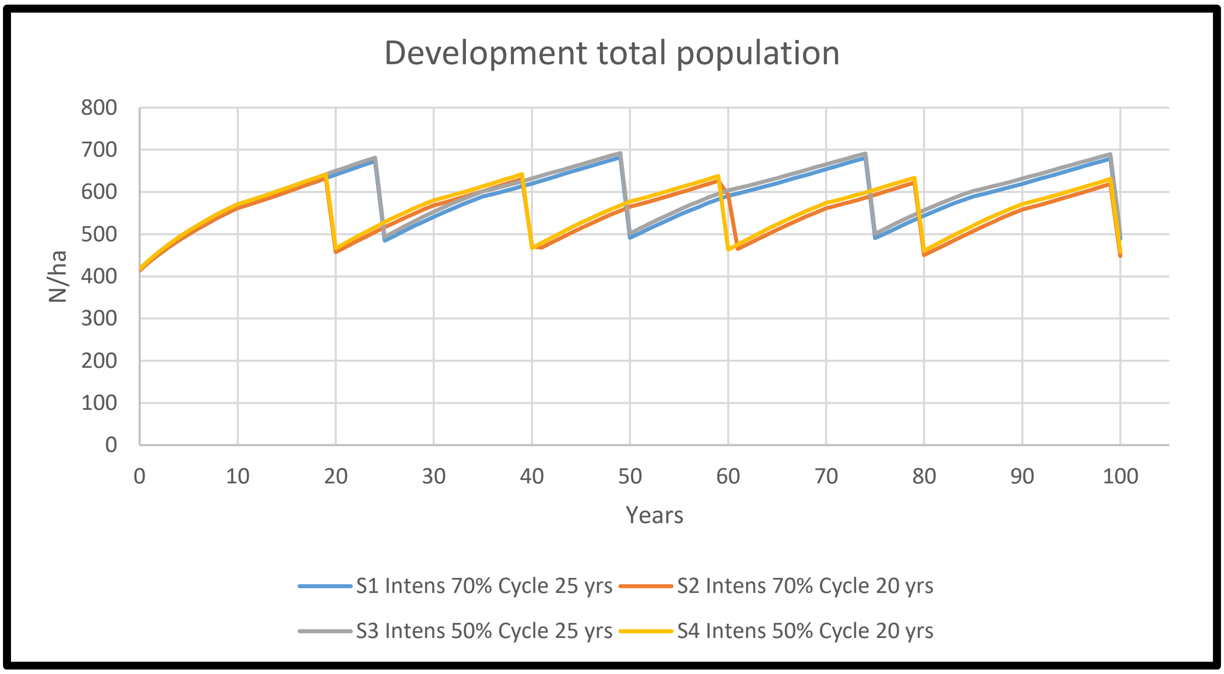


Figure 20: Projected total population

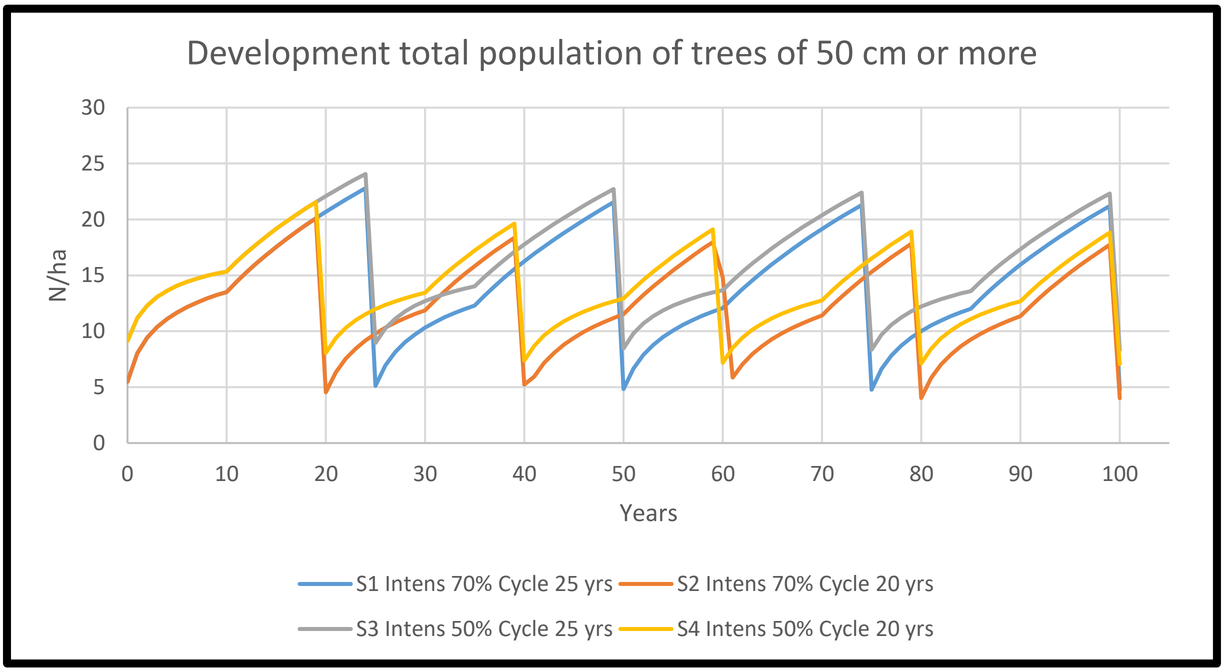


Figure 21: Projected population trees 50 cm or more

Population development for the whole stand will not be discussed in such detail as the three timber groups since it is the combined population of these groups. A positive development for the total population can be seen for all scenarios, and a negative trend for trees 50 cm or more, entailing in a shift in density towards the lower size classes (see figures 20 and 21). Furthermore, the pattern is rather similar to that of the light hardwood group. The best scenario is S3, with an increase of 19.6% and -8.8% for the total population and trees of 50 cm or more, respectively (see table 17).

Table 177: Change in total population after 100 years

Scenario	Total population	Trees 50 cm or more
1	18.1%	-13.2%
2	8.2%	-26.8%
3	19.6%	-8.8%
4	9.8%	-22.6%

4.2.5 Harvest

The harvested number of trees per rotation is determined per timber group, for each scenario. In the figures 22-25 below (see appendix 7 for the tables with actual values), the development of harvestable trees at each logging cycle can be seen. The pattern is similar to that seen in population development, the number of harvestable trees is going down slightly. However, for light hardwoods it seems to stabilize very quickly, after one or two logging cycles. This is, again, in accordance with the pattern seen in population development. Interesting to note is that the harvestable volume for medium hardwoods in scenario 3 is nearly stable, this would suggest that this is a sustainable rate of exploitation, looking from harvest perspective. Furthermore, the decrease in harvest is strongest in the heavy hardwood group, decreasing for all scenarios. This can be seen as an especially problematic development since many high-value timbers are included in this group.

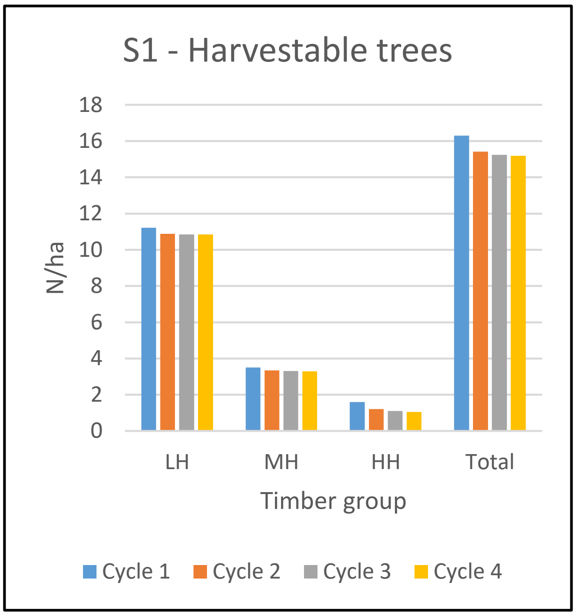


Figure 23: Scenario 1, harvestable trees

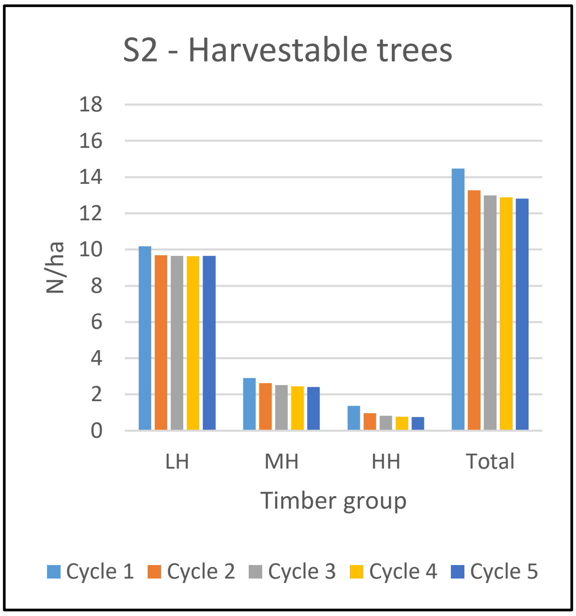


Figure 22: Scenario 2, harvestable trees

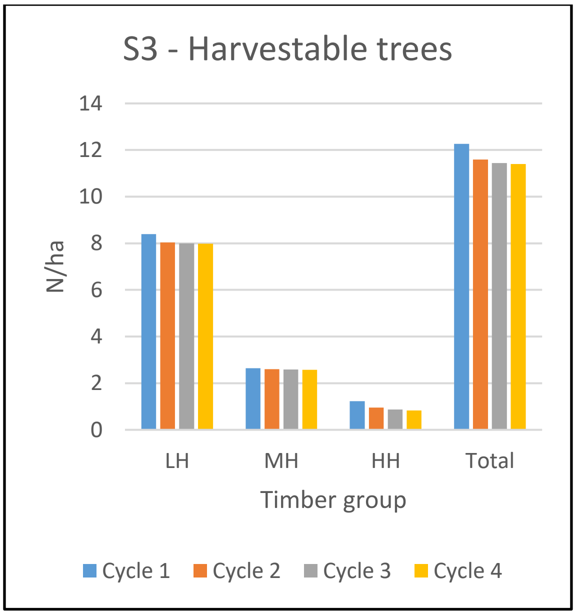


Figure 25: Scenario 3, harvestable trees

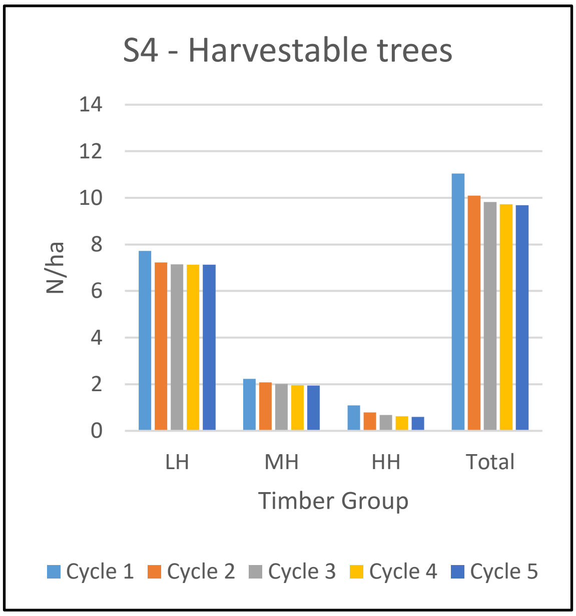


Figure 24: Scenario 4, harvestable trees

5 Conclusion and discussion

Below a conclusion of the results is given. Both the results and the methods used are discussed in detail in the next paragraphs.

5.1 Conclusion of results

Reflecting back on the first research question (*What are growth rates for three timber groups in mixed dipterocarp forests in Sarawak?*), it can be concluded that average growth rates for the three timber groups are 0.52 cm/yr for light hardwoods, 0.37 cm/yr for medium hardwoods and 0.34 cm/yr for heavy hardwoods. Looking at the sub-questions, it is evident that there is a difference between timber groups. The vital rates have been determined and can be found in the matrices in appendix 1.

The second research question (*What is a sustainable harvest level for three timber groups in mixed dipterocarp forest, and how can this be determined using a matrix model?*) will be discussed in more detail. Looking at the first sub-question, it can be said that basic matrix multiplication is a rather inaccurate way of projecting growth because of the exponential nature. To make more realistic projections, a function for density-dependence was added and this seems to work quite alright.

The main change in forest structure when projecting population development and simulating logging is a reduction in density of large trees, for all timber groups except scenario 1 and 3 for medium hardwoods. A change is noted in proportional distribution, with a shift towards a larger population in the lower size classes for light and heavy hardwoods, and a shift towards a larger population in the higher size classes for medium hardwoods.

Coming back to the sub-question of what a sustainable rate of exploitation for each of the timber groups is, the following can be said. For all timber groups, the 'best' scenario is scenario 3, which is not surprising since this is the 'mildest' scenario. The light hardwood group has a fast population recovery rate after logging, for all scenarios, but does show a decrease in trees of 50 cm or more. However, this decrease stabilizes after one or two logging cycles, and total population increases. Medium hardwoods first show an increase in trees of 50 cm or more, but this decreases again in the subsequent rotations. Total population decreases in all scenarios except scenario 3, in which projected development is nearly stable. The heavy hardwood group shows a strong decrease in both total population and for trees 50 cm or more. Looking at the total population, an increase in density for trees of all sizes can be seen, whereas a decrease for trees of 50 cm and more is detected.

Can the question of what a sustainable rate of exploitation is for the three timber groups be answered than? For a definite answer, not enough scenarios have been compared. But the following conclusions can be drawn:

- Light hardwoods have a strong capacity to recover after logging, and the population can be maintained, although average diameter is decreasing.

- Medium hardwoods are more sensitive but do show a more the less stable development when using a logging intensity of 50% and a rotation time of 25 years.

- Heavy hardwoods are very sensitive, and no sustainable scenario was projected in this thesis.

The final sub-question aims at determining recommendations based on the experiences of model construction and projection outcomes. This question is answered in chapter 6, where an evaluation of the model and its use is given, and several points reviewed in the discussion are included.

5.2 Discussion

In the first three sections of the discussion, the methods are discussed. In the last two sections, the results are discussed.

5.2.1 Timber grouping

Using timber groups is a convenient way of grouping all species in a database and is of interest for the timber industry. However, it has some limitations, which might be the reason it is not often used for projections. The main issue is that when using timber groups, species with totally different growth habits are grouped together. A good example is the grouping of pioneer species *Macaranga hosei* together with meranti species *Shorea parvifolia* into the light hardwood group.

Difference in growth habits among species enlisted in a timber group is likely to be highest in the light hardwood group, since this is the largest and most diverse group. Species grouped in the medium, and especially the heavy hardwood group will have growth characteristics more similar to other species in the group. Heavy hardwoods include many rare and slow growing species with high density timbers that would seem logical to group. But also here some *Shorea* species (Selangan batu, e.g. *Shorea laevis*) are included, which might have a different growth pattern.

For growth modelling representative of the ecological reaction of a forest after logging, a grouping into ecological groups could be of more use. Species grouping as used by Sist et al. (2002) might show a more realistic outcome when projecting population development. In this report, the authors used 3 species groups: pioneers, dipterocarps and all other species. This includes the difference in growth behaviour between species somewhat more accurate (Sist et al. 2002). Species grouping as used by Chai & LeMay (1993) was done by looking at shade tolerant and light demanding species, and for *Shorea* species by looking at growth rates and mature size. Although also a rather simple grouping, this does takes ecological differences between species into account (Chai and LeMay 1993). More thorough types of grouping are discussed by Fischer et al. (2016) for use in the FORMIND model. In this paper the authors discuss a grouping based on plant functional types, which can be seen as a more complex form of the formerly discussed species groups. Anywhere from 3 to 22 different plant functional types can be discerned here (Fischer et al. 2016; Huth and Köhler 2003). Although this will most likely result in very accurate modelling, it does significantly increase model complexity and parameter requirements.

5.2.2 Classes, class-specific parameters and plot size

The 10 cm size classes formulated in this model were used because of simplicity. Often, stand structure is expressed in population density per 10 cm class, and it is logical to use the same classes for modelling. Also, using smaller classes (e.g. 5 or 2.5 cm) reduces an already limited sample size for the higher DBH classes. However, using 10 cm classes refrains from taking the legal felling DBH limit for non-dipterocarps of 45 cm into account.

In their model for peat swamp forests, Chai & LeMay (1993) used 5 cm classes, up to 45 cm, and one class for trees >45 cm. These 5 cm classes most likely make for somewhat more accurate projections, but can only be used when sample size is adequate (Chai and LeMay 1993). Forshed et al. (2007) used 5 size classes of 15, 20 and 30 cm in width (Forshed et al. 2007). Using only 5 classes increases simplicity and decreases parameter requirements, and the large DBH range within a class increases available sample size. Although it has some advantages, this large DBH range within a class might not show smaller changes in population development that would have been projected when using smaller classes. What a right size class is will likely depend strongly on the local forest situation, complexity of the model, available data and many more factors, and are best appraised separately for every modelling application.

The grouping of size classes to increase sample size was unavoidable, making some of the parameters not class-specific, but the same for several classes. This was done mainly for the low-sample size higher classes (mostly classes 6-8), but for the heavy hardwoods group also lower classes were involved (class 3-8 have identical growth rates in the HH matrix for the first 10 years after logging). Although these grouped growth rates are likely to be quite different than actual class-specific growth, impact on population development due to grouped growth is thought to be rather limited. This claim is supported by the results of the elasticity analysis, which suggest that the lower size classes (especially class 1-3) have a far larger impact on total population development than the higher classes (see appendix 2).

The low sample size and high frequency of database and recording errors for larger trees (trees 50 cm or more) proves to be a challenge. A solution for this would be to use larger plots for only trees of 50 cm or more, but this would require additional work. Another option would be to get additional growth rates for larger trees by measuring PCT's tagged by concession staff, but this would of course require approval and close collaboration with logging contractors.

Including seed- and sapling classes could improve model accuracy. This is often done using height instead of DBH as juvenile class parameter (e.g. Hartshorn (1975); Verwer et al. (2008)). Simulating regeneration processes makes modelling more complex, requires additional parameters and can only be effectively done if sufficient data on this is available.

The use of two age classes (first 10 years and 10 or more years after logging) was done to include expected differences in vital rates directly after logging. This 'effect of logging' is thought to wear off after some time, which is why this was set at 10 years. This could improve model accuracy, but the inclusion of a density-dependence function could make this rather unnecessary since growth will already be adjusted to density. However, changes in the base vital rates, especially mortality and recruitment, are expected, which are more related to logging activities than to density.

5.2.3 Density dependence

The function for density dependence used (from Jensen 1993) was chosen because of its simplicity and low input needed. This function essentially sets an environmental carrying capacity (maximum density) for each class, making the population bottom off until it stabilizes. The necessity of such a function was highlighted when testing the exponential matrix showed rapid population development to unrealistic high figures over just 25 years of projection (for light hardwoods). The function seems to succeed in transforming exponential matrix growth into more realistic logistic growth. Although using density-dependence will deviate somewhat from the measured parameters, matrix models without a function for density dependence are of limited use, and might only be applicable for short-term projections (Liang and Picard 2012; Vanclay 1994).

Taking minimum and maximum population density figures from the dataset was done to limit the use of parameters from 'outside' the dataset. Densities as recorded in the database are most likely not the minimum and maximum values possible for MDF in Sarawak. Though it was deemed logical to use values from the same database the vital rates were calculated from, in order to avoid extrapolating outside of the available data range. The model does not take the influence of class density on other classes into account. Considering the relation between the number of large trees per hectare and the number of smaller trees, in which the number of smaller trees decreases when the number of larger trees increases (i.e. tree competition), allows for more accurate modelling. Determining this requires extensive additional information, which was not available.

Another common type of density-dependence functions is density-dependent recruitment. This has been used by, amongst others, Holm et al. (2008) and Fortini et al. (2015). This form of density dependence sets a carrying capacity only for saplings/seedlings or reduces fecundity rates as density increases. Doing this, growth for population of the other size classes will automatically bottom off until it reaches a point were fecundity and mortality are in balance. The reason this was not used for this project is that detailed information on sapling/seedling growth and the effect of density on growth and fecundity is needed, which was not present in the dataset. A similar strategy would be to use density-dependent mortality rates.

5.2.4 Growth rates and matrix construction

The projection scenarios have the main aim to test the model. Although based as much as possible on actual situations, the scenarios are not regarded to be very realistic, and the projection outcomes are of limited use for management planning. For forest management applications, scenarios are best based on the situation as it is in the management unit using the model.

Relating tree density per hectare to age after logging is a good way of checking upon the model. The expected pattern in undisturbed forest development after logging is first a strong increase in density, bottoming off at some point, after which population is expected to drop due to mass mortality of pioneer species until reaching a stationary level (Nzogang 2009). This pattern is not in accordance with the 500-year projection because a different equation has to be used to do so (adding a time lag as described by Jensen (1993) can also be used to project such a pattern, but due to increased complexity and a limited time frame, this was not done). However, the densities found in the plots suggest only an increasing density with age, and projecting this pattern was the aim.

DBH increment as calculated from the plot data were deemed rather accurate for the smaller classes (class 1-4) because of a large sample size. The higher classes have low sample sizes and accuracy will be lower. The expected pattern of highest growth in the mid-size classes is not really seen. Comparing measured increment rates with those found elsewhere yields the following.
Increment rates as recorded for MDF in peninsular Malaysia were in the range of 0.16-1.24 cm/yr for dipterocarps, 0.27-0.80 cm/yr for non-dipterocarps and averaging at 0.33-0.92, with dipterocarps normally having higher growth rates (Ismail et al. 2010). This would be in line with the recorded increments. Furthermore, diameter increment measured in peat swamp forest (PSF) in Sarawak was in the range of 0.26-0.82 cm/yr (Chiew 2004). This is also in accordance with the calculated growth rates, although it not realistic to compare PSF and MDF since these are very different forest types. Growth rates recorded by Kammesheidt et al. (2003) for MDF in Sarawak ranged from around 0.18-0.89 cm/yr, with heavy hardwood growth being clearly lower, ranging from 0.18-0.68 cm/yr (Kammesheidt et al. 2003). Again, this is roughly comparable to growth rates stated in this report. However, increment rates likely heavily depend on local conditions (soil type, rainfall etc.) and on management, which makes it hard to compare DBH increments recorded in different locations.

The lambda values (λ) for the matrices showed that the light hardwood group has the highest growth, which was expected. But the lambda values calculated for heavy hardwoods were higher than those for medium hardwoods. This is remarkable, since average growth rates are higher for medium hardwoods. It could due to the fecundity probabilities being lower for medium hardwoods (MH: 0.26/0.21 and HH: 0.43/0.27 in first and second matrix, respectively). However, this is not reflected in the elasticity analysis, which has rather similar values for fecundity probability.

Results of the elasticity analysis clearly shows the importance of the lower classes on population development. This means that although sample size is low for the higher classes and increment rates were often grouped, the effect of this on population development will be limited. It also undernotes the importance of determining accurate growth rates for smaller trees (10-30cm) when the use of a matrix model is anticipated.

5.2.5 Projections

Looking at the projections, it can be said that reducing rotation time to 20 years has a negative impact on population development. The light hardwood group is the most resilient of the three timber groups, and after a small decline in the first rotation, population stabilizes very quickly. The medium hardwood group overall shows a decline but will come close to stabilization after 100 projection years. The heavy hardwood group shows a decline in population and harvest intensities as simulated are far from sustainable, since a strong decline for all scenarios is expected.

A shift in proportional distribution per size class is noted for all scenarios. This was expected, since the initial vectors were quite different from the stable stage distributions for all timber groups. However, the shift towards a higher population in the lower classes as recorded for light and heavy hardwoods is stronger than what is to be expected based on the stable stage distribution for these matrices. The reason for this is the continuous removal of large trees from the population because of timber harvest. Although tree extraction is also happening for medium hardwoods, the proportional shift in population is reversed for this group. This is probably due to the low initial density of larger trees, which even with harvest simulations, is increasing over time.

The strong decrease in population for the heavy hardwood group in spite of having rather high lambda values is, as said before, remarkable. The reason for this is unknown, but it can be speculated that this occurs due to the initial population density being low. It could be that density is below a certain 'critical' level, a threshold below which the population cannot grow enough to reach a level similar to its initial density. A similar, albeit much less strong, pattern can be seen for medium hardwoods. By continuing logging practices, the population is severely depleted. A possible solution for this could be increasing the rotation time to give the population more time to regenerate.

When using a logging intensity of 70%, population decline is much more rapid than for 50% logging intensity. The light hardwood group has the ability to stabilize very quickly, independent of logging intensity, at a lower-than-initial population of harvestable trees, whereas total population increases. Looking at the medium hardwood group, the difference between 70% and 50% intensity can clearly be seen. Using 25-year cycles and a harvesting intensity of 50%, population is more the less stable. This would indicate a sustainable harvesting regime. For heavy hardwoods on the other hand no sustainable scenario is included in this test. Population is declining for all scenarios, with the lower logging cycles and higher cutting intensities causing a stronger drop in population than the 'milder' scenarios. An especially strong decrease in harvestable trees can be noted, quickly reducing this timber group to local commercial extinction.

A small reduction of harvestable trees can be detected for light hardwoods in the first and second rotations, afterwards the population has stabilized more the less. It might seem quite optimistic to keep the stand at a lower density and have a somewhat lower annual harvest and sustain this harvest over time. But many species were grouped into the light hardwood group, including low-value pioneer species, while very few pioneers were present in the initial vector. Therefore, it is likely that pioneer species will have a higher contribution to the population of harvestable trees, essentially lowering economic output. For medium hardwoods this small reduction of harvestable trees can also be seen. However, since most species in this group are valuable timber species, lower economic output will be mainly related to reductions in harvestable trees. This is also true for the heavy hardwood group, which consists of many high-value species. The strong reduction in harvestable trees in this group is especially problematic from an economic perspective.

6 Model evaluation and recommendations

A short evaluation of the model is given in this chapter, based on the results and on several points discussed in the previous chapter. From the outcomes of the projection several recommendations with implication on forest management will be given.

6.1 Model evaluation

The results of this modelling application suggest that transition matrix models can be conveniently used for projecting forest growth. The most important point to stress, however, is that the current model is a test only, and a more thorough study should be concluded before such a model can be used in practice. To assess the model, an overview of the current model's strengths and weaknesses is given. Furthermore, some recommendations for future matrix model development are given as well.

Strengths

- The model is rather simple to build and use, and can be constructed in commonly used database programs such as Excel.

- When the database used to calculate vital rates is sufficient, quite accurate projections of forest development and potentially harvestable trees can be made.

- Options for increasing model complexity and accuracy are plentiful. Starting with the base exponential transition matrix, additional functions can be added.

Weaknesses

- Although the basic transition matrix model is easy to construct, the density-dependence function increases complexity and the need for additional parameters, but a model without this is of very limited use. Determining the parameters for an accurate density-dependence function can be challenging.

- The current model does not succeed in taking complex ecological processes into account due to the use of timber groups. It is rather inaccurate in mimicking development into realistic stable stage (primary) forest situations. This limits use for applications other than forests managed on set logging cycles.

- Assumptions were made that will most likely decrease model accuracy and outcome representativeness. Assuming parameters will often be unavoidable, unless a very thorough database is available.

Recommendations for future model development

- A size class approach to modelling tropical selection forests is a robust approach. The number and width of the size classes should be based on the available dataset and the species/species groups used. DBH increment rates should be unique to a size class, whereas for mortality an average figure can be taken. Care should be taken when determining which classes are reproductive, especially when species are grouped.

- Species grouping is deemed necessary when an attempt to model whole forest dynamics is made. For species grouping, it would be best to look at ecological groups instead of timber groups. This makes for more accurate modelling since ecological processes are taken into account. When having a sufficiently large database, modelling can be done for some of the most important species, which would allow for very accurate projections for these species.

- Increasing sample size for trees of 50 cm or more will contribute to model accuracy. Ideally, a unique average growth rate will be determined for each size class, based on a sufficiently large sample size.

- For the density-dependence function used in this model, emphasis should be placed on determining maximum density values, also in relation to stand age and density of individuals in other size classes. For effective modelling, additional equations and parameters for e.g. competition amongst trees or density-dependent recruitment/mortality should be added.

6.2 Recommendations for forest management

The following recommendations are based on the projection outcomes. The recommendations are given with regard to sustainable forest management.

- Care should be taking when considering reducing rotation times, and this is better avoided. If a cycle reduction is unavoidable, reduce logging intensities accordingly.

- Logging intensity should be based on the timber group. The resilient nature of the light hardwood group allows for relatively intensive logging regimes, whereas the medium and especially the heavy hardwood group are more sensitive and need lower logging intensities to maintain sustainability.

- Extreme care to avoid overharvesting of heavy hardwoods should be taken. This group proves to be very sensitive and can only be exploited sustainably when using low harvesting intensities.

- Scenarios should be based on local forest conditions and management, and more scenarios should be compared to see what the impact of differing conditions will be on population development before any projection outcome is used for forest management.

Bibliography

Alder, D., and T. J. Synnott. 1992. “Permanent Sample Plot Techniques for Mixed Tropical Forest.” *Tropical forestry papers* 25.

Angelsen, A., and D. Kaimowitz. 2001. *Agricultural Technologies and Tropical Deforestation*.

Appanah, S., and Jennifer M. Turnbull. 2015. A review of dipterocarps: taxonomy, ecology and silviculture *A Review of Dipterocarps: Taxonomy, Ecology and Silviculture*.

Bruenig, E. F. 2006. “Integrated and Multi-Sectoral Approaches to Achieve Sustainability of Ecosystem Development: The Sarawak Forestry Case.” *Global Ecology and Biogeography Letters* 3(4/6): 253.

C. Y., Ling, and Julia S. 2012. “Diversity of the Tree Flora in Semenggoh Arboretum , Sarawak , Borneo.” *Gardens’ Bulletin Singapore* 64(1): 139–69.

Chai, Francis Y. C. 1991. “Diameter Increment Models for the Mixed Swamp Forests of Serawak.” (August).

Chai, Francis Y. C., and Valerie M. LeMay. 1993. “Development and Testing of Diameter Increment Models for Mixed Swamp Forests of Sarawak.” *Forest Ecology and Management* 58: 51–64.

Chiew, Sia Puon. 2004. Forest Research Centre, Sarawak Forestry Corporation *Growth and Yield of Logged-over Peat Swamp Forests of Sarawak*.

Davies, Stuart James. 2001. “Tree Mortality and Growth in 11 Sympatric Macaranga Species in Borneo.” *Ecology* 82(4): 920–32.

Demies, Malcom, Hiromitsu Samejima, Alexander K Sayok, and Gabriel T Noweg. 2019. “Tree Diversity, Forest Structure and Species Composition in a Logged-over Mixed Dipterocarp Forest, Bintulu, Sarawak, Malaysia.” *Transactions on Science and Technology* 6(1–2): 102–10.

Department of Statistics Malaysia. 2011. “Population Distribution and Basic Demographic Characteristic Report 2010.” https://www.dosm.gov.my/v1/index.php?r=column/ctheme&menu_id=L0pheU43NWJwRWVSZklWdzQ4TlhUUT09&bul_id=MDMxdHZjWTk1SjFzTzNkRXYzcVZjdz09 (September 19, 2019).

Enters, Thomas et al. 2001. Asia-Pacific Forestry Commission International Conference 26 February to 1 March 2001 *Applying Reduced Impact Logging to Advance Sustainable Forest Management*. http://www.fao.org/docrep/005/ac805e/ac805e04.htm#TopOfPage.

Fah, Liew Chin. 2007. “SUSTAINABLE FOREST MANAGEMENT IN SARAWAK.” (January).

Favrichon, Vincent, Nicolas Nguyen-The, and Anna Enggelina. 2001. “Estimation of the Harvestable Potential after Logging in a Lowland Mixed Dipterocarp Forest of East Kalimantan.” *Journal of Tropical Forest Science* 13(1): 62–75.

Figueira, Adelaine Michela E.S. et al. 2008. “Effects of Selective Logging on Tropical Forest Tree Growth.” *Journal of Geophysical Research* 114(1): 1–11.

Fischer, Rico et al. 2016. “Lessons Learned from Applying a Forest Gap Model to Understand Ecosystem and Carbon Dynamics of Complex Tropical Forests.” *Ecological Modelling* 326: 124–33. http://dx.doi.org/10.1016/j.ecolmodel.2015.11.018.

Forest Department Sarawak. 2019a. “Facts & Figures.” https://forestry.sarawak.gov.my/page-0-140-1170-FACTS-FIGURES.html (September 19, 2019).

———. 2019b. “Issues and Challenges.” https://forestry.sarawak.gov.my/page-0-245-1010-tid.html (September 18, 2019).

———. 2019c. “Types and Categories of Sarawak’s Forests.” https://forestry.sarawak.gov.my/page-0-160-593-Types-and-Categories-of-Sarawak-s-Forests.html (September 19, 2019).

Forshed, Olle, Anders Karlsson, Jan Falck, and Jonas Cedergren. 2007. “Stand Development after Two Modes of Selective Logging and Pre-Felling Climber Cutting in a Dipterocarp Rainforest in Sabah, Malaysia.” *Forest Ecology and Management* 255(3–4): 993–1001.

Fujiwara, Masami, and Jasmin Diaz-Lopez. 2017. “Constructing Stage-Structured Matrix Population Models from Life Tables: Comparison of Methods.” *PeerJ* 5.

Gagen, Mary. 2019. “The World’s Tallest Known Tropical Tree Has Been Found-and Climbed.”

National Geographic. https://www.nationalgeographic.com/environment/2019/04/worlds-tallest-tropical-tree-discovered-climbed-borneo/.
van Gardingen, Paul R., Denis Valle, and Ian Thompson. 2006. "Evaluation of Yield Regulation Options for Primary Forest in Tapajós National Forest, Brazil." *Forest Ecology and Management* 231(1–3): 184–95.
Gaveau, David L.A. et al. 2014. "Four Decades of Forest Persistence, Clearance and Logging on Borneo." *PLoS ONE* 9(7): 1–11.
Global Forest Watch. 2019. "Forest Cover Change Map." https://www.globalforestwatch.org/map (September 30, 2019).
Gunarso, Petrus, Manjela Eko Hartoyo, Fahmuddin Agus, and Timothy J Killeen. 2013. "Oil Palm and Land Use Change in Indonesia, Malaysia and Papua New Guinea." *Roundtable on Sustainable Palm Oil*: 29–64. http://www.rspo.org/file/GHGWG2/4_oil_palm_and_land_use_change_Gunarso_et_al.pdf.
Harja, D., S. Rahayu, and S. Pambudi. 2019. "Tree Functional Attributes an Ecological Database: Wood Density." http://db.worldagroforestry.org//wd (July 17, 2019).
Hartshorn, Gary. 1975. "A Matrix Model of Tree Population Dynamics." *Tropical ecological systems* (January 1975).
Hastings, A, and L Gross. 2012. "Matrix Models." In *Encyclopedia of Theoretical Ecology*, , 415–23.
Higuchi, Francisco et al. 2019. "Dynamics of Tropical Forest Twenty-Five Years after Experimental Logging in Central Amazon Mature Forest." *Forests* 10(2): 89.
Hood, G. M. 2010. "Poptools Version 3.2.5." http://www.poptools.org.
Huth, Andreas, and Peter Köhler. 2003. "Impacts of Logging in Tropical Rain Forests With Disturbed - a Simulation Study." *Decision Support for Multiple Purpose Forestry*: 1–10.
Imai, Nobuo et al. 2016. "Response of Tree Species Diversity to Disturbance in Humid Tropical Forests of Borneo." *Journal of Vegetation Science* 27(4): 739–48.
International Forest Management Consultants. 2015. *Feasibility Study Forest Management Certification for Forest Management Unit Kubaan-Puak, Sarawak*. Petaling Jaya / Selangor.
Ismail, H. et al. 2010. "Second Growth Forests: Are They Growing and Have They Recovered?" *Malaysian Forester* 73(2): 171–85.
ITTO. 1990. "The Promotion of Sustainable Forest Management: A Case Study in Sarawak, Malaysia." (May).
Jawa, Rantai, and Paul P. K. Chai. 2007. *A New Checklist of the Trees of Sarawak*. Rantai Jawa & Paul Chai P.K.
Jensen, A. L. 1993. "Simple Density-Dependent Matrix Model for Population Projection." *Ecological Modelling* 77(1): 43–48.
Kammesheidt, Ludwig, Ago Dagang Aaron, Joachim Weidelt Hans, and Wolfgang Schwarzwaeller. 2003. "Growth Patterns of Dipterocarps in Treated and Untreated Plots." *Forest Ecology and Management* 174(1–3): 437–45.
Lamprecht, Hans. 1989. GTZ, Eschborn *Silviculture in the Tropics: Tropical Forest Ecosystems and Their Tree Species – Possibilities and Methods for Their Long-Term Utilization.*
Land and Survey Department Sarawak. 1968. "Soil Map of Sarawak Sheet A and B."
Lee, H. S. et al. 2002. "Floristic and Structural Diversity of Mixed Dipterocarp Forest in Lambir Hills National Park, Sarawak, Malaysia." *Journal of Tropical Forest Science* 14(3): 379–400.
Liang, Jingjing, and Nicolas Picard. 2012. "Matrix Model of Forest Dynamics: An Overview and Outlook." *Forest Science* 59(3): 359–78.
Marn, Harald Mattsson, and Wybrand Jonker. 1981. *Logging Damage in Tropical High Forest*.
Matthews, John D. 1989. *Silvicultural Systems*.
Miller, David H., Al L. Jensen, and James H. Hammill. 2001. "Density Dependent Matrix Model for Gray Wolf Population Projection." *Ecological Modelling* 151(2–3): 271–78.
Mittelmeijer, Kasper. 2019. "Scriptieverslag: Lean Inkopen Zet Alfen Een Stap Voor Op de Concurrentie." Hogeschool van Amsterdam.
Naito, Yoko et al. 2008. "Size-Related Flowering and Fecundity in the Tropical Canopy Tree Species,

Shorea Acuminata (Dipterocarpaceae) during Two Consecutive General Flowerings." *Journal of Plant Research* 121(1): 33–42.
Nzogang, André. 2009. "Tropical Forest Dynamics after Logging - Natural Regeneration and Growth of Commercial Tree Species - in Southeast Cameroon (Doctoral Thesis)." : 200.
Pakhriazad, H. Z., I. Mohd Hasmadi, and U. R. Gerten. 2010. "The Effects of Reduced Impact Logging (RIL) on Forest Regeneration in ULu Baram, Sarawak, Malaysia." *Malaysian Forester*.
Pasin Sdn. Bhd. 2019. "Pasin FMU." http://www.pasinfmu.com.my/ (September 18, 2019).
Pastur, Guillermo Martínez, María Vanessa Lencinas, Juan Manuel Cellini, and Ignacio Mundo. 2007. "Diameter Growth: Can Live Trees Decrease?" *Forestry* 80(1): 83–88.
Pinard, M. A., and W. P. Cropper. 2000. "Simulated Effects of Logging on Carbon Storage in Dipterocarp Forest." *Journal of Applied Ecology* 37(2): 267–83.
Pinard, Michelle A., F. E. Putz, and John Tay. "Lessons Learned from the Implementation of Reduced-Impact Logging in Hilly Terrain in Sabah, Malaysia."
Rahman, A. B D, and A. B D Rahim. 2010. "Issues and Challenges in Managing Second Rotation Forest, Particularly for Timber Production in the Dry Inland Forest of Johor." *Malaysian Forester* 73(2): 125–44.
Raplex Sdn. Bhd. 2019. "Raplex FMU." http://www.raplexfmu.com.my/ (September 17, 2019).
Sarawak Forestry Corporation. 2006. "Biodiversity Conservation." http://www.sarawakforestry.com/SFC/sarawak-national-park/biodiversity-conservation/ (September 19, 2019).
———. 2018. "RIL Guidelines for Ground-Based Harvesting System Part 1 and 2."
Sarawak Government. 2019a. "Sarawak Population." https://www.sarawak.gov.my/web/home/article_view/240/175/ (September 19, 2019).
———. 2019b. "The Geography of Sarawak." https://www.sarawak.gov.my/web/home/article_view/159/176/ (September 19, 2019).
Shifley, Stephen R. et al. 2017. "The Past and Future of Modeling Forest Dynamics: From Growth and Yield Curves to Forest Landscape Models." *Landscape Ecology* 32(7): 1307–25.
Sist, P., D. P. Dykstra, and R. Fimbel. 2015. "Reduced Impact Logging Guidelines for Lowland and Hill Dipterocarp Forest in Indonesia." *Reduced impact logging guidelines for lowland and hill dipterocarp forest in Indonesia* 62(15).
Sist, P., N. Picard, and S. Gourlet-Fleury. 2002. "Sustainable Cutting Cycle and Yields in a Lowland Mixed Dipterocarp Forest of Borneo." 60(773508920): 803–14.
Skovsgaard, J. P. 2018. "Lecture on Silvicultural High Forest Systems."
Sun, Hong Gang, Jian Guo Zhang, Ai Guo Duan, and Cai Yun He. 2007. "A Review of Stand Basal Area Growth Models." *Forestry Studies in China* 9(1): 85–94.
Ta Ann Holdings Berhad. 2019. "Kapit FMU." http://www.kapitfmu.com.my/ (September 18, 2019).
Tan, S., R. B. Primack, E. O. K. Chai, and H. S. Lee. 1987. "The Silviculture of Diperocarp Trees in Sarawak, Malaysia." *The Malaysian Forester* 50(2): 148–61.
Tawie, Sulok. 2015. "Blame 'big Six' Timber Firms for Deforestation, Not Illegal Loggers, Sarawak DAP Says." *MalayMail*. https://www.malaymail.com/news/malaysia/2015/05/28/blame-big-6-timber-firms-for-deforestation-not-illegal-loggers-sarawak-dap/905219.
Tian, Yuan et al. 2019. "The Relationship between Stem Diameter Shrinkage and Tree Bole Moisture Loss Due to Transpiration." *Forests* 10(3).
Twery, Mark J. 2004. "Modelling in Forest Management." *Environmenal Modeling: Finding Simplicity in Complexity*.
Usher, M. B. 1966. "A Matrix Approach to the Management of Renewable Resources, with Special Reference to Selection Forests." *Journal of Applied Ecology* 3(2): 355–67.
Vanclay, J. K. 1989. "Modelling Selection Harvesting in Tropical Rain Forests." *Journal of Tropical Forest Science* 1(3): 280–94. http://espace.library.uq.edu.au/eserv/UQ:8398/R014_jfts_pp.pdf.
———. 1994. *Modelling Forest Growth and Yield: Applications to Mixed Tropical Forests*.
———. 1995. "Vanclay , J . K ., 1995 . Sustainable Silvicultural Systems : Lessons from Queensland , Australia . In : Ø . Sandbukt (Ed .) Management of Tropical Forests : Towards an Integrated

Perspective . Centre for Development and the Environment , University Of.” : 169–81.
———. 1996. “Estimating Sustainable Timber Production from Tropical Forests.” *CIFOR* 62(11).
Vanclay, J. K., and J. P. Skovsgaard. 1997. “Evaluating Forest Growth Models.” *Ecological Modelling* 98(1): 1–12.
Verwer, Caspar et al. 2008. “Silviculture Enhances the Recovery of Overexploited Mahogany Swietenia Macrophylla.” *Journal of Applied Ecology* 45(6): 1770–79.
Wong, Jack. 2018. “Log Shortage Forcing Some Plywood Mills to Stop Production.” *The Star*. https://www.thestar.com.my/business/business-news/2018/12/10/log-shortage-forcing-some-plywood-mills-to-stop-production.
Wong, T. M., S. C. Lim, and R. C. K. Chung. 2002. *A Dictionary of Malaysian Timbers - Second Edition*. Kuala Lumpur.
Woon, Weng-Chuen, and Haron Norini. “Trends in Malaysian Forest Policy + Overview of Forest Policy Trends in Malaysia.” https://pub.iges.or.jp/system/files/publication_documents/pub/policyreport/180/02_Malaysia.pdf.
Yasin, Mohd Hizamri Mohd, N. I.K. Mohd Shah Mustafa, L. I.M. Erik Chong Ping And, and D. Zulkifli-Tukiman. 2010. “Stocking of Second Growth Forest Based on the Fourth National Forests Inventory (NFI 4).” *Malaysian Forester* 73(2): 145–54.
Zedtee Sdn. Bhd. 2019. “Anap Muput FMU.” http://www.anapmuputfmu.com/index.php (September 17, 2019).
Zimmerman, Barbara L., and Cyril F. Kormos. 2012. “Prospects for Sustainable Logging in Tropical Forests.” *BioScience* 62(5): 479–87. https://academic.oup.com/bioscience/article-lookup/doi/10.1525/bio.2012.62.5.9.
Zuidema, Pieter A., and René G. A. Boot. 2001. “Demography of the Brazil Nut Tree (Bertholletia Excelsa) in the Bolivian Amazon : Impact of Seed Extraction on Recruitment and Population Dynamics.” *Journal of Tropical Ecology* (2002–18): 1–31.

Appendices

Appendix 1 Matrices

Light Hardwoods

First 10 years after logging

Class	1	2	3	4	5	6	7	8
1	0,926836	0	0,414414	0,414414	0,414414	0,414414	0,414414	0,414414
2	0,043164	0,910381	0	0	0	0	0	0
3	0	0,059619	0,886979	0	0	0	0	0
4	0	0	0,083021	0,874482	0	0	0	0
5	0	0	0	0,095518	0,882352	0	0	0
6	0	0	0	0	0,087648	0,882352	0	0
7	0	0	0	0	0	0,087648	0,882352	0
8	0	0	0	0	0	0	0,087648	0,97

More than 10 years after logging

Class	1	2	3	4	5	6	7	8
1	0,936291	0	0,281526	0,281526	0,281526	0,281526	0,281526	0,281526
2	0,043709	0,921586	0	0	0	0	0	0
3	0	0,058414	0,90458	0	0	0	0	0
4	0	0	0,07542	0,901394	0	0	0	0
5	0	0	0	0,078606	0,913407	0	0	0
6	0	0	0	0	0,066593	0,890892	0	0
7	0	0	0	0	0	0,089108	0,872481	0
8	0	0	0	0	0	0	0,107519	0,98

Medium Hardwoods

First 10 years after logging

Class	1	2	3	4	5	6	7	8
1	0,937743	0	0,26026	0,26026	0,26026	0,26026	0,26026	0,26026
2	0,032257	0,92723	0	0	0	0	0	0
3	0	0,04277	0,914641	0	0	0	0	0
4	0	0	0,055359	0,926593	0	0	0	0
5	0	0	0	0,043408	0,926593	0	0	0
6	0	0	0	0	0,043408	0,926593	0	0
7	0	0	0	0	0	0,043408	0,926593	0
8	0	0	0	0	0	0	0,043408	0,97

More than 10 years after logging

Class	1	2	3	4	5	6	7	8
1	0,949643	0	0,208108	0,208108	0,208108	0,208108	0,208108	0,208108
2	0,030357	0,940834	0	0	0	0	0	0
3	0	0,039166	0,936924	0	0	0	0	0
4	0	0	0,043076	0,912899	0	0	0	0
5	0	0	0	0,067101	0,894109	0	0	0
6	0	0	0	0	0,085891	0,914286	0	0
7	0	0	0	0	0	0,065714	0,914286	0
8	0	0	0	0	0	0	0,065714	0,98

Heavy Hardwoods

First 10 years after logging

Class	1	2	3	4	5	6	7	8
1	0,941717	0	0,43095	0,43095	0,43095	0,43095	0,43095	0,43095
2	0,028283	0,930614	0	0	0	0	0	0
3	0	0,039386	0,919946	0	0	0	0	0
4	0	0	0,050054	0,919946	0	0	0	0
5	0	0	0	0,050054	0,919946	0	0	0
6	0	0	0	0	0,050054	0,919946	0	0
7	0	0	0	0	0	0,050054	0,919946	0
8	0	0	0	0	0	0	0,050054	0,97

More than 10 years after logging

Class	1	2	3	4	5	6	7	8
1	0,950083	0	0,273425	0,273425	0,273425	0,273425	0,273425	0,273425
2	0,029917	0,948013	0	0	0	0	0	0
3	0	0,031987	0,926907	0	0	0	0	0
4	0	0	0,053093	0,920046	0	0	0	0
5	0	0	0	0,059954	0,920046	0	0	0
6	0	0	0	0	0,059954	0,920046	0	0
7	0	0	0	0	0	0,059954	0,920046	0
8	0	0	0	0	0	0	0,059954	0,98

Appendix 2 Elasticity analysis

Light Hardwoods

First 10 years after logging

Class	1	2	3	4	5	6	7	8
1	0,255773	0	0,01458	0,007259	0,004364	0,002407	0,001328	0,001634
2	0,031571	0,219639	0	0	0	0	0	0
3	0	0,031571	0,181529	0	0	0	0	0
4	0	0	0,016991	0,089103	0	0	0	0
5	0	0	0	0,009733	0,054048	0	0	0
6	0	0	0	0	0,005369	0,029815	0	0
7	0	0	0	0	0	0,002962	0,016447	0
8	0	0	0	0	0	0	0,001634	0,022246

More than 10 years after logging

Class	1	2	3	4	5	6	7	8
1	0,249399	0	0,012075	0,006604	0,004124	0,001851	0,000989	0,001793
2	0,027436	0,214813	0	0	0	0	0	0
3	0	0,027436	0,18423	0	0	0	0	0
4	0	0	0,01536	0,100407	0	0	0	0
5	0	0	0	0,008756	0,063534	0	0	0
6	0	0	0	0	0,004632	0,027808	0	0
7	0	0	0	0	0	0,002781	0,014548	0
8	0	0	0	0	0	0	0,001793	0,029633

Medium Hardwoods

First 10 years after logging

Class	1	2	3	4	5	6	7	8
1	0,259427	0	0,010458	0,006292	0,002968	0,0014	0,000661	0,00059
2	0,022369	0,227005	0	0	0	0	0	0
3	0	0,022369	0,196806	0	0	0	0	0
4	0	0	0,011912	0,119961	0	0	0	0
5	0	0	0	0,00562	0,056595	0	0	0
6	0	0	0	0	0,002651	0,0267	0	0
7	0	0	0	0	0	0,001251	0,012597	0
8	0	0	0	0	0	0	0,00059	0,011778

More than 10 years after logging

Class	1	2	3	4	5	6	7	8
1	0,257148	0	0,009688	0,003823	0,002005	0,001598	0,000974	0,001522
2	0,01961	0,227135	0	0	0	0	0	0
3	0	0,01961	0,215801	0	0	0	0	0
4	0	0	0,009922	0,082973	0	0	0	0
5	0	0	0	0,006099	0,042617	0	0	0
6	0	0	0	0	0,004094	0,034729	0	0
7	0	0	0	0	0	0,002496	0,021175	0
8	0	0	0	0	0	0	0,001522	0,03546

Heavy Hardwoods

First 10 years after logging

Class	1	2	3	4	5	6	7	8
1	0,271415	0	0,013248	0,006159	0,002863	0,001331	0,000619	0,000538
2	0,024757	0,237512	0	0	0	0	0	0
3	0	0,024757	0,211526	0	0	0	0	0
4	0	0	0,011509	0,098336	0	0	0	0
5	0	0	0	0,005351	0,045716	0	0	0
6	0	0	0	0	0,002487	0,021253	0	0
7	0	0	0	0	0	0,001156	0,00988	0
8	0	0	0	0	0	0	0,000538	0,009051

More than 10 years after logging

Class	1	2	3	4	5	6	7	8
1	0,254916	0	0,009261	0,004677	0,002668	0,001521	0,000868	0,001152
2	0,020146	0,247538	0	0	0	0	0	0
3	0	0,020146	0,190041	0	0	0	0	0
4	0	0	0,010885	0,095271	0	0	0	0
5	0	0	0	0,006208	0,054336	0	0	0
6	0	0	0	0	0,003541	0,03099	0	0
7	0	0	0	0	0	0,002019	0,017675	0
8	0	0	0	0	0	0	0,001152	0,02499

Appendix 3 Growth rates per size class

As can be seen in the tables, growth rates are often the same for higher classes. This is because of a lack of data, growth data per class had to be grouped, and an average of this was taken to determine growth.

Light Hardwoods

Size class	First 10 years	Sample size	10 or more years	Sample size
1	0.44	652	0.45	1530
2	0.61	211	0.60	516
3	0.86	81	0.77	165
4	0.98	38	0.80	87
5	0.90	9	0.68	37
6	0.90	2	0.91	22
7	0.90	2	1.10	9
8	0.90	2	1.10	9

Medium Hardwoods

Size class	First 10 years	Sample size	10 or more years	Sample size
1	0.33	208	0.31	519
2	0.44	50	0.40	180
3	0.57	26	0.44	69
4	0.45	9	0.68	35
5	0.45	6	0.88	16
6	0.45	3	0.67	7
7	0.45	1	0.67	6
8	0.45	1	0.67	1

Heavy Hardwoods

Size class	First 10 years	Sample size	10 or more years	Sample size
1	0.29	89	0.31	204
2	0.41	28	0.33	66
3	0.52	7	0.54	24
4	0.52	4	0.54	11
5	0.52	0	0.61	2
6	0.52	0	0.61	1
7	0.52	0	0.61	1
8	0.52	1	0.61	1

Appendix 4 Diameter distribution control plots

Class	N/ha	Stable stage distribution
1	324.5	58.7%
2	96.5	17.5%
3	55.5	10.0%
4	38.5	7.0%
5	13.5	2.4%
6	7.5	1.4%
7	3.5	0.6%
8	13	2.4%
Total	552.5	100%

Appendix 5 Stable stage distribution as calculated from the matrices

Class	LH	MH	HH	AV for matrices
1	57.6%	58.1%	60.2%	58.6%
2	21.4%	21.7%	23.3%	22.1%
3	9.3%	10.0%	7.6%	8.9%
4	5.1%	3.9%	3.8%	4.3%
5	3.2%	2.1%	2.2%	2.5%
6	1.4%	1.6%	1.2%	1.4%
7	0.8%	1.0%	0.7%	0.8%
8	1.4%	1.6%	0.9%	1.3%

Appendix 6 Minimum and maximum values used in the density dependence function

The values were taken from the database. They represent the highest and lowest values for each size class.

First 10 years	LH		MH		HH	
Class	Min	Max	Min	Max	Min	Max
1	184	316	47	106	24	39
2	60	98	5	37	3	19
3	21	46	8	9	0	5
4	12	14	1	5	0	3
5	2	5	1	6	0	1
6	0	4	0	2	0	1
7	0	1	0	1	0	1
8	0	2	0	2	0	1

More than 10 years	LH		MH		HH	
Class	Min	Max	Min	Max	Min	Max
1	159	345	55	130	19	60
2	71	139	21	52	5	21
3	21	38	4	23	2	5
4	10	21	3	16	1	5
5	1	10	1	10	0	4
6	1	10	0	2	0	3
7	1	3	0	2	0	1
8	0	3	0	1	1	1

Appendix 7 Harvestable trees per hectare, per scenario

Scenario 1	LH	MH	HH	Total
Cycle 1	11.21	3.50	1.59	16.30
Cycle 2	10.87	3.35	1.20	15.42
Cycle 3	10.85	3.30	1.10	15.25
Cycle 4	10.85	3.28	1.06	15.19

Scenario 2	LH	MH	HH	Total
Cycle 1	10.18	2.91	1.38	14.47
Cycle 2	9.69	2.63	0.96	13.28
Cycle 3	9.64	2.51	0.83	12.99
Cycle 4	9.64	2.46	0.78	12.88
Cycle 5	9.64	2.42	0.75	12.81

Scenario 3	LH	MH	HH	Total
Cycle 1	8.39	2.64	1.23	12.26
Cycle 2	8.03	2.60	0.96	11.59
Cycle 3	7.99	2.58	0.87	11.44
Cycle 4	7.99	2.58	0.83	11.39

Scenario 4	LH	MH	HH	Total
Cycle 1	7.72	2.24	1.09	11.04
Cycle 2	7.23	2.08	0.79	10.09
Cycle 3	7.15	2.01	0.67	9.83
Cycle 4	7.14	1.96	0.63	9.73
Cycle 5	7.14	1.94	0.60	9.68

Appendix 8 Trees with DBH lower than 10

Type	Number	Percentage
Total	167	100%
LH	128	76.6%
MH	32	19.2%
HH	6	3.6%
NC/Unknown	1	0.6%
AV growth	0.39	

Appendix 9 Plot locations