Forest management for climate change mitigation: Cases from Indonesia

Yonky Indrajaya

PROPOSITIONS

1. More realistic models give better guidance to decision-makers to identify the best management option but may hamper the understanding of mechanisms at work.
   (this thesis)
2. The ability of managed tropical forests to store carbon is grossly underestimated.
   (this thesis)
3. Lock-down and home office reduce pressure on the environment and trigger a change of human-nature interaction in the long run.
4. As do-it-yourself information becomes more readily available through the internet, the availability of jobs in the service sector declines.
5. Working separated from one's family allows being more productive but hampers opportunities for stress-relief.
6. A longer time to study towards a PhD degree leads to a more capable researcher.

Propositions belonging to the thesis, entitled

"Forest management for climate change mitigation: Cases from Indonesia"

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Wageningen, 6 September 2022

Forest management for climate change mitigation: Cases from Indonesia

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Table of Contents

List of Figures

List of Tables

List of Appendices

CHAPTER 1

1

Chapter 1. General Introduction

1.1. Background

Forests, which cover nearly a third of the Earth's land area - just over 4 billion hectares (FAO 2020) - play an important role in the global carbon cycle (Canadell and Raupach 2008) and are home to a significant portion of the world's terrestrial biodiversity (Betts et al. 2017). Forests provide a wide range of other ecosystem services, including supporting services like nutrient cycling and soil formation (Vitousek and Sanford 1986; Attiwill and Adams 1993; Foster and Bhatti 2006; Šamonil et al. 2010); provisioning services like food (Dlamini 2020), timber (Burgess 1993), and medicinal plants (Caniago and Stephen 1998; Begossi et al. 2002); and regulating services like erosion control (Vatandaşlar et al. 2020), flood mitigation (Calder and Aylward 2006), water and air purification (Lee 1997; Song et al. 2016; Vilhar 2017), pollination (Taki et al. 2007), and pest and disease control (Reid et al. 2005; Ji et al. 2011). Carbon sequestration, the removal of carbon from the atmosphere and its long-term storage in biomass, dead organic matter, and soil carbon pools, is one of the most important supporting services supplied by forests in times of global warming (Canadell and Raupach 2008; Pan et al. 2011).

FAO (2020) reports that over the period 1990-2020, the rate of net forest loss fell significantly due to reduced deforestation in some countries and increases in forest area in others due to afforestation and natural forest expansion. Net forest loss decreased from 7.8 million hectares per year between 1990 and 2000 to 5.2 million hectares per year between 2000 and 2010 and 4.7 million hectares per year between 2010 and 2020. Moreover, FAO (2020) also reports that the total carbon stock in forests fell from 668 Gt carbon (C) in 1990 to 662 Gt C in 2020, while carbon density increased from 159 to 163 tonnes per ha during the same period. An estimated 55% of worldwide forest carbon stocks are stored in (sub-)tropical forests, with more than half of that stored in biomass (Pan et al. 2011). Tubiello et al. (2021) report that the worldwide emissions from net forest conversion decreased significantly, from 4.3 Gt carbon dioxide (CO_2) per year (equal to 1.17 Gt C) in 1991-2000 to 2.9 Gt CO_2 (equal to 0.79 Gt C) per year in 2016-2020.

In the tropics and subtropics, deforestation and forest degradation have significant detrimental impacts on terrestrial biodiversity (Parrotta et al. 2012; Vijay et al. 2016; Giam 2017). Deforestation increases the likelihood of a species being listed as threatened or being listed in a higher threat category or having a diminishing population (Tracewski et al. 2016; Di Marco et al. 2018). More significantly, these dangers are disproportionately greater in comparatively unaltered areas; even minor deforestation has had devastating effects on vertebrate species (Betts et al. 2017). In Borneo, the center of the Amazon and the Congo Basin spatial analyses show high-risk hotspots. Under current rates of forest loss, Betts et al. (2017) project that 121-219 vertebrate species will become vulnerable in these regions during the next 30 years.

Over a period of 15 years (2001-2015), deforestation due to permanent land-use change for the cultivation of agricultural crops accounts for 27% of global forest loss; the remaining areas which maintained the same land-use, the forest loss was attributable to harvest (26%), shifting agriculture (24%), and forest fire (23%) (Curtis et al. 2018). IPCC (2021) estimates that Agriculture, Forestry, and Other Land Use (AFOLU) activities accounted for around 13% of CO_2, 44% of methane, and 82% of nitrous oxide emissions from human activities between 2007 and 2016, accounting for 23% (12.0±3.0 $GtCO_2e$ per year) of total net anthropogenic greenhouse gas (GHG) emissions. Pan et al. (2011) estimate a total global forest sink of 2.4 Gt C per year from 1990 to 2007. They also estimate a source of 1.3 Gt C per year from tropical land-use change, offset mainly by a carbon sink in tropical forest regrowth of 1.6 Gt C per year.

Indonesia is committed to contributing to climate change mitigation and adaptation in line with the balance between the current and future development and poverty reduction priorities (Government of Indonesia 2016). In 2018, Indonesia's national greenhouse gas (GHG) emissions were 1.637 Gt CO_2e, increase of 0.451 Gt CO_2e from GHG emissions in 2000 (Ministry of Environment and Forestry 2020). Land-use change and peat and forest fires account for the majority of emissions (63%), with fossil fuel combustion accounting for about 19% of total emissions. According to Indonesia's First Biennial Update Report (BUR), which was submitted to the United Nations Framework Convention on Climate Change (UNFCCC) in January 2016, national GHG emissions in 2012 were 1.453 Gt CO_2e, up 0.452 Gt CO_2e from 2000. In 2021, Indonesia submitted the Nationally Determined Contribution (NDC) in COP 22. The Business as Usual (BAU) scenario was set at 2.869 Gt CO_2e in 2030 (Government of Indonesia 2021). The biggest contributors were land-use change and forestry (LUCF), which included peat fires (47.8 %) and energy (34.9 %). Indonesia has promulgated relevant legal and policy instruments, including the national action plan on GHG emissions reduction and GHG inventory as stipulated in Presidential Decree number 61/2011 (Government of Indonesia 2011), since it voluntarily pledged to reduce emissions by 26% on its own efforts, and up to 41% with international support, by 2020, compared to the business as usual scenario. Indonesia plans to go beyond its current commitment to carbon reductions after 2020. Indonesia has established an unconditional reduction objective of 29% and a conditional reduction target of up to 41% of the business as usual scenario by 2030, based on the country's most recent emissions level assessment (Ministry of Environment and Forestry 2021).

1.2. Forest management in the global context

Around 1.15 billion hectares of forest are maintained for the production of wood and non-wood forest products around the world (FAO 2020). In addition, 749 million hectares are set aside for different uses, including agriculture. Since 1990, the area of forest devoted only to production has been largely constant, but the area of multiple-use forest has dropped by around 71 million ha (FAO 2020). A total of 424 million hectares of forest have been set aside for biodiversity conservation around the world. Since 1990, 111 million hectares have been designated as such, the majority of which was awarded between 2000 and 2010. In the last 10 years, the rate of growth of forest areas designated largely for biodiversity conservation has slowed down.

Forests provide a wide range of products (e.g., wood, resin, leaves) and services (e.g., biodiversity, carbon storage, watershed protection). Different types of forest management are applied globally across forests to provide one (usually timber production) or more products or services (Schulze et al. 2019). Schulze et al. (2019) distinguish two different forest management types, the so-called "conventional", aiming at timber yields and harvest efficiency, and the "alternative" type, aiming at more diversity in age, species, and structure. These two types of forest management have been implemented globally. For Europe, Schulze et al. (2019) revised the classification of Duncker et al. (2012): conventional forest management refers to high management intensity and alternative forest management to low management intensity. In the tropics, in natural forests with a wide variety of species, only a few species are harvested for timber production (Chaudhary et al. 2016). Here selective logging with high intensity and heavy machinery corresponds to "conventional", and logging with improved planning and reduced impact practices corresponds to "alternative" forest management.

There are a variety of management approaches available, each with a different level of potential for balancing human economic needs with the well-being of ecological systems. Rotation forestry management (RFM) and continuous cover forest management (CCF) are the two broad categories of forest management approaches (Schütz et al. 2012). RFM is distinguished by three distinct development phases: establishment, thinning, and clear-felling, while in CCF, at least two of these phases, if not all three, occur concurrently. CCF is defined as "the avoidance of clear-felling of areas much more than two tree heights wide without the retention of some mature trees," Pukkala (2016) observes that there is a global trend in forest management, away from clear-felling and plantation forestry to continuous cover forestry (CCF). The even-aged monocultures in plantation forests are no longer considered the best management practice when all ecosystem services are considered (Fürstenau et al. 2007).

1.3. Theory of forest management

Optimal forest management is related to the general theory of the intertemporal allocation of resources since there are long time spans between planting and harvesting. Faustmann (1849) was the first to develop a theory of optimal harvesting and replanting of a forest. However, his work remained largely unnoticed and was forgotten for more than a century (Löfgren 1983). Only after Samuelson (1976) had argued that Faustmann had correctly solved the problem of repeated investments, thereby determining the optimal steady-state cutting cycle (i.e. rotation), of a forest stand, hundreds of papers on Faustmann-type rotation models were published (Newman 2002). Forest rotation theory can be grouped into two schools, namely an "ecologists" and an "economists" school (Amacher et al. 2009). The "ecologists" use biological features to define the preferred rotation age. The most commonly used criterion for the optimal rotation is the maximum sustained yield (MSY), where the forest should be harvested at the time when the mean annual increment (MAI) is equal to the current annual increment (CAI) (Amacher et al. 2009; Bettinger et al. 2016). Forest management based on these concepts boils down to maximizing the timber volume produced on a given area of forest land over time. The "economists", in line with Faustmann (1849), determine the optimal rotation of a forest by maximizing profits from forest land over time.

The traditional Faustmann approach was used by forest managers to model timber production on forest land with no alternative land-use option (Amacher et al. 2009). A forest manager starts with planting trees on bare land with certain planting costs. The timber volume of the trees grows over time. At the time of harvest, the manager receives revenue from the timber sales at the certain timber price net the harvesting cost. After the harvest, the land is replanted again, and the cycle repeats. Appendix 1.1 presents Faustmann's seminal model in more detail. Faustmann (1849) recognized the relevance of opportunity costs for determining the most advantageous silvicultural system and forest rotation. A later (earlier) harvest will not only imply that the current harvest is postponed (advanced) but also replanting, and therefore, the next harvest is also postponed (advanced) and so on. Ohlin (1921) established mathematical prerequisites and economic justifications for an optimal forest rotation when prices, costs, growth function, and interest rate are known and unchanging over time (Löfgren 1983). Under these assumptions, the cutting cycle should remain constant over time. The interpretation of the Faustmann rotation is that the forest should be harvested at that time T when the marginal increase in value from further growth just equals the opportunity cost of delaying the harvest (Bowes and Krutilla 1985).

Faustmann's approach was initially applied in even-aged forest stands. Later it was generalized to uneven-aged forests (Chang 1981; Buongiorno and Lu 1990; Tahvonen 2009) and multi-age multi-species forests (Ingram and Buongiorno 1996). In multi-age forests, forest growth is usually represented by a transition matrix representing forest growth. This matrix is often used in the multi-age forest (Buongiorno and Michie 1980) and multi-age multi-species forest (Mendoza and Setyarso 1986; Sist, Picard, et al. 2003; Martin Bollandsås et al. 2008).

Gaffney (1957) and Pearse (1967) later evaluated the key conditions for optimal forest rotation using marginal (neo-classical) methodologies and established that they were identical to the criteria identified by Faustmann. In the 1970s-2000s, modified economic rotation formulations incorporating input and price uncertainty, market failures, and multiple values have dominated forest economics research. These models include not only single-stand and single-criterion models, but also multi-stand and multi-criteria models and include the economic value of ecological and environmental goods and services (Kant 2003). By and large, all of these fundamental components of forest economics have been developed within a neo-classical economic philosophy, defined by rational agents (*homo-economicus*) maximizing utility (or profit) and interacting on markets governed by an 'invisible hand' to achieve an efficient equilibrium. Under this notion, people's preferences are static, and no institution other than the market is involved.

Economic models built on a neoclassical paradigm have significant constraints but many economists have suggested alternative economic models that overcome some of the neoclassical paradigm's drawbacks and incorporate behavioral characteristics of people involved (Kant 2003). Several heterodox strands of economics, such as ecological economics, socio-economics, behavioral economics, and evolutionary economics, have challenged the concepts of static and well-ordered preferences and the maximizing agent. Recent works have proposed agent-based models that are flexible in capturing arbitrary behavioral traits of agents (Dislich et al. 2018; Suwarno et al. 2018). Game-theoretic models have been constructed to comprehend and explain co-operative and non-cooperative strategic behaviors of people in various circumstances. However, in the domain of forest economics, no considerable effort has been made to incorporate the concepts and principles coming from these new economic ideas. This kind of criticism applies more to explanatory models that are made to understand forest managers' behaviors. However, the main purpose of this thesis is on the normative side, i.e., to determine optimal management.

Some non-timber benefits like carbon (C) sequestration are external benefits that cannot usually be appropriated by the (private) forest owner. Therefore, the owner's management plan prioritizes the value of a forest as a source of timber. Thus, managing forests only for the goal of producing timber may result in socially inefficient woodland management (Tassone et al. 2004; Perman et al. 2011). Non-timber benefits, which may have a substantial impact on the optimal harvesting age, must be taken into consideration in order to make a socially efficient decision (Bowes and Krutilla 1985). For a welfare assessment, then, of forest management options, a social planner's perspective is adopted. A social planner is conceived as a welfare-maximizing decision-maker who takes into account all benefits and costs of parties concerned.

The forest manager or landowner has a narrower perspective and would harvest a stand of trees when the sum of the marginal harvest revenue from delaying harvest for one period is equal to the opportunity cost of delaying harvest, where the opportunity cost is defined as the rent on stand value (timber plus non-timber benefits) plus the rent on land value. If the marginal valuation of the landowner increases (or drops) with rotation age, the rotation age is longer (or shorter) than the Faustmann rotation age that only takes timber values into account (Amacher et al. 2009).

As forests may also produce non-timber benefits, Hartman (1976) adds a flow of non-timber benefit values to the Faustmann model (see Appendix 1.1). Because the forest service of carbon sequestration is one of the positive externalities, the forest owner and the social planner may manage a forest differently. Non-timber benefits from the forest may increase, decrease, or remain constant as the age of a forest stand progresses. All of these cases necessitate reasonable non-timber benefit function specifications for empirical simulations. Non-timber value functions must be calibrated to obtain meaningful monetary estimates to be able to aggregate different timber and non-timber values for optimal management.

The Faustmann-Hartman model has been widely applied in various non-timber benefits such as resin production, carbon sequestration, habitat provision for biodiversity, or water regulation in different types of forests (e.g., monoculture vs. mixed-species, even-aged vs. uneven-aged). Hampicke (2001) discusses various obstacles in applying the Faustmann-Hartman approach to conservation policies, i.e., considering biodiversity. Koskela et al. (2007) analyzed the optimal rotation age of boreal forest with the Hartman model and found that biodiversity conservation may lengthen the socially optimal rotation age, and biodiversity benefits may even mean that non-harvest is optimal. A Faustmann-Hartman model with biodiversity service was also applied in uneven-aged (Buongiorno et al. 1994) and multi-age multi-species tropical forests (Ingram and Buongiorno 1996).

Among other forest services, the carbon sequestration service is the most discussed service in the recent literature, in particular after parties agreed to the Kyoto Protocol in 2002. The forestry projects (e.g., afforestation/reforestation) under the Clean Development Mechanism (CDM) of the United Nations Framework Convention and Climate Change (UNFCCC) were widely discussed in the literature. Most studies of forestry projects under CDM in the even-aged forest use the Faustmann-Hartman model (Van Kooten et al. 1995; Huang and Kronrad 2001; Diaz-Balteiro and Rodriguez 2006; Köthke and Dieter 2010; Assmuth and Tahvonen 2018). Other papers applied the Faustmann-Hartman model with carbon service to uneven-aged (Buongiorno et al. 2012) and multi-aged multi-species of tropical forest (Indrajaya et al. 2016).

The Faustmann-Hartman model has not only been used to analyze single non-timber services (e.g., biodiversity or carbon sequestration, or other services) but also multiple non-timber forest services (e.g., water and carbon sequestration). For example, Creedy and Wurzbacher (2001) analyze a forested watershed's economic value with timber, water, and carbon sequestration benefits using the Faustmann-Hartman model.

1.4. Optimal forest management with additional income from carbon sequestration

Optimal forest management with additional income from carbon sequestration has been widely discussed in the literature (Susaeta et al. 2014; West et al. 2019). The results obtained are based on carbon payment schemes employing specific carbon accounting methods. The first two carbon accounting methods under the IPCC that appeared in 2000 are the stock-change method and the average-stock method (IPCC 2000). The stock-change method estimates the carbon stocks in any period over the duration of a forest project. It applies when forests are planted solely for carbon sequestration and are never harvested. In this case, the total carbon benefits of a project are equal to the difference in carbon levels between the baseline and the project scenario, as determined at the end of the project (IPCC 2000). Carbon uptake payments are made until the forest has reached a stable level. The disadvantage of this method is that it does not account for potential carbon emissions when trees burn or die. By contrast, the average-stock method estimates the average amount of carbon in a forest over the project time.

The average-storage method is applicable when forests are planted, harvested, and replanted. Carbon uptake payments are made until the forest reaches the average storage level (IPCC 2000).

In 2000, at the Sixth Conference of the Parties (COP6), the Colombian government proposed that Certified Emission Reductions (CER) expire (IISD 2000). This resulted in a decision by the Ninth Conference of the Parties (COP9) in December 2003 that CER arising from CDM sink projects would be considered non-permanent, and two methods for accounting CER would be valid: temporary and long-term crediting (tCER and lCER, respectively). A temporary credit (tCER) is a CER issued under the CDM for an afforestation project activity that expires at the end of the commitment period following the one in which it was issued (UNFCCC, 2003). A long-term credit (lCER) is similar to a tCER, but it expires at the end of the afforestation project's crediting period. Under both accounting systems, the crediting period for an afforestation project should be either (i) a maximum of 20 years that can be renewed twice or (ii) a maximum of 30 years. The primary distinction between tCER and lCER is the expiration date: the former expires at the end of commitment periods, while the latter expire at the end of credit periods. In most cases, lCER credits would have a longer expiration date than tCER credits. In addition to accounting rules, COP9 mandates that tCER and lCER be verified and certified every five years.

Some authors have studied the effect of tCER and lCER for the optimal forest rotation (Olschewski and Benitez 2010; Galinato and Uchida 2011). Previous studies on the effects of remuneration for carbon sequestration on the optimal rotation focus on afforestation/reforestation activities (these activities are agreed as the forest activities under CDM for climate change mitigation) with carbon accounting of stock change method (Van Kooten et al. 1995; Huang and Kronrad 2001; Diaz-Balteiro and Rodriguez 2006; Köthke and Dieter 2010; Assmuth and Tahvonen 2018). The average stock method is currently used in the voluntary carbon market (Vacchiano et al. 2018; West et al. 2019). The general findings in this literature are that the optimal forest rotation is always longer than the Faustmann rotation (i.e., the optimal rotation with only timber as the source of income) if carbon has value (see Appendix 1.1).

Plantinga and Birdsey (1994) argue that the optimal rotation is almost always infinite when only carbon is valued. That is, harvesting is never the best option. This outcome is contingent on society's preference for carbon sequestration benefits over time. Harvesting is generally optimal if only timber is valued. As a result, the socially optimal rotation, which includes carbon and timber benefits, lies between these two rotations. As a result, carbon benefits on private lands are likely to be undersupplied in terms of social welfare. Furthermore, if the benefits from carbon outweigh the benefits from timber, it may be socially optimal never to harvest forest stands (Van Kooten et al. 1995; Price and Willis 2011).

1.5. Improved forest management under REDD+

Reducing emissions from deforestation and forest degradation and fostering conservation, sustainable management of forests, and enhancing forest carbon stocks (REDD+) has been agreed upon as one of the mitigation approaches under the UNFCCC in 2007 (Maniatis et al. 2019). However, after the expiration of the first commitment period of the Kyoto Protocol in 2012 and the uncertainty of the implementation of the Paris Agreement, the only option for carbon sequestration from forestry activities is from voluntary carbon trading (Vacchiano et al. 2018). Although some European countries and Australia have agreed to jointly reduce the emission in the second commitment of Kyoto (2013-2020), the Land Use, Land Use Change and Forestry sector (LULUCF) was excluded in this second commitment period (Vacchiano et al. 2018; Matthews 2019). In the period of 2021-2030, LULUCF will be included in the EU's climate regime. The Council and Parliament have agreed on a number of pieces of legislation that establish the framework for measuring and monitoring emissions from the LULUCF sector, as well as the role they will play in meeting the EU's 2030 targets (Matthews 2019). One of the forestry activities under the voluntary market is improved forest management (IFM), that is, forest management that increases the carbon stock in the forest (by better logging practices, longer rotations, or other means) (Olander et al. 2010; Vacchiano et al. 2018). IFM and REDD+ were outside of the scope of the compliance market, i.e., CDM, before 2020 (van der Gaast et al. 2018) and seem to remain outside the compliance market due to the uncertainty of the Paris Agreement implementation (Vacchiano et al. 2018)

Better logging practices in multi-age multi-species tropical forests have already been introduced in the 1990s, known as Reduced Impact Logging (RIL). However, without any incentives for RIL adoption, restrictions on harvesting steep slope forests and prohibition of ground-based timber yarding, companies will continue to use conventional logging in their logging practices (Putz et al. 2000). Nevertheless, through intensively planned and carefully controlled timber harvesting conducted by trained workers, RIL may reduce the residual stand's damage and, therefore, reduce carbon emissions (Zimmerman and Kormos 2012). Putz et al. (2008) and Griscom et al. (2013) estimate that improved tropical forest management with RIL adoption may reduce carbon emissions by approximately 30-50% relative to conventional logging (CL). With this potential emission reduction, Griscom and Cortez (2013) argue that IFM should be a priority of the REDD+ strategy because it can (i) achieve robust emission reductions without generating leakage or risk of non-permanence, (ii) generate a variety of local community benefits as a low-carbon development strategy, (iii) maintain native forest biodiversity, and (iv) reduce the likelihood of deforestation.

Extending forest rotation is an important forest management option that may generate carbon credits under REDD+ (Vacchiano et al. 2018; West et al. 2019) because extending forest rotation increases carbon stock in the standing forest (see Appendix 1.1). The carbon accounting method used in extending forest rotation projects under the voluntary market is the average-stock method. The most prominent carbon remuneration scheme is the Verified Carbon Standard (VCS).

The CDM in the compliance market and VCS in the voluntary market are the two most crucial carbon credit mechanisms until recently (Lee et al. 2018; Von Avenarius et al. 2018).[1,2] More than 70% of the voluntary market uses the VCS standard for the development of carbon sequestration projects (Lee et al. 2018). In addition, VCS accepts afforestation, reforestation, and revegetation (ARR), IFM, and REDD projects.

1.6. Research objective

This thesis studies optimal forest management of plantation forests and multi-age multi-species forests under the climate change mitigation regime in Indonesia. As one of the largest GHG emitting countries, Indonesia focuses LULUCF activities in reducing its GHG emissions by reducing forest and peat fires, reducing deforestation, and improving forest management. Therefore, this thesis aims to analyze the optimal management of production forests (i.e., forests designated for wood production) with additional income from carbon storage. Numerical optimization models based on detailed data were developed to achieve this objective. I approach this objective starting with carbon sequestration in a single species plantation forest for wood production. Then I introduce further complexities, such as multiple-use and multi-species forests. More specifically, I address the following research questions:

[1] After the expiration of the second commitment of Kyoto Protocol in 2020, parties agreed that it would not be efficient to have the CDM running indefinitely and in parallel with the Article 6.4 mechanism of the Paris Agreement , especially if both mechanisms have similar objectives and scope. Article 6.4 establishes a new, unnamed multilateral mechanism that resembles the function of the CDM.

[2]A compliance market is a market for carbon offsets created by the need to comply with a regulatory act. Companies and governments who are required by law to account for their GHG emissions use the compliance market. Mandated carbon reduction regimes govern it at the national, regional, and international levels.

1. How would the incentives for carbon storage change the optimal forest management of a short-rotation plantation in Indonesia? How efficient is the Verified Carbon Standard (VCS) remuneration scheme in incentivizing forest managers to lengthen the rotation?

The current global agreement (Paris Agreement) in climate change mitigation, which explicitly includes REDD+ as part of the agreement, has the potential to incentivize carbon sequestration to extend the forest rotation in plantation forests. Recently, the voluntary carbon remuneration schemes have issued a more significant portion of carbon credits than the compliance schemes (Santikarn et al. 2020). The most important voluntary carbon remuneration scheme is VCS (Santikarn et al. 2020). I analyze the cost-effectiveness of the application of VCS on a short-rotation plantation forest in Indonesia. By answering this research question through a case study in a short-rotation plantation forest in the tropical region, I can provide guidance to forest plantation managers who would change forest management to make it "climate-smart" (i.e., a targeted approach or strategy to increase the climate benefits from forests and the forest sector, in a way that creates synergies with other needs related to forests).

2. How do multiple uses affect the optimal forest management decisions in plantation forests with different soil conditions?

Plantation forests can be designated for wood production only or include non-timber forest products (NTFP). Additional income from NTFP – here I look at resin and carbon services – may change a plantation forest's optimal management compared to a forest with timber as the only source of income. Different soil conditions, represented by site classes, that affect pine forest growth are also analyzed and discussed in optimal forest management. By answering this research question, forest managers gain insight into the contribution of income sources from timber and NTFP to overall profits and how the presence of a second NTFP (i.e., resin) affects the optimal rotation of a carbon credit scheme.

3. How do incentives from REDD+ affect the optimal management of a multi-age multi-species forest in Indonesia?

REDD+ can incentivize carbon sequestration in the multi-age multi-species forest in Indonesia that mainly applies conventional logging (CL). The implementation of reduced-impact logging (RIL) by intensively planned and carefully controlled timber harvesting conducted by trained workers reduces damages to the residual stand. It, therefore, increases the amount of carbon stored in forest biomass. By incentivizing improved forest management, the REDD+ scheme has the potential for financing RIL implementation that reduces forest degradation. By answering this research question through a systematic study, the REDD+ potential for tropical forest management can be better understood. Moreover, I analyze the conditions under which tropical forest managers would change the logging technique from CL to RIL. The carbon supply curve for carbon sequestration under REDD+ is also provided.

4. How do logging damage and injured trees in the selective logging system affect stand composition, carbon stored in aboveground biomass, and ultimately optimal management decisions?

Selective logging activities in tropical forests cause damage to the residual stand and reduce the pool of stored carbon. Conventional logging (CL), when workers lack training and preparation, causes more extensive damage and injured trees in the residual stand than RIL. The harvest damage and injured trees play an essential role in forest growth, stand composition, and carbon stored in aboveground biomass. A model that explicitly takes the role of harvest damage and the biophysical and economic effects of the presence of injured trees into account will help improve forest management such as regarding the harvesting intensity and cutting cycle.

1.7 Outline of the thesis

Chapters are organized as follows. Chapter 2 studies the impact of forest carbon remunerations on rotations and the cost-effectiveness of the VCS. Chapter 3 elaborates on the multi-use forest management of a pine forest plantation with different soil conditions (site classes). Chapter 4 analyzes the effects of carbon incentives under REDD+ on the optimal multi-age, multi-species tropical forest management. Chapter 5 investigates the role of logging damage and injured trees for the stand composition and carbon sequestration and its effect on the optimal forest management in the multi-age, multi-species tropical forest. Chapter 6 summarizes the findings and discusses recommendations for policy and further research.

Appendix 1.1. Derivation of the Faustmann rotation

Under the assumption that prices, costs, growth function, and interest rate are known and unchanging over time, also the optimal cutting cycle would not change over time. A forest manager begins by planting trees on bare land at a cost of C. The volume of timber $V(t)$ increases over time. The manager receives revenue $PV(T)$ after clear-cutting at the time of harvest $t = T$, where P is the net price of timber, and r is the discount rate. The problem is to find the rotation T that maximizes the present value π of the current and all future harvest cycles:

$$\pi(T) = \max_{T} \left\{ \frac{PV(T)e^{-rT} - C}{1 - e^{-rT}} \right\} \tag{1.1a}$$

$$\Leftrightarrow \pi(T) = \max_{T} \left\{ \frac{PV(T) - C}{e^{rT} - 1} - C \right\} \tag{1.1b}$$

Differentiating 1.1b with respect to T and setting the result equal to zero gives

$$\frac{PV'(T)}{PV(T) - C} = \frac{re^{rT}}{e^{rT} - 1} = \frac{r}{1 - e^{-rT}} \tag{1.2a}$$

The alternative version of the first-order condition for the maximization problem in Equation (1.1a) is:

$$PV'(T) = \frac{r(PV(T) - C)}{1 - e^{-rT}}$$

$$PV'(T) = \frac{rPV(T) - rPV(T)e^{-rT} + rPV(T)e^{-rT} - rC}{1 - e^{-rT}}$$

$$PV'(T) = \frac{rPV(T)\left(1 - e^{-rT}\right) + rPV(T)e^{-rT} - rC}{1 - e^{-rT}}$$

$$PV'(T) = rPV(T) + r\left(\frac{PV(T)e^{-rT} - C}{1 - e^{-rT}}\right)$$

$$PV'(T) = rPV(T) + r\pi \tag{1.2b}$$

Either version of Equation (1.2) is the efficiency condition for present-value-maximizing forestry, and implicitly determines the optimal rotation length in an infinite rotation model with constant prices and costs. Given knowledge of the function $V = V(t)$ and values of P, r, and C, one can deduce which value of T fulfils Equation (1.2a) (assuming the solution is unique, which it usually will be). The term in Equation (1.2b) is known as the site value or capital value of the land. This site value is equal to the maximum present value of an infinite number of rotations.

Hartman (1976) adds non-timber service values related to the age of the standing stock to the basic Faustmann timber harvesting problem. Let us denote N as the value of non-timber products. The benefits flowing from a hectare of standing stock of age τ is represented by $a(\tau)$.

The integral $\int_0^T (a(\tau)e^{-r\tau})d\tau \equiv N(T)$ then represents the present value of these non-timber values from a single forest rotation of T years. Starting with a single unstocked hectare, the problem is to select the harvest age T that maximizes the combined present value of timber and non-timber benefits from current and future harvest cycles. Again, the problem is to find the rotation T that maximizes the present value π of the current and all future harvest cycles

$$\pi = \max_T \{(PV(T)e^{-rT} + N(T) - C)/(1 - e^{-rT})\} \tag{1.3}$$

The first-order condition of the maximization problem (1.3) gives

$$PV'(T) + N'(T)e^{rT} = rPV(T) + r\pi \tag{1.4}$$

The interpretation of Equation (1.4) is similar to Equation (1.2b). It says that at the time of optimal harvest the marginal benefit of delaying harvest is equal to the opportunity costs of the revenue from the harvested timber and the forest land. The benefits of delay include the increment in the value due to timber growth and the non-timber benefits that accrue during the period of delay (Bowes and Krutilla 1985). Non-timber benefits affect the optimal rotation through two different channels (Amacher et al. 2009; Perman et al. 2011):

- The marginal value of the flows of non-timber benefits over a rotation;
- On the right-hand side of Equation (1.4) positive non-timber benefits increase the total value of land and hence the opportunity cost of maintaining timber on the land; this tends to reduce the rotation interval.

Both effects work in opposite directions. Koskela and Ollikainen (2001) show that if the non-timber benefit function $a(\tau)$ is constant, i.e. non-timber benefits are independent of the age of the stand, then the rotation length is unaffected. If, however, $a(\tau)$ is an increasing function of the age of the stand, then the value of waiting dominates the opportunity cost and the optimal rotation is lengthened compared to the optimal rotation for timber harvest only. Likewise, if $a(\tau)$ is a decreasing function of the age of the stand, then the value of waiting is dominated by the opportunity cost and the optimal rotation is shortened.

This result has an unambiguous implication for carbon sequestration services of the forest. As long as the forest grows and biomass accumulates, carbon storage is increasing over time and thus accounting for the benefits from carbon storage will lengthen the optimal rotation compared to the optimal Faustmann rotation when only timber is valued.

CHAPTER 2

2

Chapter 2. Cost-Effectiveness of Forest Carbon Remuneration: Verified Carbon Standard (VCS) Credits for Indonesian *Acacia mangium*[1]

Abstract

Forests play an essential role in climate change mitigation by absorbing carbon dioxide from the atmosphere and storing carbon in biomass. The extension of rotation cycles in existing plantation forests fosters carbon sequestration. This study examines the cost-effectiveness of the remuneration scheme employed by Verified Carbon Standard (VCS), a commonly used carbon accounting method based on the average amount of carbon stored in the forest. We compare the net present value of carbon remuneration under VCS with those of a scheme that remunerates actual carbon storage in each year, i.e., a theoretically ideal scheme that uses current carbon accounting. We use data for an *Acacia mangium* plantation in Indonesia, where the forestry sector is expected to contribute more than half of the reductions of carbon emissions according to Indonesia's Intended Nationally Determined Contribution (INDC) under the Paris Agreement. For our baseline scenario, we find, first, that the payments needed to incentivize additional carbon storage under VCS are considerably higher than under current carbon accounting. Second, the inefficiency is more pronounced at lower discount rates. Third, recent prices reported for VCS forest credits are not sufficient to incentivize forest managers to lengthen the forest rotation in Indonesian plantation forests.

Keywords: carbon sequestration, improved forest management, plantation forest, cost-effectiveness, Faustmann model, Hartman model, Verified Carbon Standard

2.1. Introduction

After the expiration of the first commitment period of the Kyoto Protocol in 2012, voluntary carbon trading has gained importance in rewarding carbon sequestration through forest activities (Vacchiano et al. 2018). In 2019, 65% of the annual carbon credits were issued under independent mechanisms associated with voluntary markets, an almost a fourfold increase compared to 2015 (Santikarn et al. 2020). Among the voluntary carbon trading schemes, the forest sector has seen a rising importance and is currently the largest sector in terms of issued carbon credits, ahead even of renewable energy (Santikarn et al. 2020). Verified Carbon

[1] Paper by Yonky Indrajaya, Frits Mohren, Hans-Peter Weikard & Edwin van der Werf, submitted

Standard (VCS) is the largest crediting scheme in this sector and, in 2019, released more credits (Verified Carbon Units, VCUs) than the Clean Development Mechanism (CDM) (Santikarn et al. 2020). For forestry activities, VCS accepts Afforestation, Reforestation, and Revegetation (ARR), Improved Forest Management (IFM), and Reducing Emissions from Deforestation and forest Degradation (REDD) projects (VCS 2017). In contrast to payments under the CDM, where amounts of carbon credited equal the total amount of carbon stored in forest biomass and hence only covers afforestation projects (Olschewski and Benitez 2010), VCS carbon accounting uses the average amounts of carbon stored in tree biomass (forest stand) above a baseline. Under VCS, carbon payment starts when the amount of carbon stored under the project is larger than under the baseline. It is thus suitable to incentivize forest management practices that increase carbon storage in existing forests.

According to its Intended Nationally Determined Contribution (INDC) under the Paris Agreement, Indonesia has committed to unconditionally reduce its net emission by 29% in 2030 compared to 2010 emissions (UNFCCC 2016). The forestry sector is expected to contribute more than half, 17.2 percentage points (Tacconi and Muttaqin 2019). Four forestry practices will help to mitigate climate change: (1) increasing forest areas through reforestation, (2) increasing carbon density in established forestland, (3) substituting fossil fuels by forest products, and (4) reducing emissions from deforestation and degradation (Canadell and Raupach 2008). The focus of our paper is on the second option. With currently existing plantation forests in Indonesia of about 11.6 million ha (Ministry of Environment and Forestry 2019), the extension of rotation cycles can considerably contribute to forest carbon sequestration.

Our study determines the minimum carbon payment needed to incentivize forest managers to lengthen the forest rotation and, hence, to sequester more carbon for two remuneration schemes. We compare the cost-effectiveness of VCS, which is based on *average* additional carbon storage over a rotation period, with that of an ideal remuneration scheme developed from Hartman's (1976) model of optimal forest management with non-timber benefits. In the latter scheme, carbon remunerations are based on the additional *current* carbon stock in each year. For both schemes, additionality is determined by comparison with a baseline consisting of the amount of carbon stored under an optimal rotation of forest managed for timber production only. Carbon stored under the baseline would not be eligible for remuneration (lack of additionality). We consider the case of an *Acacia mangium* plantation forest in Indonesia. *A. mangium* is one of the most planted tree species in Indonesia's plantation forests (Barry et al. 2004). Its main products are pulpwood and sawn wood (Krisnawati et al. 2011).

The difference between average (VCS) and current carbon accounting can be understood as follows. Under current carbon accounting, carbon additionality is calculated for each year (and may be negative in a given year). Under VCS, the carbon additionality is measured as the difference between the average of the amount of carbon stored over the rotation period of the VCS project and the average amount stored over the baseline rotation. The different carbon accounting methods and associated remuneration schemes affect the carbon payments received by forest managers and, therefore, may affect forest management decisions. We analyze an existing plantation forest that would not qualify for funding under CDM, which rewards carbon projects that started on bare land or other non-forested areas. West et al. (2019) use the average amount of carbon approach to analyze the optimal management of plantation forests of several tree species and find that planting slower-growing species is a more cost-effective strategy to increase forest carbon sequestration. Different from West et al. (2019), We compare the impacts of different accounting standards (current vs. average carbon stocks) in terms of cost-effectiveness for a given tree species.

This chapter contributes to the literature on forest carbon remuneration that builds on Hartman's (Hartman 1976) forest management model with non-timber benefits. In the literature, the Hartman model has been used to analyze optimal forest management when the value of carbon storage in a standing forest is accounted for (Englin and Callaway 1993; Plantinga and Birdsey 1994; Van Kooten et al. 1995; Tassone et al. 2004; West et al. 2019). The general finding is that the optimal forest rotation will be lengthened when carbon stored in tree biomass has value. In other words, carbon remuneration lengthens the rotation. We find that the current carbon remuneration scheme of VCS is less cost-effective than a remuneration scheme based on current accounting, which can be explained by the sub-optimal time structure of the remuneration payments.

The remainder of this chapter is organized as follows. The next section describes the economic optimization model for plantation forests, including carbon storage service, and introduces our measure of cost-effectiveness. In Section 3, we present the parameterization of the model for an Indonesian *A. mangium* plantation forest. We present our results in Section 4, including a sensitivity analysis. Section 5 offers a discussion. Section 6 concludes.

2.2. Model

2.2.1. Faustmann model

A traditional Faustmann (1849) model is used to determine a business-as-usual scenario (baseline) for optimal plantation forest management, not assuming any additional income from carbon storage. A Faustmann model only takes timber values into account:

$$NPV_{Faustmann} = \frac{p_w V(T) - \sum_{t=1}^{T} \kappa_t (1+r)^{T-t} - K(1+r)^T}{(1+r)^T - 1} \quad (2.1)$$

where $NPV_{Faustmann}$ is the net present value (NPV) from all future timber sales net of planting costs where p_w is the timber price per cubic meter, V represents the stumpage volume (m^3/ha), κ_t represents the maintenance costs at time t, K are planting costs, T is the optimal rotation age (Faustmann rotation), i.e., the harvest time that maximizes the net present value of the forest, and r is the discount rate relevant for the forest manager's decision making. The optimal Faustmann rotation constitutes our baseline (i.e., a business as usual scenario).

2.2.2. A model with annual carbon payments

We now introduce a Hartman model to explore optimal forest management with annual payments for carbon sequestration. Carbon storage in living biomass increases with tree growth. Revenues from payments for additional carbon stored in forest biomass can change the optimal rotation. The baseline against which the additionality of carbon storage is assessed is the amount of carbon stored in any given year in a forest without a carbon project, i.e., the Faustmann baseline described above. In our model, we account for the carbon stored in forest biomass, that is, aboveground biomass and roots (measured in ton CO_2); see Section 3 for details. We assume that verification and payments take place in every year t and we refer to this accounting scheme as 'current carbon 'accounting.' Such a scheme can be considered a theoretically ideal scheme as the payment scheme follows the time structure of carbon storage and the associated benefits. Following Hartman (1976), the NPV of timber and carbon stored in forest biomass under current carbon accounting is as follows:

$$NPV_{cc} = \frac{p_w V(T_{cc}) - \sum_{t=1}^{T_{cc}} \kappa_t (1+r)^{T_{cc}-t} - K(1+r)^{T_{cc}}}{(1+r)^{T_{cc}} - 1} + p_{cc} \sum_{t=1}^{\infty} \left(C_{\gamma_t} - C_{\delta_t} \right) (1+r)^{-t} \quad (2.2)$$

where NPV_{cc} represents the NPV of timber and carbon in forest biomass (above ground and roots) under the current carbon accounting system. The first and second terms on the RHS represent timber value and carbon value, respectively. The carbon price per ton CO_2 in the annual assessment of carbon stock is denoted as p_{cc}. Notice that this is a carbon price for storing one additional ton of CO_2 for one year.[2] $C_{\gamma t}$ indicates the amount of carbon stored in forest biomass in any year t under a forest carbon project, while $C_{\delta t}$ indicates the amount of carbon stored in year t under the Faustmann baseline. The optimal rotation of the current carbon approach is denoted as T_{cc}. Under the current carbon remuneration scheme, the forest manager will get paid when $C_{\gamma_t} > C_{\delta_t}$, and has to pay a fee when $C_{\gamma_t} < C_{\delta_t}$ (see Figure 2.1).

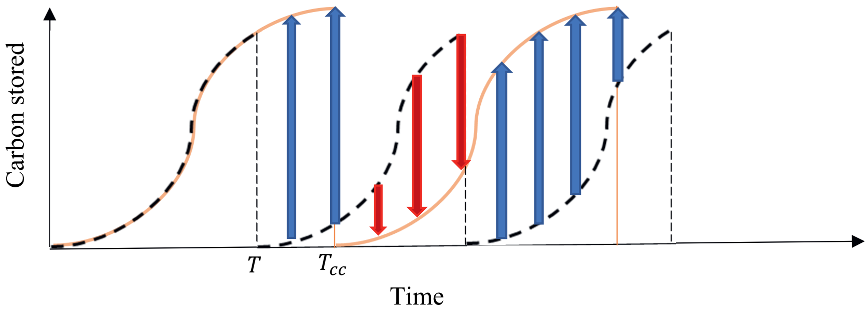

Figure 2.1. A Hartman model with the current carbon approach in an existing forest plantation. The upward blue arrows represent the carbon payment when the amount of carbon stored under the carbon project (i.e., orange solid lines) is larger than the amount of carbon stored under the Faustmann baseline (i.e., the dashed black lines). The downward red arrows represent the carbon fees to be paid when the amount of carbon stored under the carbon project is lower than the amount of carbon stored under the baseline.

2.2.3. VCS model

In contrast to a Hartman model with current carbon accounting, the total amount of carbon that can be credited under the VCS rules is based on the average amount of carbon stored in biomass within a certain rotation T_{ac} (i.e. $\frac{1}{T_{ac}}\sum_{t=1}^{T_{ac}} C_{\gamma_t}$). According to the VCS rules, the carbon payments are received for carbon *sequestered* in year t provided the total amount of carbon stored in that year exceeds the baseline average ($\frac{1}{T}\sum_{t=1}^{T} C_{\delta_t}$) and does not exceed the average amount stored under project rotation.[3] The payment scheme is illustrated in Figure 2.2.

[2] We express prices of carbon credits in US dollars per ton of CO_2, rather than per ton of C, to allow for comparison with prices that are observed on carbon markets. Note, however, that such prices would apply to carbon stored for one rotation (see below) or even permanently, not just for one year.
[3] Our design for the VCS model is based on the description of the VCS Methodology for Improved Forest Management through Extension of Rotation Age in VCS (2017).

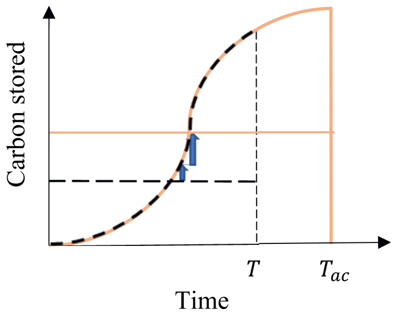

Figure 2.2. The VCS remuneration scheme for extending the rotation of an existing forest plantation forest. The average amount of carbon stored is represented by dashed black and orange horizontal lines for the baseline and for the VCS project. The vertical blue arrows represent the carbon payment received under the VCS scheme.

Formally, the value of the forest under VCS remuneration can be written as follows:

$$NPV_{ac} = \frac{p_w V(T_{ac}) - \sum_{t=1}^{T_{ac}} \kappa_t (1+r)^{T_{ac}-t} - K(1+r)^{T_{ac}}}{(1+r)^{T_{ac}}-1} + \frac{p_{ac} \sum_{t=1}^{T_{ac}} [max\Big(0,\ min(C_{\gamma_t},\ \frac{1}{T_{ac}} \sum_{\tau=1}^{T_{ac}} C_{\gamma_\tau}) - max(C_{\gamma_{t-1}},\ \frac{1}{T} \sum_{\tau=1}^{T} C_{\delta_\tau})\Big)(1+r)^{T_{ac}-t}]}{(1+r)^{T_{ac}}-1} \quad (2.3)$$

where NPV_{ac} represents the value of timber and carbon stored in forest biomass according to the VCS model and T_{ac} denotes the optimal rotation length under the' average carbon 'accounting' approach. The numerator of the first term in the RHS of Eq. (3) represents the timber value, while the numerator of the second term represents the value of carbon stored in forest biomass under VCS, each over one rotation. The denominators translate the values per rotation into net present values. The carbon price per ton CO_2 in forest biomass under VCS is denoted as p_{ac}. Notice that this is a carbon price for storing an additional ton of CO_2 over one rotation period. The amount of carbon stored in forest biomass at time t under the project is denoted as C_{γ_t}. Essentially the payment is received for an amount sequestered, $C_{\gamma_t} - C_{\gamma_{t-1}}$. The first max operator ensures that the payment received is always positive. In Eq. (3), the min operator limits the payments to the average amount stored under the VCS project. The second max operator ensures that sequestration payments are confined to amounts above the baseline average. By paying for the average additional carbon stored, VCS avoids having to demand payments back from the project manager in years where $C_{\gamma_t} < C_{\delta_t}$ as would be the case under current carbon accounting.

2.2.4. Cost-effectiveness and carbon discounting

Our objective is to assess the cost-effectiveness of the average carbon approach of VCS as compared to the current carbon accounting approach in which payments follow the time structure of carbon storage. We do so by comparing the remuneration payments specified in Sections 2.2 and 2.3. More specifically, we calculate and compare the minimum amount of carbon payment needed to incentivize a given amount of carbon sequestration in the forest under VCS and under the current carbon approach. Generally, carbon sequestration implies a lengthening of the rotation, and higher carbon payments will incentivize longer rotations with more carbon stored.

We also assess the accumulated amount of additional carbon under each approach by discounting the accumulated amount of carbon stored. Lengthening the forest rotation does not just imply that more carbon is stored; it also affects the timing of carbon storage. As carbon storage is viewed as a public service, the discount rate must reflect society's valuation of a marginal delay of that service (see Arrow et al., 1996, and Polasky and Dampha, 2021, for a recent survey). Generally, the level of the social discount rate has significant consequences for resource allocation. Setting the social discount rate too high can prevent beneficial public initiatives from being implemented, whereas setting it too low can result in the adoption of inefficient public projects. Furthermore, the higher the social discount rate, the more favorable are projects with net benefits that occur sooner as less weight is given to benefits and costs in the distant future. The social discount rate chosen affects not only the ex-ante decision of whether a particular public sector project merits funding but also the ex-post assessment of its results. For the social assessment of forest carbon storage, and from the perspective of a funding organization such as VCS, it matters when carbon is stored (Van Kooten et al., 2004). Under a positive discount rate, a ton of carbon stored earlier is worth more than a ton of carbon stored later. Hence, we calculate the discounted amount of physical carbon stored, DC, using the social discount rate i:

$$DC = \sum_{t=1}^{\infty}\left(C_{\gamma_t} - C_{\delta_t}\right)(1+i)^{-t} \qquad (2.4)$$

According to Richards (1997), if physical carbon is not discounted, damages from rising CO_2 concentrations in the atmosphere increase at the same rate as the social rate of discount. A positive discount rate on physical carbon is appropriate if damages rise faster than atmospheric CO_2. Because a zero discount rate on physical carbon implies that there is no difference between removing a unit of carbon from the atmosphere today, tomorrow, or at some future time, this could be extrapolated to conclude that it makes no difference whether the carbon is ever removed from the atmosphere. As a result, discounting carbon emphasizes the significance of any carbon sequestration, particularly that which occurs in the near future.

Notice that the discount rate relevant for the forest manager's decision is rate r which is determined by the private opportunity cost of capital. Usually $i \leq r$ (see Kula and Evans, 2011). Weikard and Zhu (2005) provide a comprehensive discussion of dual discounting.

2.3. Carbon accounting and parameterization

In our study, there are two carbon pools to consider: the aboveground biomass (C_{AGB}) and root biomass (C_{RB}). The weight of aboveground biomass (AGB_t) in year t is estimated by the following allometric equation:

$$AGB_t = V_t \rho \eta \tag{2.5}$$

where V_t is the merchantable timber volume per hectare at time t, ρ is wood density, and η represents the biomass expansion factor which is the ratio of the total aboveground tree biomass to the biomass of the merchantable timber. The weight of root biomass is predicted from the weight of aboveground biomass (Cairns et al. 1997):

$$RB_t = \exp(\alpha + \beta \ln AGB_t) \tag{2.6}$$

where RB_t represents the weight of root biomass at time t. The carbon dioxide stored in aboveground biomass and root biomass is:

$$C_{AGB_t} = AGB_t \theta \varepsilon \text{ ; } C_{RB_t} = RB_t \theta \varepsilon \tag{2.7}$$

where θ represents the fraction of carbon in tree biomass, and ε represents the weight ratio of the molecular mass of CO_2 and carbon.

We apply the forest growth model of an *A. mangium* plantation forest using the logistic growth function as suggested by Englin and Callaway (1993) based on Heriansyah et al. (2007), i.e.: $\ln V_t = 5.893 - 5.409\, t^{-1}$; see Appendix 2.1. For *A. mangium*, $\rho = 0.501$ (Zanne et al. 2009) and the biomass expansion factor η is 1.33 (Wicaksono 2004). The coefficients for root biomass estimation (Eq. 6) are based on Cairns et al. (1997) where $\alpha = -1.085$, and $\beta = 0.926$. The proportion of carbon in tree biomass is $\theta = 0.47$ (IPCC 2006), and the ratio of molecular mass of CO_2 to the atomic mass of carbon $\varepsilon = 44/12$.

The cost parameters are taken from the cost standard of forest plantations determined by the Indonesian Ministry of Forestry (2009c). The costs consist of multiple components, i.e., planning, infrastructure, administration, plantation, maintenance, forest protection and security, taxes, and obligation to the environment. The cost values are presented in USD of 2018, and they are the average value of the minimum and maximum costs as in the Ministry of

Forestry decree. The total cost of planting a 1 ha plantation forest is 1,326 USD (see Appendix 2.2). The net price of *A. mangium* timber is 29 USD per cubic meter.[4] Following Kula and Evans (2011), we use a lower discount rate for physical carbon values than for monetary values ($i < r$). We use an interest rate $r = 8\%$ for monetary values[5] (World Bank 2021), while we use a social discount rate $i = 3\%$ to discount physical carbon. The latter value is used by the UK Treasury (UK Treasury 2003) and is the (rounded) middle point of the upper and lower bounds of the mean value in a recent survey of experts on the social discount rate (Drupp et al. 2018). For the calculations, we use a time horizon of 300 years. For any time horizon beyond this, we observe only negligible changes in the numerical values obtained.

2.4. Results

In this section, we first present the results for the optimal management of *A. Mangium* without carbon payment, our baseline case. Next, we present the effect of carbon pricing and carbon payment schemes on the optimal rotation and the NPV of forest operations for both the current carbon scheme and for the VCS average carbon scheme.

2.4.1. Optimal forest management without carbon remuneration

Table 2.1 presents the results of optimal forest plantation management of *A. mangium* without carbon remuneration. The optimal rotation of *A. mangium* without carbon payment is seven years with a $NPV_{Faustmann}$ of 2,618 USD/ha. The rotation length commonly used for an *A. mangium* plantation for pulp production in Indonesia is 6-8 years (Krisnawati et al. 2011). This NPV is lower than what Cuong et al. (2020) report for Vietnam, i.e., 99.71 million VND/ha or about 4,000 USD/ha, but larger than what Tang et al. (2009) find for China, i.e., 2,375 Yuan/ha or about 370 USD/ha.

The mean annual increment (MAI) is 23.9 m^3/ha at year 7, with a total volume of 167 m^3/ha. The MAI is within the range of the annual growth rates of 20-35 m^3/ha for *A. mangium* in Sumatera as found by Hardiyanto and Nambiar (2014). The undiscounted average amount of carbon stored in tree biomass at its optimal rotation is 127.4-ton CO_2/ha, which is very close

[4] The net price of *A. mangium* is 792.000 IDR/ton. As the wood density of *A. mangium* is $\rho = 0.501$, the volume of 1 ton of *A. mangium* equals 1/0.501=1.996 m^3. With the exchange rate 1 IDR = 14,237 USD in 2018 and an inflation rate of 4.1% (based on the average inflation rate for 2012-2018), the timber price of one m^3 is 37 USD. The harvesting cost of *A. mangium* is 8 USD/m^3. Hence, the net price of *A. mangium* timber is 29 USD/m^3.

[5] The average real interest rate for Indonesia for 2012-2019 is 8% (World Bank, 2021).

to the 124.3 ton CO_2/ha reported by Tiryana et al. (2016) for South Sumatera. The resulting total amount of discounted carbon stored over the infinite time horizon is 4,082 ton CO_2/ha.

Table 2.1. The stand characteristics of *A. mangium* at optimal rotation

	Value
$NPV_{Faustmann}$ (USD/ha)	2,618
Optimal rotation (years)	7
Extracted volume (m^3/ha)	167
Mean Annual Increment (m^3/ha)	23.9
Average amount of CO_2 stored in AGB & root biomass (ton/ha)	127.4
Total discounted carbon (ton CO_2/ha)	4,082

2.4.2. Optimal Forest Management with Carbon Remuneration

We simulate carbon prices that incentivize forest managers to store more carbon in the forest by lengthening the forest rotation. The results for the current carbon accounting scheme are presented in Table 2.2. The NPV of stored CO_2 can be interpreted as the minimum carbon payment needed for the forest manager to lengthen the forest rotation to store more carbon. For example, the minimum carbon payment to extend the 7-year Faustmann forest rotation by one year is 125 USD/ha.

Table 2.2. Effects of carbon remuneration with current carbon accounting

Rotation (years)	Minimum CO_2 annual price p_{cc} (USD/tCO_2)	NPV of CO_2 payments (USD/ha)	NPV timber (USD/ha)	Total NPV (USD/ha)	Average additional CO_2 (ton/ha)	Discounted additional CO_2 (ton/ha)
8	0.71	125	2,494	2,619	17	533
9	1.35	449	2,283	2,732	33	1,013
10	1.78	839	2,036	2,876	47	1,448
11	2.08	1,238	1,779	3,017	60	1,841
12	2.30	1,624	1,524	3,148	72	2,200
13	2.46	1,981	1,280	3,261	83	2,527
14	2.58	2,308	1,050	3,358	93	2,827
15	2.68	2,613	835	3,448	102	3,103
16	2.75	2,881	636	3,517	111	3,357
17	2.80	3,118	452	3,570	119	3,591
18	2.84	3,333	282	3,615	127	3,809
19	2.88	3,537	126	3,662	134	4,011
20	2.90	3,705	-18	3,687	141	4,199
21	2.92	3,863	-150	3,713	147	4,375
22	2.94	4,011	-272	3,740	153	4,539
23	2.95	4,137	-384	3,753	158	4,693
24	2.96	4,254	-486	3,768	164	4,838
25	2.97	4,357	-581	3,776	169	4,974
no harvest	2.97	4,450	-581	3,869	297	7,738

The second column shows the minimum carbon price (remuneration for storing one additional ton of CO_2 for one year, p_{cc}) that is needed to obtain the cutting cycle indicated in the first column. The third column presents the corresponding NPV of carbon payments ($r = 8\%$). A longer rotation requires a higher NPV of carbon payments. The NPV of timber (fourth column of Table 2.2) decreases with the rotation length because the NPV of timber is maximized in the baseline scenario (i.e., Faustmann rotation). A rotation longer than the baseline results in a lower NPV of timber. The final two columns present the average total additional amount of CO_2 stored and the additional discounted amount of CO_2 stored over the infinite time horizon ($i = 3\%$). Note that the increase in carbon price that is needed to lengthen the rotation from 24 to 25 years and from 25 years to no harvest (climax forest) is less than one cent per additional ton of CO_2 stored for one year.

Table 2.3 shows the effects of carbon payments under VCS (average carbon accounting). The VCS carbon price p_{ac} is a carbon price for storing one additional ton of CO_2

over one rotation period and hence has a different interpretation than that of the carbon price under current carbon accounting. The information in all other columns, however, can be interpreted in the same way as in Table 2.2. Note that the numbers for the NPV of timber revenues and for average and discounted carbon stored are the same as in Table 2.2 as they are directly linked to the rotation length and not to carbon payments. However, the minimum carbon payments required to induce a given rotation length differ between the two carbon accounting schemes. Under VCS, the minimum carbon payment needed to extend the rotation by one year from the Faustmann rotation is 127 USD/ha, which is marginally higher than that under current carbon accounting. For longer rotations, the difference between NPV of carbon payments between the two carbon accounting schemes becomes larger. Carbon prices that induce the forest owner to extend the rotation beyond 17 years lead to an infinite rotation length (climax forest).

Table 2.3. Minimum carbon payment to incentivize forest managers to lengthen the rotation to store more carbon under VCS

Rotation (Year)	Minimum CO_2 rotation price p_{ac} (USD/tCO_2)	NPV of CO_2 payments (USD/ha)	NPV of timber (USD/ha)	Total NPV total (USD/ha)	Average additional CO_2 (ton/ha)	Discounted additional CO_2 (ton/ha)
8	4.80	127	2,494	2,620	17	533
9	11.03	502	2,283	2,786	33	1,013
10	16.62	1,004	2,036	3,041	47	1,448
11	23.48	1,677	1,779	3,456	60	1,841
12	29.29	2,346	1,524	3,871	72	2,200
13	33.93	2,962	1,280	4,243	83	2,527
14	42.17	3,913	1,050	4,963	93	2,827
15	47.08	4,584	835	5,419	102	3,103
16	50.32	5,099	636	5,735	111	3,357
17	58.76	6,138	452	6,590	119	3,591
no harvest	61.47	8,595	-1,721	6,874	297	7,738

Figure 2.3(a) presents the minimum carbon payments (in USD/ha) needed to store various amounts of carbon in aboveground and root biomass under both remuneration schemes. Amounts of carbon stored are expressed as average (over one rotation, or, equivalently, over the infinite time horizon) amounts of undiscounted CO_2 per hectare. The minimum carbon payments needed to incentivize additional carbon storage in the *A. mangium* plantation are lower for the current carbon approach than for the VCS approach. For example, to increase the

average amount of CO_2 stored by 26% (33 tons, i.e., a nine-year rotation) requires a payment of USD 449 per hectare with the current carbon approach, but a payment of USD 502 per hectare with VCS. This is a 12% difference in payments and is an indication of the inefficiency of the VCS average accounting scheme as compared to the current accounting scheme. The difference in payments between the two schemes is largest for the 17-year rotation and the climax forest for which payments under VCS are almost double the payments under current carbon accounting. We find threshold NPVs of carbon payments of 4450 USD/ha and 8595 USD/ha that incentivize a no-harvest management regime for current carbon and VCS, respectively. This explains the kinks in Figure 2.3. Figure 2.3(b) shows that our findings are robust when carbon stored is measured as discounted CO_2. The additional carbon stored expressed as a percentage of the baseline is somewhat smaller. For example, for the 9-year rotation, we find a 25% increase compared to the discounted baseline carbon (one percentage point less than the increase of average carbon).

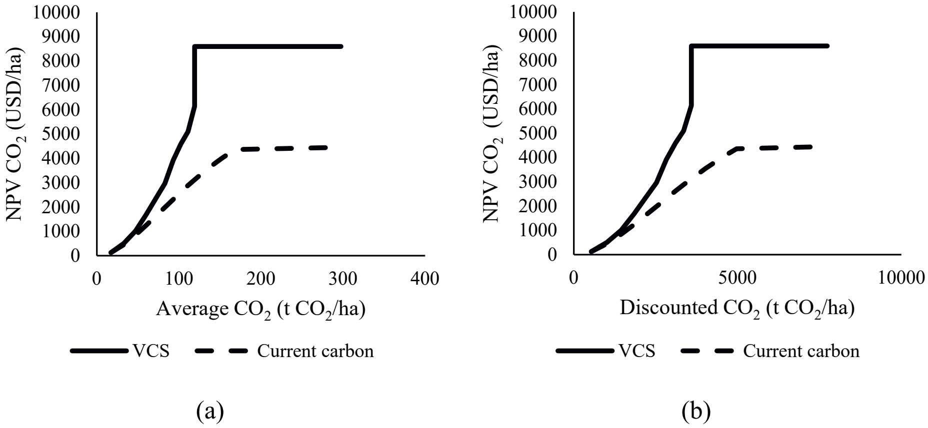

Figure 2.3. NPV of the minimum carbon payment needed to incentivize carbon storage under current carbon and VCS schemes ($\boldsymbol{r} = \mathbf{8}\%$). The left panel shows payments for additional average carbon, the right panel for additional discounted carbon ($\boldsymbol{i} = \mathbf{3}\%$). Carbon is measured in t CO_2 /ha.

2.4.3. Sensitivity analysis

In this section, we examine the robustness of our findings with respect to our assumptions concerning the financial discount rate. Our results in Section 4.2 are obtained for $r = 8\%$. I present the results of a sensitivity analysis in which we use values of 12% and 4% for the monetary discount rate in Figures 4(a) and 4(b), respectively. Here we measure the additional amount of carbon stored as the average over the rotation.

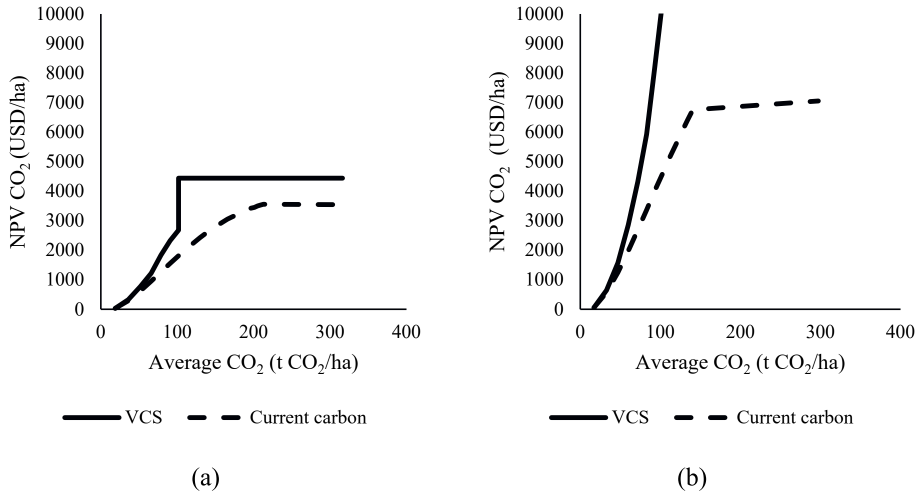

Figure 2.4. Minimum carbon payment needed to incentivize carbon storage under the current carbon and VCS: (a) $\boldsymbol{r = 12\%}$ and (b) $\boldsymbol{r = 4\%}$.

As Figures 2.3 and 2.4 indicate, the VCS approach is less cost-effective than the current carbon approach at all discount rates as smaller payments are needed under the latter scheme for each amount of carbon stored. For example, at a 12% discount rate, the average amount of CO_2 in the baseline is 109 t CO_2 (i.e., a six-year rotation). To increase the average amount of CO_2 stored by 33% (36 tons, i.e., an eight-year rotation) requires a payment of USD 288 per ha with the current carbon approach, but of USD 322 per ha with VCS. At a 4% discount rate, where the baseline rotation is the same as for an 8% discount rate, to increase the amount of CO_2 stored by 26%, the carbon payment needed is 570 and 643 USD/ha for the current carbon and VCS scheme, respectively. In both cases, the compensation required for forest managers to increase the amount of carbon stored is about 12% higher for VCS than for the current carbon scheme.

A comparison of the cost-effectiveness of the current carbon and the VCS for three different discount rates is presented in Figure 2.5, where we present the ratio of the NPV of CO_2-payments under VCS and under current carbon for different cutting cycles (additional years as compared to the Faustmann rotation). Each line ends when the carbon payments induce a no-harvest rotation in one of the schemes. For each discount rate, the relative inefficiency of VCS increases with the cutting cycle (amount of carbon stored). The difference in cost-effectiveness is more pronounced for lower discount rates, notably when $r = 4\%$. This finding is hardly surprising. If a cost-effectiveness gap (in US dollars) between the current carbon and the VCS scheme is observed for a given rotation in a model with an infinite time horizon, then this gap will be more pronounced when evaluated with a lower discount rate.

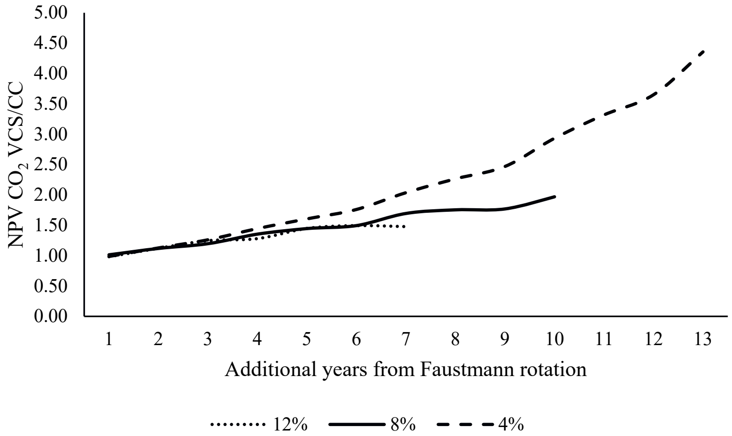

Figure 2.5. Ratio of minimum carbon payments under VCS and current carbon at various discount rates. (Discontinuities in the graph are due to rounding and discrete-time modelling.)

2.5. Discussion

To understand our findings, we need to point to a general feature of the impact of non-timber benefits on rotation length revealed in the Hartman model. Hartman's (1976) analysis shows that non-timber benefits can affect the rotation in different ways depending on the time structure of the benefits. Benefits that come early in the rotation might shorten the rotation because such early benefits would then occur more often over a given planning horizon. Additional carbon stored is, by contrast, a benefit that comes late in the rotation. Accounting for such benefit at the time when it accrues lengthens the rotation. Current carbon accounting sets the incentives right as the payment scheme follows the time structure of carbon storage and the associated benefits: the largest payments are received at the end of the rotation, followed by a fee that is due after cutting. The payment scheme thus incentivizes the delay of cutting directly. By contrast, the VCS average carbon accounting scheme offers payments in the middle of the cycle. Such payments are less suitable to incentivize the delay of cutting. A longer rotation is incentivized only indirectly through a payment that rewards a larger average carbon storage.

Our finding that the gap in cost-effectiveness is more pronounced for lower discount rates is explained by the fact that the misalignment of incentives and carbon sequestration under the VCS repeatedly occurs in the future. With a lower discount rate, the effectiveness gap between VCS and the current carbon scheme will weigh heavier. Figure 2.5 illustrates this argument.

We find that the minimum VCS carbon price required to extend the rotation cycle by one year (from 7 to 8 years) under the assumption of an 8% monetary discount rate is USD 4.80/tCO_2. The average 2019 price for VCS credits for forestry and land use was USD 3.56 (Ecosystem Marketplace 2021), which suggests that a forest manager would prefer the Faustmann rotation under current prices. To effectively cut emissions in line with the Paris Agreement's temperature goals, carbon prices for *permanent* carbon storage of at least USD 40-80/tCO_2 by 2020 and USD 50-100/tCO_2 by 2030 are required (Stiglitz et al. 2017). Current (August 2021) carbon prices at the European Union Emission Trading Scheme are around USD 65/tCO_2. To put these prices in perspective, we can calculate the implicit price for a *permanent* credit under VCS by dividing the NPV of CO_2 payments by the average additional amount of CO_2 stored. The implicit price for permanent storage is USD 7.50/tCO_2 for the 8-year rotation and USD 28/tCO_2 for the 11-year rotation. This suggests that voluntary carbon markets such as VCS can play a role in making global carbon markets more cost-efficient (assuming that carbon stored under the VCS scheme is permanent and additional).

Managed forests are living systems and carbon stored in forests is never removed permanently from the atmosphere but is released again, at least partially, at harvest. Nevertheless, managed forests store, on average, large amounts of carbon. If a positive social discount rate applies to the global economy, it matters not just how much but also when carbon is stored. Van Kooten et al. (2004) argue that in order to obtain a consistent assessment of carbon projects, both project costs and physical carbon need to be discounted, perhaps even at different discount rates. As with any NPV calculation, it is essential to choose an appropriate discount rate. If carbon is viewed as serving the public interest, using the social discount rate will be appropriate. The use of a carbon discount rate does not imply that future carbon is less environmentally damaging than current carbon. However, if the discount rate reflects, among other things, the long-term rate of economic growth (through the Ramsey equation; see, e.g., Drupp et al., 2018, and references therein), a richer society in the future will be better able to cope with damages.

According to West et al. (2019), *Acacia sp.* plantations have low cost-effectiveness for carbon sequestration service as compared to some other species (*Tectona sp., Eucalyptus sp. and Pinus sp.*) because *Acacia* has a short rotation and the least valuable wood. Still, in Indonesia, *Acacia mangium* is the most planted tree in the industrial plantation for pulp;

therefore, it has a high potential to be developed for carbon projects under the 'improved forest management with extension 'rotation' remuneration programs of verification organizations like Verified Carbon Standard and Gold Standard.

2.6. Conclusions

We analyze the cost-effectiveness of a prominent voluntary carbon scheme, the Verified Carbon Standard for Improved Forest Management. We consider the lengthening of the forest rotation for *A. mangium* plantations in Indonesia. We compare the costs of carbon sequestration under the VCS rule with a current carbon approach that remunerates additional carbon stored each year. This chapter offers three findings. First, the VCS model is less cost-effective than the current carbon scheme. This is because the payments of our current carbon scheme are better aligned with forest carbon flows than the carbon payments of VCS. Second, the cost-effectiveness gap is more pronounced for lower discount rates. Third, the recent price of VCS forestry and land use credits appears to be insufficient to incentivize Indonesian forest managers of *A. mangium* to lengthen the rotation.

Appendix 2.1. Growth of *A. mangium* in Indonesia.

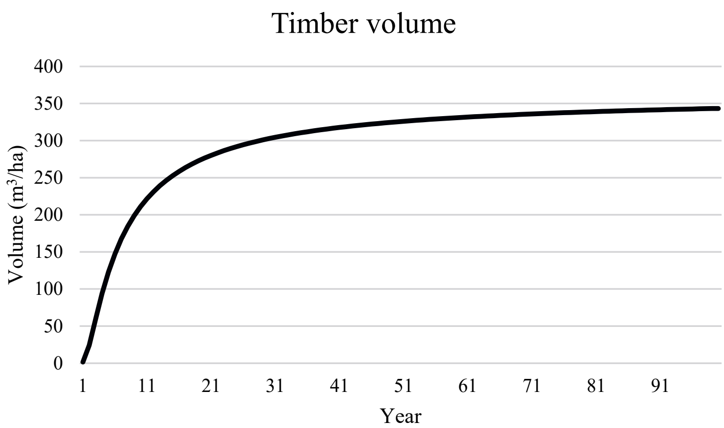

Figure A2.1.: Growth of *A. mangium* in Indonesia following the data reported in Heriansyah et al. (2007)

Appendix 2.2. Plantation costs

Table A2.1. Plantation costs; all values in 2018 US dollars

	Year					
	0	1	2	3	4	5
Planning	**40.06**					
Feasibility study and EIA	4.10					
Development of a master plan	3.07					
Detail plan	1.57					
Forest inventory	1.63					
Border arrangement	5.12					
Working area	24.58					
Infrastructure	**311.31**					
Building, equipment, bridges	307.21					
Maintenance	4.10					
Administration	**153.61**					
Training	6.14					
Research and development	12.29					
General costs	122.88					
Assessment	12.29					
Planting	**792.48**					
Nursery	303.59					
Land preparation	403.14					
Plantation	85.75					
Taxes	**1.34**					
Concession license fee	0.90					
Land and building taxes	0.44					
Obligation to environment	**27.65**					
Physics, chemistry, biology	12.29					
Social environment	15.36					
Total planting costs (K)	**1326.45**					
Maintenance						
Maintenance Year 1		135.72				
Maintenance Year 2			106.90			
Maintenance Year 3				93.84		
Maintenance Year 4					53.37	
Maintenance Year 5						26.68
Forest protection and security						
Pest and disease control		6.53	6.53	6.53	6.53	6.53
Fire control		2.77	2.77	2.77	2.77	2.77
Forest security		3.07	3.07	3.07	3.07	3.07
Annual costs (κ_t)		**148.90**	**119.27**	**106.21**	**65.74**	**148.90**

Source: Ministry of Forestry (2009c)

CHAPTER 3

3

Chapter 3. Joint Production of Wood, Resin, and Carbon Storage in Pine Plantation Forests in Java[1]

Abstract

Pine (*Pinus merkusii*) plantation forests in Java Island are managed with a clear-cutting and artificial regeneration silviculture system. The main products are wood and resin. The Indonesian government has unconditionally committed to a 29% reduction of greenhouse gas (GHG) emissions by 2030 and pine plantation forests may contribute to reducing GHGs emissions by enhancing carbon stocks. This study analyzes the effects of additional income from resin and carbon benefits on the optimal forest rotation of pine plantations in Java. A modified Faustmann model is used to determine the optimal rotation. Several findings are presented in this chapter. First, the current price of VCS FOLU credits incentivizes forest managers to extend the rotation of Indonesian pine forests by 1-2 years, resulting in an additional 8-17% CO_2 storage. Second, additional income from pine resin may increase rotation length by 1-3 years and aid in the storage of 8-26% more CO_2. Resin production has contributed to more carbon storage in the forest without taking carbon into account. Third, taking into account the additional income from carbon and resin has a significant impact on the additional carbon stored in pine forest biomass.

Keywords: Optimal forest rotation, Faustmann-Hartman model, pine forest management, non-timber benefits, resin production, carbon storage, Java Island

3.1. Introduction

The typical management of pine plantation forests in Indonesia is usually based on the maximum sustained yield (MSY) approach, i.e., the forest will be clear cut and replanted when the mean annual increment (MAI) is the same as the current annual increment (CAI) (Bettinger et al. 2016). Foresters commonly use this MSY approach to determine the optimal rotation of a monoculture forest (Krisnawati et al. 2019). This approach gives the largest volume of wood per ha that a forest can produce sustainably. However, this approach does not consider critical economic aspects of planting and harvesting costs and the opportunity cost of land use for the

[1] This chapter is an updated and revised version of : Indrajaya, Y. 2020. Joint production of wood, resin, and carbon from pine plantation forest in Java. IOP Conference Series: Earth and Environmental Science 487: 012021. http://dx.doi.org/10.1088/1755-1315/487/1/012021.

next generation of trees. Samuelson (1976) has argued that the correct approach for determining an optimal forest rotation in order to obtain maximum net benefits is following Faustmann's (1849) rule. It says that the optimal time to harvest is when the value of timber added in a short time period equals the marginal cost of delaying the harvest. The rule applies when the wood is the only product from the forest. The Faustmann formula has been applied to determine optimal forest rotations in many countries in the world (Chang 2001).

Expanding upon Faustmann's rule, Hartman (1976) has determined the optimal rotation when non-timber forest products (NTFPs) provide additional revenues. Studies on the effects of non-timber forest products on optimal forest rotation have been conducted for many species in monoculture (Chang 2001) and multi-age multi-species (Buongiorno et al. 1995; Buongiorno et al. 2012). The strategy to maximize profit in the pine plantation forest with additional income from, e.g., resin sales (Wang et al. 2006) or carbon sales (Huang and Kronrad 2006; Manley and Maclaren 2012), will lengthen the rotation. Moreover, Hampicke (2001) has shown that the conservation value of a standing forest might even result in a no-harvest policy. Although several NTFPs may be produced simultaneously in a forest, studies considering the utilization of more than one NTFP in the forest economics area are still limited due to the complexities of the study (Rosser 2005). A pine forest, for example, may produce wood, resin, ecotourism services, soil and water conservation, carbon sequestration, and others. This chapter determines the optimal rotation length when two NTFPs are considered in addition to timber production.

Pine (*Pinus merkusii*) plantation forests have been developed on Java Island under the management of a state-owned company (i.e., Perum Perhutani) using a clear-cutting and artificial regeneration silviculture system. The main products of pine plantation forests in designated production forest areas are wood and resin, while in designated protected areas, these are wood, resin, and ecotourism. The total area of pine forest managed by Perum Perhutani in Java is 163.150 ha, producing 83,059 tons of resin in 2016 (Perum Perhutani 2016).

The Government of Indonesia (GoI) has committed to reducing greenhouse gases (GHG) by 29% voluntarily without international support and by 41% with international support in 2030 (Sekretariat Kabinet Republik Indonesia 2011; Government of Indonesia 2021). One of the sectors contributing to this commitment is Land Use, Land Use Change, and Forestry (LULUCF) via several activities: avoiding deforestation, avoiding forest fire (including peatland management), conservation & rehabilitation, and increasing carbon stocks. Plantation forests may also contribute to climate change mitigation by reforestation, afforestation, and increasing carbon stocks by lengthening harvest rotation (Richards and Stokes 2004).

The inclusion of carbon sales in forestry's profit maximization problem has been discussed in the forest economics literature. In afforestation projects under the Clean Development Mechanism (CDM), additional revenue from carbon sales will lengthen the rotation age (Olschewski and Benitez 2010; Galinato and Uchida 2011; see also Chapter 2). The carbon price incentivizes postponing the harvest due to the higher opportunity cost of harvesting.

This chapter aims to analyze the effects of additional income from more than one NTFP on the optimal plantation forest rotation. We use a pine plantation forest on Java Island as a case study in our analysis and study additional income from resin production and carbon sequestration. Our analysis will consider different site classes reflecting the productivity of different soil types.

The next section introduces the method. Sections 3.3. and 3.4 present data and results. Section 3.5 briefly summarizes the main finding.

3.2. Method

We start with establishing, as a benchmark, a Faustmann model, where the forest manager maximizes the Net Present Value (NPV) over an infinite time horizon when timber is the only product. The NPV is as follows:

$$NPV_w = \frac{p_w V_T - K(1+r)^T}{(1+r)^T - 1} \tag{3.1}$$

Where p_w is the wood price, V_T represents stumpage volume per ha at rotation year T, K is the planting cost, and r is the interest rate. The wood prices depend on size (diameter), where the larger sizes fetch higher prices. We use the wood prices p_w (in IDR/m^3) predicted by Prasetyo et al. (2017):

$$p_w = \nu \ln T - \sigma \tag{3.2}$$

where ν and σ are positive parameters to calibrate timber values. The wood prices and planting costs are assumed to be constant across rotations and will be specified in the next section. The stumpage volume is estimated for Indonesian pine forests based on Suharlan et al. (1975). The volume and diameter estimation in the forest stand table of Suharlan et al. (1975) are presented in a 5-year growth period. The forest stand table is used for estimating tree dimensions (tree height and diameter) and volume per ha in a certain site class of plantation forest. Indrajaya (2016) develops more precise volume per ha growth models with a logistic function following Englin and Callaway (1993) for pine forests of different site classes reflecting different soil conditions, indexed by s:

$$\ln V_{T,s} = \alpha_s - \beta_s/T \tag{3.3}$$

where α_s and β_s are site class-specific positive parameters.

Following Wang et al. (2006), resin is assumed to be produced by pine trees with diameter breast height (DBH) > 20 cm. Trees that are older, thicker, and stubby produced more resin than those that are younger, thinner, and slender (Zas et al. 2020). In diverse pine species, including *Pinus merkusii*, tree size, particularly bole diameter, is a well-known modulator of resin production (McDowell et al. 2007; Davis and Hofstetter 2014; Rodríguez-García et al. 2014; Audina et al. 2021). Thicker trees acquire a greater number of resin ducts in absolute terms (Hood and Sala 2015), and prior research has established a link between the abundance of axial and radial resin ducts and resin flow (Rodríguez-García et al. 2014). Although the tree size, age, and thickness are positively correlated to resin production per tree, the number of trees per ha are in general decreases due to thinning. As a result, the resin productivity in one ha of pine forest may decrease in the older age class (Sukarno et al. 2012). Following Fauziyah (2003), the resin production function is as follows:

$$R_t = [(\eta + \omega t) * N * \varphi] \text{ for } t \geq \tau$$
$$\text{and } R_t = 0 \text{ for } t < \tau \tag{3.4}$$

where R_t is the production of resin (kg/ha) in year t, η, and ω are positive coefficients, N is the population of the trees per ha, φ represents the number of days in a year, and τ represents the year when the DBH of pine reaches 20 cm, i.e., the time at which the resin is starting to be produced. Equation (3.4) applies for all site classes. The estimation of the number of trees per ha is presented in Appendix 3.1. We assume that this resin production function is applied in all site classes. The NPV of resin production from pine plantation forests is as follows:

$$NPV_r = \frac{\sum_{t=0}^{T} p_e R_t (1+r)^{T-t}}{(1+r)^T - 1} \tag{3.5}$$

where p_e is the price of resin.

The NPV from carbon sales is the total amount of carbon credits sold in the market. For all site classes, the weight of above ground forest biomass was estimated from the volume of tree and biomass expansion factor:

$$AGB_t = V_t \times \rho \times BEF \tag{3.6}$$

where AGB_t is the above-ground biomass at year t (ton/ha), V_t represents the wood volume (m^3/ha), ρ is the wood density of pine, and BEF is the biomass expansion factor.

The weight of root biomass was estimated by the allometric equation of Cairns et al. (1997), i.e.:

$$RB_t = \exp\left(\mu + \pi \ln AGB_t\right) \tag{3.7}$$

where RB_t is the weight of root biomass (ton/ha). If the fraction of carbon in tree biomass is θ and the ratio of CO_2 and C is ε, then the total amount of CO_2 stored in tree biomass is

$$C_t = (AGB_t + RB_t) * \theta * \varepsilon \tag{3.8}$$

Similar to the previous chapter, in this chapter, we use the VCS carbon remuneration scheme for the case of pine forests. Let's denote $C_{\gamma t}$ as the amount of carbon stored in forest biomass in any year *t* under a forest carbon project, while $C_{\delta t}$ indicates the amount of carbon stored in year *t* under the Faustmann baseline. The total amount of carbon that can be credited under the VCS rules is based on the average amount of carbon stored in biomass within a certain rotation T_c (i.e. $\frac{1}{T_c}\sum_{t=1}^{T_{ac}} C_{\gamma_t}$). According to the VCS rules, the carbon payments are received for carbon sequestered in year t provided the total amount of carbon stored in that year exceeds the baseline average ($\frac{1}{T}\sum_{t=1}^{T} C_{\delta_t}$) and does not exceed the average amount stored under project rotation. The NPV of carbon under VCS remuneration is as follows:

$$NPV_c = \frac{p_c \sum_{t=1}^{T_c}\left[max\Big(0,\ min(C_{\gamma_t},\ \frac{1}{T_c}\sum_{\tau=1}^{T_c} C_{\gamma_\tau}) - max(C_{\gamma_{t-1}},\ \frac{1}{T}\sum_{\tau=1}^{T} C_{\delta_\tau})\Big)(1+r)^{T_c-t}\right]}{(1+r)^{T_c}-1} \tag{3.9}$$

where, NPV_c denotes the value of timber and carbon stored in forest biomass according to the VCS model and, T_c denotes the optimal rotation length under the 'average carbon' accounting method. In the RHS of Eq. (3.9), the numerator represents the value of carbon stored in forest biomass under VCS over one rotation. The denominators convert the rotational values into net present values. Under VCS, the carbon price per ton CO_2 in forest biomass is denoted as, p_c. It is important to note that this is a carbon price for storing an additional ton of CO_2 over a single rotation period. Under the project, the amount of carbon stored in forest biomass at time t is denoted as C_{γ_t}. Essentially, the payment is received for an amount that has been sequestered, $C_{\gamma_t} - C_{\gamma_{t-1}}$. The first max operator ensures that the received payment is always positive. The min operator in Eq. (3.9) limits the payments to the average amount stored under the VCS project. The second max operator limits sequestration payments to amounts greater than the baseline average. VCS avoids having to demand payments back from the project manager in years where, $C_{\gamma_t} < C_{\delta_t}$.

Total NPV of joint production of timber, resin, and carbon is as follows:

$$NPV \quad = NPV_w + NPV_r + NPV_c \tag{3.10}$$

3.3. Parameters

We consider pine forests growing on four different site classes associated with different soil types, cf. site conditions on Java, Indonesia. Parameter estimates for the values of α and β are presented in Table 3.1 for four site classes.

Table 3.1. The values of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ for estimating volume and diameter of pine tree

		Value	τ (year)
Site class III	α	6.131	11
	β	17.096	
Site class IV	α	6.131	10
	β	14.494	
Site class V	α	6.136	9
	β	12.658	
Site class VI	α	6.123	8
	β	10.437	

Note: The site classes for pine forest were determined by calculating the growth of the dominant trees (i.e., trees whose crowns are higher than the general level of the canopy and which receive light from the sides as well as from above) in a stand. The site index is a measurement of the height of the dominant and codominant trees (i.e., trees whose crowns form the general level of the crown cover and receive full light from above, but comparatively little light from the sides) in a stand at certain base age. Dominant and codominant trees are used to describe the site index because they should be presumed to have been "free to grow" throughout their lives; consequently, the growth of these trees should have been relatively independent of other vegetation (Suharlan et al. 1975; Bettinger et al. 2016).

Other parameters used in this study are presented in Table 3.2. The exchange rate used is the exchange rate of 2018, i.e., 1 USD = IDR 14,237 (World Bank 2021).

Table 3.2. Parameters for optimal forest management simulation

Variable	Symbol	Value	Source
Wood price parameter	ν	200,948	Prasetyo et al. (2017)
	σ	181,909	Prasetyo et al. (2017)
Resin production parameter	η	1.88	Fauziyah (2003)
	ω	0.35	Fauziyah (2003)
Resin price (IDR/kg)	p_r	3,247	Ministry of Trade (2012)
Days of resin production in a year	φ	365	
Wood density	ρ	0.53	Zanne et al. (2009)
Root biomass parameter	μ	-1.085	Cairns et al. (1997)
	π	0.9256	
Biomass expansion factor	BEF	1.33	Krisnawati et al. (2012)
Carbon fraction	θ	0.47	IPCC (2006)
Ratio of CO_2/C	ε	44/12	
Planting costs (IDR/ha)	K	5,776,291	Prasetyo et al. (2017)
Interest rate	i	0.04	World Bank (2020)

3.4. Results and discussion

3.4.1. Optimal rotation with wood production only (MSY)

In general, wood production is larger in the pine forest with a higher site class. Site class represents the site's suitability for certain species. A more suitable site class shows faster growth. In the pine forest in Java, the fastest growth is for site class VI, where the mean annual increment (MAI) may reach 16.1 m^3/year at year 11 (see Figure 3.1). By contrast, the maximum MAI of pine forest for site class III is only 9.9 m^3/year that is reached in year 15. Traditional foresters typically determine optimal forest rotation using maximum sustained yield (MSY), where the forest will be clear cut when MAI = CAI (current annual increment).

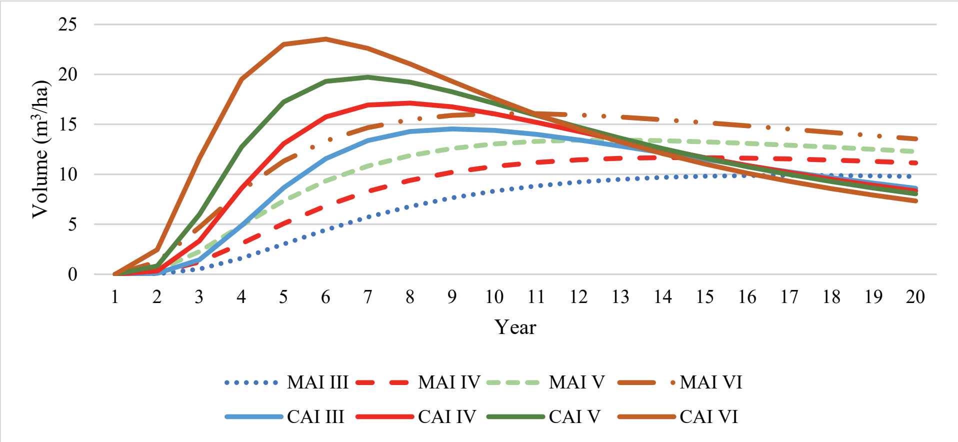

Figure 3.1. MAI and CAI of pine forest in Java

Optimal rotation with Maximum Sustained Yield (MSY) for site classes III, IV, V, and VI are 18, 15, 13, and 11 years respectively (see Table 3.3). Economists criticize the approach of MSY and argue that MSY may not give an optimal rotation age for maximum profit. The NPVs of pine plantation forests when timber is the only source of income are presented in Table 3.3. The optimal rotation age for site classes III, IV, V, and VI are 16, 15, 14, and 13 years, respectively. The faster the growth of the pine forest, the shorter the optimal rotation. The highest NPV is achieved at site class VI (i.e., USD 2,143/ha), which is the most suitable site for pine trees.

Table 3.3. Stand characteristics of pine forest in Java at optimal rotation for wood production

Parameter	Site Class III	Site Class IV	Site Class V	Site Class VI
Rotation (year)	16	15	14	13
NPV (USD/ha)	1,143	1,457	1,749	2,143
Timber (m^3/ha)	158	175	187	204
T-average CO_2 (ton/ha)	102	119	131	151

Notes: T-average is the average amount of CO_2 stored in forest biomass in one rotation

3.4.2. Optimal rotation with wood production only (Faustmann)

Pine forests may absorb and store carbon in their biomass through the photosynthesis process. The amount of carbon stored in the tree biomass of pine forest at its optimal rotation is presented in Figure 3.2. The baseline for the carbon project is the average amount of carbon stored in tree biomass at its optimal rotation (Faustmann rotation), i.e., 16, 15, 14, and 13 years for site classes III, IV, V, and VI, respectively. The baselines for site classes III, IV, V, and VI are 102, 119, 131, and 196 ton CO_2/ha (Table 3.3).

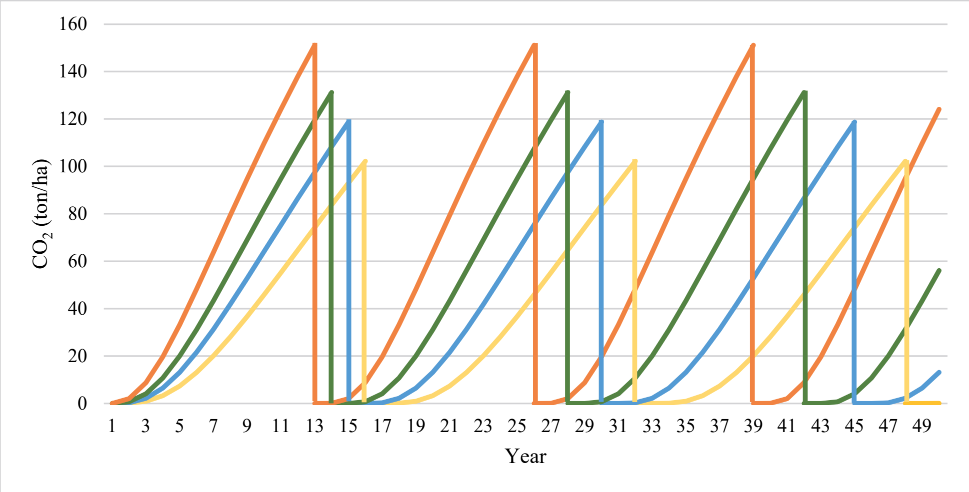

Figure 3.2. Carbon dynamics of pine forest on site-class III-VI. The orange, green, blue, and yellow lines represent the carbon stored in pine forest on site class VI, V, IV, and III respectively.

At the current carbon price in 2021 (i.e., 3.56 USD/tCO_2) (Ecosystem Marketplace 2021) the optimal rotation of pine forest lengthens 1-2 years with the additional carbon stored by 8-17%. This finding is different from that in *A. mangium* in the previous chapter that at this carbon price is insufficient to incentivize the forest manager to lengthen its rotation (Indrajaya et al. 2021). This is because the pine forest grows slower than the mangium forest, and the increment value from timber growth is relatively slower than mangium[2]. Under the Hartman rule, delay benefits include increased value from timber growth as well as the flow of carbon benefits during the delay period. The costs include the interest income lost as a result of the harvest's delayed receipt, as well as the interest cost of deferring benefits from future harvest cycles. Therefore, at the same carbon price, pine forest is more cost-efficient than mangium forest under the VCS FOLU remuneration scheme.

[2] The net timber price of mangium is the same for all diameter class, i.e., 29 USD/m^3 and the net timber price of pine varies among diameter class. The net timber price of pine reaches 29 USD/m^3 at year 19.

Table 3.4. Stand characteristics of pine forest in Java at the optimal rotation of joint production of wood and carbon (at 3.56 USD per ton CO_2)

Parameter	Site Class III	Site Class IV	Site Class V	Site Class VI
Rotation (year)	18	16	15	14
NPV (USD/ha)	1,162	1,472	1,768	2,158
Timber (m^3/ha)	178	186	199	216
Resin (kg/ha)	784	667	573	465
T-average CO_2 (ton/ha)	120	129	143	164
Additional CO_2 (%)	17%	9%	9%	8%

3.4.3. Optimal rotation of joint production of wood and resin

Pine trees produce wood for many purposes, and resin for rosin and turpentine (Zinkel 2018) used as industrial chemicals. Rosin is the raw material for adhesives, paper sizing agents, printing inks, detergents, etc. (Coppen and Hone 1995). Turpentine is widely used for varnishes, perfume, disinfectants, cleaning agents, and others (Coppen and Hone 1995). The production of resin in Java is presented in Figure 3.3.

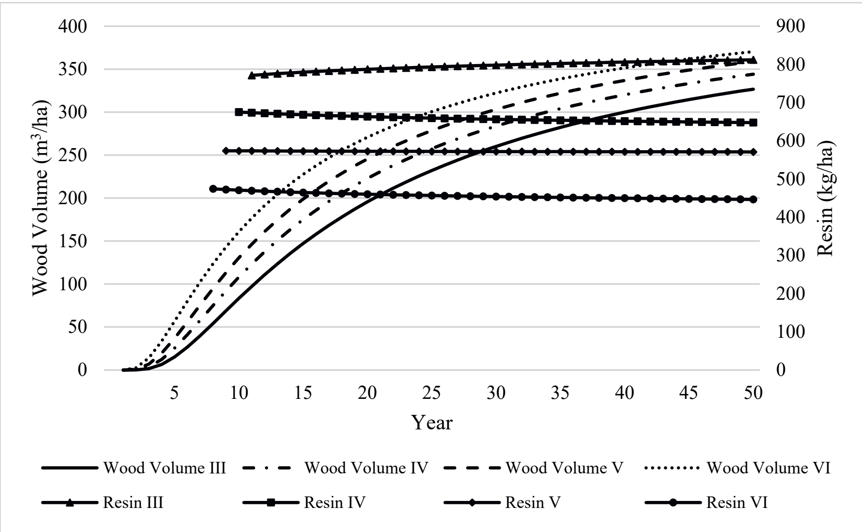

Figure 3.3. Wood and resin production of pine forest in Java

Figure 3.3 shows that the wood volume of pine forest still increases until year 50 but with a lower increment. Wood production is positively correlated to site classes. The better the site classes, the more wood is produced from the forest. Site class VI produces the largest wood volume, and the minimum tree size for raisin production is the earliest. However, the better site class of pine produces less resin per ha because the number of trees per ha is less in the better site class at the same age class. The optimal rotation of pine forest with resin production is lengthened by 2-5 years compared with a forest for timber production only, and we find 21, 19, 17, and 15 years for site classes III, IV, V, and VI, respectively (Table 3.5). Postponing wood harvest beyond the Faustmann rotation (wood production only) produces more resin until the additional income from resin decreases. Since resin is only produced in the older forest (i.e. at trees with DBH>20 cm), shorter rotations limit resin production. Perhutani has set the rotation of pine forest with wood and resin production of 35 years (Andayani, 2006), longer than the optimal rotation calculated in this study. This result is similar to findings by (Wang et al. 2006) and Prasetyo et al. (2017). They also find that additional benefits from the resin may lengthen the rotation age. However, this finding is different from Andayani (2006), who finds that resin inclusion may shorten the rotation period when forest management adopts the MAI = CAI criterion.

The NPVs increase by 22-54% for site class VI-III when joint production of wood and resin is adopted instead of timber production only. Because the resin production is larger at the lower site class, the lower site class obtain a larger proportion of the additional benefit from resin production. The NPV of site class III increases from 1,143 USD/ha to 1,764 USD/ha (54%); while the NPV of site class VI only increases from 2,143 USD/ha to 2,613 USD/ha (22%). The NPV of wood and resin is presented in Figure 3.4.

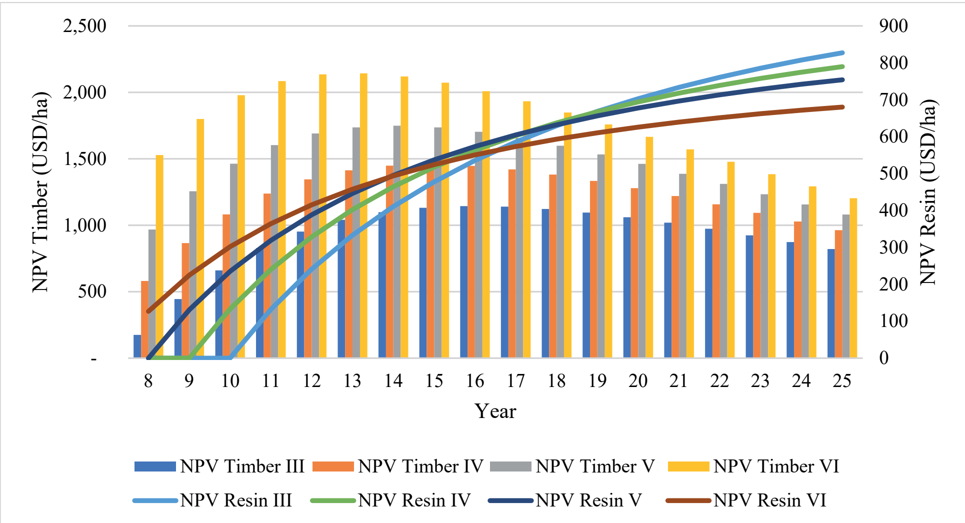

Figure 3.4. NPV of wood resin of pine forest

Table 3.5. Stand characteristics of pine forest in Java at the optimal rotation of joint production of wood and resin

Parameter	Site Class III	Site Class IV	Site Class V	Site Class VI
Rotation (year)	19	17	16	14
NPV (USD/ha)	1,764	2,023	2,277	2,613
Timber (m^3/ha)	187	196	210	216
Resin (kg/ha)	786	666	573	465
T-average CO_2 (ton/ha)	129	139	153	164
Additional CO_2 (%)	26%	17%	17%	8%

3.4.4. Joint Production of wood, resin, and carbon

The optimal management of joint production of wood, resin, and carbon at carbon prices of 3.56 USD/ton CO_2 is presented in Table 3.6. Additional income from resin and carbon sales changes the optimal rotation of the pine forest. At the current carbon price (i.e., 3.56 USD/ton CO_2), the optimal rotation on site class III, IV, V, and VI are 21, 19, 17, and 15 years (about three years longer than the baseline for each site class). The NPVs are slightly larger than those for the joint production of wood and resin. The additional income from carbon and resin has considerably increase CO_2 stored in pine forest biomass by 16-42%.

Table 3.6. Optimal management of joint production of wood, resin, and carbon of pine forest

Parameter	Site Class III	Site Class IV	Site Class V	Site Class VI
Rotation (year)	21	19	17	15
NPV (USD/ha)	1,839	2,088	2,344	2,667
Timber (m^3/ha)	204	214	220	228
Resin (kg/ha)	788	664	573	464
T-average CO_2 (ton/ha)	145	158	164	176
Additional CO_2 (%)	42%	33%	25%	16%

3.5. Conclusions

We analyze the effect of additional income from resin and carbon under the FOLU (Forestry and Land Use) VCS. We compare the optimal rotation of the Indonesian pine forest (*Pinus merkusii*) plantation with timber, timber+carbon, timber+resin, and timber+carbon+resin. This chapter has several findings. First, the current price of VCS FOLU credits incentivizes the forest managers to lengthen the rotation of Indonesian pine forest by 1-2 years and additional CO_2 stored by 8-17%. Second, additional income from pine resin may increase the rotation length by 1-3 years and help in storing additional CO_2 of 8-26%. Without carbon consideration, resin production has contributed to storing more carbon in the forest. Third, considering the additional income from carbon and resin significantly affects the additional carbon stored in pine forest biomass.

Appendix 3.1. Coefficient estimates for DBH and tree population of pine forest in Java

DBH of pine trees are predicted with the following equation (Harbagung 2010):

$$\ln D(t) = \alpha_D - \beta_D/t$$

Whereas, population per ha of pine trees is predicted with the following equation (Harbagung 2010):

$$N = \pi t^{\chi}$$

where t represent years

Table A3.1. Estimates parameters for predicting DBH and tree population based on Suharlan et al. (1975)

Parameter	Site Class III	Site Class IV	Site Class V	Site Class VI
α_D	4.144	4.281	4.375	4.555
β_D	12.246	12.528	12.223	12.721
π	5551.537	5595.139	4506.324	3958.668
χ	-0.966	-1.026	-1.003	-1.033

CHAPTER 4

Chapter 4. The Potential of REDD+ for Carbon Sequestration in Tropical Forests: Supply Curves for Carbon Storage for Kalimantan, Indonesia[1]

Abstract

We study the potential of tropical multi-age multi-species forests for sequestering carbon in response to financial incentives from REDD+. Following existing carbon crediting schemes, the use of reduced impact logging techniques (RIL) allows a forest manager to apply for carbon credits whereas conventional logging (CL) does not. This chapter is the first to develop a Hartman model with selective cutting in this setting that takes additionality of carbon sequestration explicitly into account. We apply the model using data for Kalimantan, Indonesia, for both private and government forest managers. The latter have a lower discount rate and are exempt from taxes. RIL leads to less damages on the residual stand than CL and has lower variable but higher fixed costs. We find that a system of carbon credits through REDD+ can increase carbon stored per hectare by 15.8% if the forest is privately managed and the carbon price equals the average 2015 price in the European Union's Emission Trading Scheme. Interestingly, awarding carbon credits to carbon stored in end-use wood products does not increase the amount of carbon stored, nor Land Expectation Value.

Keywords: REDD+, carbon credits, carbon sequestration, sustainable forest management, reduced impact logging, optimal forest management

4.1. Introduction

Forests play an important role in the carbon cycle and may be a low cost option to offset carbon emissions (Richards and Stokes 2004; van Kooten and Sohngen 2007; Kindermann et al. 2008). This has been acknowledged at the 16th Conference of the Parties (CoP 16) of the UNFCCC in Cancun in 2010, where the Parties recognized reduction of emissions from deforestation and forest degradation (REDD), including reduced emissions through conservation of forest carbon stocks combined with sustainable management of forests and the enhancement of forest carbon stocks (REDD+), as a means to offset carbon emissions.

[1] Published as: Indrajaya, Y., E. van der Werf, E. van Ierland, F. Mohren, and H.-P. Weikard. 2016. The Potential of REDD+ for Carbon Sequestration in Tropical Forests: Supply Curves for carbon storage for East-Kalimantan. Forest Policy and Economics 71: 1-10. http://dx.doi.org/10.1016/j.forpol.2016.06.032.

The harvest of mature trees in managed tropical forests causes damage to the remaining stand. Through intensively planned and carefully controlled timber harvesting conducted by trained workers, reduced impact logging (RIL) decreases damages to the remaining stand (Zimmerman and Kormos 2012). Therefore, ceteris paribus, the growing stock and the amount of carbon stored in the remaining forest stand are larger as compared to conventional logging (CL) (Putz and Pinard 1993; Pinard and Putz 1996; Putz et al. 2008). While previous literature has studied the effects of carbon storage and biodiversity constraints on optimal cutting cycles of managed tropical forests (Ingram and Buongiorno 1996; Boscolo and Buongiorno 1997; Boscolo and Vincent 2003), the potential of REDD+ carbon payments on tropical forest carbon sequestration has not been studied systematically.

In this chapter, we analyze the potential of REDD+ to induce carbon sequestration and we present supply curves for carbon storage in a tropical multi-age, multi-species forest; that is, for a range of prices of carbon credits we show the corresponding amount of carbon stored in above-ground biomass. we do so considering both private and public forest management; these differ in tax liability and the relevant discount rate. This chapter is the first that develops a Hartman (1976) model for multi-age, multi-species forests and analyzes the tradeoffs between timber revenues and income from carbon credits for a tropical forest with additionality taken explicitly into account. Carbon credits are only granted under RIL while the amount of carbon stored under CL in the absence of carbon credits serves as a benchmark (see for example the Verified Carbon Standard, the largest voluntary greenhouse gas reduction program). Hence we take additionality explicitly into account. We also explicitly consider the case where no harvesting takes place. We use detailed data on the characteristics of a multi-age, multi-species forest in central Kalimantan, Indonesia, and solve the model for a range of carbon prices. Our data allow us to develop a detailed model in which the damage from harvesting to the residual stand depends on harvest intensity, forest density and logging technique, and differs across diameter classes (Macpherson et al. 2010). Furthermore we use detailed data on fixed and variable harvest costs from a forest company in East Kalimantan, according to which RIL has slightly lower variable costs than CL but higher fixed costs. Following the rules of existing voluntary schemes for forest carbon sequestration under REDD+ (Dangerfield et al. 2016), an additional novel element of this chapter is the study of the effect of payments for carbon stored in end-use wood products such as building materials. As we will show, additionality plays a crucial role in determining whether receiving credits for carbon stored in end-use wood products is beneficial for land managers, while explicit modeling of the 'no-harvest' case has important ramifications for the interpretation of supply curves for carbon storage. Our carbon supply curves can be used in simulation models for mitigation policies (see Bosetti et al., 2011; Rose and Sohngen, 2011; Sohngen and Mendelsohn, 2003).

The effects of carbon payments on timber harvesting regimes have been studied extensively for plantation forests. Van Kooten et al. (1995) analyze effects of carbon payments on the optimal management of boreal and coastal forest in Canada. Galinato and Uchida (2011) study the effects of temporary and long term credits under the Clean Development Mechanism (CDM) in plantation forests in tropical countries while Köthke and Dieter (2010) and Tassone et al. (2004) study the effects of carbon crediting schemes on forest management for even-aged forests in Germany and Italy respectively. Boscolo et al. (1997) and Buongiorno et al. (2012) study carbon storage in un-even aged multi-species forests, but do not allow for optimizing behavior of forest managers. In addition, Buongiorno et al. (2012) study a forest in the northern hemisphere dominated by Norway spruce. The common finding is that an increasing carbon price leads to larger amounts of carbon stored in forests. However, none of these papers studies the incentives stemming from REDD+ where payments are received only for additional carbon stored as compared to a baseline, nor do they consider payments for carbon stored in end-use wood products. Furthermore, these papers typically use a discount rate that is too low for private forestry companies in Indonesia. These firms manage 96% of managed tropical forests in Indonesia (Hutan-Aceh 2014). Therefore, we study the case of a private forest manager with a 12% discount rate, and the case of a government forest manager (who does not have to pay taxes) with a 4% discount rate.

In the remainder of this chapter, we first describe the forest growth model and the economic optimization model. Next, in Section 4.3, we parameterize the model. We present our results in Section 4.4 and conclude in Section 4.5.

4.2. Model

4.2.1. Forest growth model

To describe the forest dynamics, we use a matrix stand growth model. Such models are extensions of population growth models applied to forest stands (Buongiorno and Michie 1980) and have been applied to tropical forest stands to study management strategies for maximizing economic returns (Ingram and Buongiorno 1996; Boscolo and Buongiorno 1997; Boscolo and Vincent 2003; Tassone et al. 2004).

At time t a forest stand is represented by column vector $\mathbf{y}_t = [y_{ijt}]$, where y_{ijt} is the number of trees per ha of species (or species group) $i \in \{1, \dots, m\}$ and diameter class $j \in \{1, \ldots, n\}$. The harvest is represented by vector $\mathbf{h}_t = [h_{ijt}]$. A tree living in species group i and diameter class j at time t will, at time $t + \theta$, either: (1) die, which happens with probability o_{ij}, (2) stay alive and move up from class j to class $j + 1$, which happens with probability b_{ij}, or (3) stay alive in the same diameter class j, which happens with probability $a_{ij} = 1 - b_{ij} - o_{ij}$. Parameter θ represents the growth period in years.

We use I_{it} to denote the expected ingrowth, i.e. the number of trees entering the smallest size class of species group i during a growth period θ. The stand state at time $t + \theta$ is determined by the stand at time t, the harvest at time t, and the ingrowth during interval θ. Ignoring damages from harvesting for the moment, each species in the stand is represented by the following n equations:

$$y_{i\,1\,t+\theta} = I_{it} + a_{i1}(y_{i1t} - h_{i1t}) \tag{4.1}$$
$$y_{i\,2\,t+\theta} = b_{i1}(y_{i1t} - h_{i1t}) + a_{i2}(y_{i2t} - h_{i2t})$$
$$\ldots$$
$$y_{i\,n\,t+\theta} = b_{i\,n-1}(y_{i\,n-1\,t} - h_{i\,n-1\,t}) + a_{in}(y_{int} - h_{int})$$

Ingrowth I_{it} is affected by the conditions of the stand (i.e. basal area and number of trees). The ingrowth function is a function of basal area B_{ij}, the initial stand and the harvest:

$$I_{it} = \beta_{0i} - \beta_{1i} \sum_{j=1}^{n} B_{ij} \left(y_{ijt} - h_{ijt}\right) + \beta_{2i} \sum_{j=1}^{n} \left(y_{ijt} - h_{ijt}\right), \tag{4.2}$$

$\beta_{0i}, \beta_{1i}, \beta_{2i} > 0$. Substituting Eq. (2) into the first equation of (1) gives:

$$y_{i\,1\,t+\theta} = \beta_{0i} + e_{i1}(y_{i1t} - h_{i1t}) + \cdots + e_{in}(y_{int} - h_{int}) \tag{4.3}$$

where:

$$e_{i1} = a_{i1} + \beta_{1i} B_{i1} + \beta_{2i} \tag{4.4}$$
$$e_{ij} = \beta_{1i} B_{ij} + \beta_{2i} \text{ for } j > 1$$

(5)

Ignoring damage for now, the stand after harvest is:

$$\mathbf{y}_{t+\theta} = \mathbf{G}(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{c} \tag{4.6}$$

where

$$\mathbf{G} = \mathbf{A} + \mathbf{R} \tag{4.7}$$

and

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_1 & 0 & \dots & 0 \\ 0 & \mathbf{A}_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \mathbf{A}_m \end{bmatrix}; \ \mathbf{A}_i = \begin{bmatrix} a_{i1} & & & 0 \\ b_{i2} & a_{i2} & & \\ & \ddots & \ddots & \\ 0 & & b_{in} & a_{in} \end{bmatrix} \tag{4.8}$$

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_{11} & \mathbf{R}_{12} & \dots & \mathbf{R}_{1m} \\ \mathbf{R}_{21} & \mathbf{R}_{22} & \dots & \mathbf{R}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{R}_{m1} & \mathbf{R}_{m2} & \dots & \mathbf{R}_{mm} \end{bmatrix}; \ \mathbf{R}_{ik} = \begin{bmatrix} e_{i1} & e_{i2} & \dots & e_{in} \\ 0 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 \end{bmatrix} \tag{4.9}$$

$$\mathbf{c} = \begin{bmatrix} \mathbf{c}_1 \\ \mathbf{c}_2 \\ \vdots \\ \mathbf{c}_m \end{bmatrix}; \ \mathbf{c}_i = \begin{bmatrix} \beta_{i0} \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{4.10}$$

Matrix $\mathbf{G}$ is the growth matrix. $\mathbf{A}$ is an $mn \times mn$ matrix consisting of species upgrowth matrices $\mathbf{A}_i$. It represents the probability of a tree to stay alive in the same diameter class j, move up the next diameter class $j + 1$, or die. Ingrowth matrix $\mathbf{R}$ is an $mn \times mn$ matrix representing the effect of stand structure on the probability of a tree entering the smallest diameter class in one growth period. Vector $\mathbf{c}$ contains the ingrowth constants representing the number of trees exogenously entering the smallest diameter class for each species.

4.2.2. Maximizing land expectation value: Timber only

The unit of analysis in this study is one hectare of a forest stand. The economic harvesting decision involves three variables: (i) the type of harvesting practice, i.e. CL or RIL, (ii) the length of the cutting cycle in years, and (iii) the intensity of the harvest in trees per ha for each species group.

For a given harvesting practice $s \in \{\text{CL}, \text{RIL}\}$, we can formulate the problem of maximizing the land expectation value (LEV) over an infinite time horizon subject to damage, harvest and steady state constraints:

$$\max_{\mathbf{y}_T, \mathbf{h}_T, T} LEV = \frac{\mathbf{v}_s{}'\mathbf{h}_T - F_s}{(1+r)^T - 1} - \mathbf{v}_s{}'\mathbf{z}_T \tag{4.11}$$

subject to

$$\mathbf{z}_T = (\mathbf{y}_T - \mathbf{h}_T - \mathbf{d}_{sT}) \tag{4.12}$$

$$\mathbf{d}_{sT} = f_s(h_{ijT}, y_{ijT}) \tag{4.13}$$

$$\mathbf{y}_{t+\theta} = \mathbf{G}\mathbf{z}_t + \mathbf{c}; \mathbf{y}_{t+2\theta} = \mathbf{G}(\mathbf{y}_{t+\theta}) + \mathbf{c}; \dots; \mathbf{y}_{t+\gamma\theta} = \mathbf{G}(\mathbf{y}_{t+\theta(\gamma-1)}) + \mathbf{c} \tag{4.14}$$

$$\mathbf{y}_T \geq \mathbf{h}_T + \mathbf{d}_{sT} \tag{4.15}$$

$$\mathbf{h}_T, \mathbf{y}_T, \mathbf{z}_T \geq 0 \tag{4.16}$$

$$h_{ij} = 0 \text{ for all } j < \eta \tag{4.17}$$

$$\mathbf{y}_t = \mathbf{y}_{t+\gamma\theta} \text{ for all } t = 1, \ldots, \infty \quad (4.18)$$

Vector $\mathbf{v}_s$ represents the value of the trees (i.e. price minus variable costs and taxes) under logging practice $s \in \{\text{CL}, \text{RIL}\}$, where v_{ij} is the value of a tree of species i in diameter class j. F_s represents the fixed costs per ha of forest management using harvesting practice s; r represents the real discount rate; $\mathbf{z}_t$ represents residual stand after harvest, where z_{ij} is the number of trees of species i that remain in diameter class j after harvest and accounting for damage; and γ is the number of growth periods θ within the harvesting cycle T. Equation (4.11) represents the value of the land, that is, the net present value of all projected revenues minus costs over an infinite time horizon of identical forest rotations net of the opportunity cost of initially not harvesting the steady state growing stock; see Chang (1981). Note that the first-order conditions in our model set-up are equivalent to those from a model where the manager harvests from a given initial stand in year 0 and the growing stock remains. The relevant choice variables are the size and composition of the stand just before harvest $\mathbf{y}_T$, the harvest $\mathbf{h}_T$, and the rotation length T. Equation (4.12) describes the growing stock $\mathbf{z}_T$ that remains after harvest. Equation (4.13) represents the damage to the residual stand caused by harvesting activities. This damage is a function of harvest intensity and is represented by the $mn \times 1$ vector, $\mathbf{d}_{sT}$. Equation (4.14) represents the growth of the forest. Equations (4.15) and (4.16) are the harvest and non-negativity constraints. Equation (4.17) is the harvesting policy constraint with η as the minimum diameter eligible for cutting set by government regulation. Equation (4.18) shows the steady state constraint.

4.2.3. Maximizing LEV: Timber and carbon

4.2.3.1. Carbon revenues from tree biomass

Payments for carbon stored in forest biomass can change the optimal harvesting intensity, the cutting cycle, and the optimal (steady-state) stand before harvest. We use a baseline to determine additionality of carbon storage. The baseline is given by the average amount of carbon that is stored in above ground biomass under CL calculated over one rotation. Although trees store carbon, not CO_2, we report carbon storage in tons of CO_2 throughout the paper as the price of carbon credits is conventionally given in USD/tCO_2. We assume that verification and payments for carbon storage take place every θ years, starting in year θ of every cycle, and carbon credits are awarded for the amount of carbon stored in commercial and non-commercial trees at the instant of verification. In our application we set $\theta = 2$ years.

Following Verified Carbon Standard (Dangerfield et al. 2016) forest managers receive temporary carbon credits that expire after θ years.[2] The relation between the price of temporary carbon credits from permanent carbon projects where payment starts at $t = \theta$ and takes place every θ years, p, and the price of permanent credits (such as the price for emission allowances in the EU ETS) p_∞, can be expressed as follows: $p_\infty = p\left((1+r)^\theta - 1\right)^{-1}$. For example, for a two-year credit of 0.7 USD/tCO_2 the equivalent permanent credit has a value of 8.50 USD/tCO_2 (the average 2015 price in the EU ETS), using $r = 0.04$.

Forest managers get paid for carbon stored in addition to the amount stored under a baseline. Hence we subtract the present value of the carbon stored in the case of optimal forest management when the forest manager uses conventional logging techniques and does not receive carbon payments (cf. Equation (4.11) with $s = \mathrm{CL}$). The LEV maximization problem under this payment scheme is written as follows:

$$\max_{\mathbf{y}_T,\mathbf{h}_T,T} LEV = \frac{\mathbf{v}'_{RIL}\mathbf{h}_{T_{RIL}} - F_{RIL}}{(1+r)^{T_{RIL}}-1} - \mathbf{v}'_{RIL}\mathbf{z}_{T_{RIL}} + \frac{p\boldsymbol{\chi}'\sum_{t=\theta}^{T_{RIL}}\mathbf{y}_{RIL,t}(1+r)^{T_{RIL}-t}}{(1+r)^{T_{RIL}}-1} - \frac{p\boldsymbol{\chi}'\sum_{t=\theta}^{T_{CL}}\bar{\mathbf{y}}_{CL,t}(1+r)^{T_{CL}-t}}{(1+r)^{T_{CL}}-1} + p\boldsymbol{\chi}'\left(\mathbf{z}_{T_{RIL}} - \bar{\mathbf{z}}_{T_{CL}}\right) \qquad (4.19)$$

The first two terms in Equation (4.19) are the same as the terms in Equation (4.11) and denote the net present value of profits from timber sales over an infinite time horizon net of the opportunity costs of initially not harvesting the growing stock. The third term denotes the present value of the carbon stored over an infinite horizon in the presence of a carbon payment program under REDD+. To qualify for such a program the forest manager needs to implement sustainable forest management techniques (RIL). Vector $\boldsymbol{\chi}$ represents the amount of CO_2 implicitly stored in above-ground forest biomass (AGB) per tree of species i and diameter class j. The fourth term denotes the present value of the carbon stored under the baseline (indicated by a bar over the vector denoting the stand); it is subtracted from the value of the carbon stored in the presence of a carbon credit scheme to account for additionality. The final term represents the carbon value difference between RIL and CL of the initial growing stock and is added as an ‘opportunity benefit’.

Equation (4.19) applies to cases with positive harvest (i.e. $h_{ij} > 0$ for some i, j). However, when carbon prices are sufficiently high it may be preferable not to harvest at all ($\mathbf{h} = \mathbf{0}$). In this case the LEV is given by

[2] Cf. the tCERs for afforestation or reforestation projects under the CDM; see also Olschewski and Benitez (2010) and Galinato and Uchida (2011).

$$LEV = \frac{p\boldsymbol{\chi}'\mathbf{y}_{climax}(1+r)}{(1+r)-1} - \frac{p\boldsymbol{\chi}'\sum_{t=\theta}^{T_{CL}}\bar{\mathbf{y}}_{CL,t}(1+r)^{T_{CL}-t}}{(1+r)^{T_{CL}}-1} - \mathbf{v}'_{RIL}\mathbf{y}_{climax} + p\boldsymbol{\chi}'\left(\mathbf{y}_{climax} - \bar{\mathbf{z}}_{T_{CL}}\right) \tag{4.20}$$

The first two terms of Equation (4.20) denote the value of the additional carbon stored with RIL as compared to the baseline over an infinite time horizon. The last two terms correct for the value of the initial (steady state) stand, i.e. the opportunity cost of not harvesting the stand.

4.2.3.2.Carbon revenues from tree biomass and end use wood products

Carbon is not only stored in trees but for some period of time also in end-use wood products (EWP). Following REDD+ as implemented by Verified Carbon Standard (Dangerfield et al. 2016), we allow for credits for carbon stored in EWP. The LEV maximization problem with additional income from carbon in EWP is written as follows:

$$\max_{\mathbf{y}_T,\mathbf{h}_T,T} LEV = \frac{\mathbf{v}'_{RIL}\mathbf{h}_{T_{RIL}} - F_{RIL}}{(1+r)^{T_{RIL}}-1} - \mathbf{v}'_{RIL}\mathbf{z}_{T_{RIL}} + \frac{p\boldsymbol{\chi}'\sum_{t=\theta}^{T_{RIL}}\mathbf{y}_{RIL,t}(1+r)^{T_{RIL}-t}}{(1+r)^{T_{RIL}}-1} - \frac{p\boldsymbol{\chi}'\sum_{t=\theta}^{T_{CL}}\bar{\mathbf{y}}_{CL,t}(1+r)^{T_{CL}-t}}{(1+r)^{T_{CL}}-1} + p\boldsymbol{\chi}'\left(\mathbf{z}_{T_{RIL}} - \bar{\mathbf{z}}_{T_{CL}}\right) + \frac{p\boldsymbol{\chi}'\omega\zeta(1+\delta)(1+r)}{(1+\delta)(1+r)-1}\left(\frac{\mathbf{h}_{T_{RIL}}(1-u_{RIL})}{(1+r)^{T_{RIL}}-1} - \frac{\bar{\mathbf{h}}_{T_{CL}}(1-u_{CL})}{(1+r)^{T_{CL}}-1}\right) \tag{4.21}$$

The first five terms in Equation (4.21) are equal to the terms in Equation (19). The last term denotes the present value of CO_2 stored in EWP in RIL minus the present value of CO_2 stored in EWP under the baseline. Note that $\bar{\mathbf{h}}_{T_{CL}}$ is the number of the trees harvested under CL at time T when the LEV from timber revenues only is maximized.

Kim Phat et al. (2004) point out that not all harvested timber will be used in EWP, but a proportion u_s will be wasted due to logging, skidding, and transportation activities. From the remaining timber arriving at the sawmill, only a proportion ω is used in EWP. We assume that the carbon stored in logging waste u_s and sawmill waste $(1-\omega)$ is released immediately after harvesting and wood processing. Winjum et al. (1998) suggest that from total carbon in EWP, a fraction $1-\zeta$ is also immediately released, for example used as firewood, and only a fraction ζ is used in durable wood products and is assumed to decay at rate δ.

4.3. Parametrization of the model

4.3.1. Forest growth data

We use the growth matrix developed by Krisnawati et al. (2008) for lowland dipterocarp forest in central Kalimantan. The soil type of the study area is dominated by podzolic soils. The climate is classified as type A (Schmidt and Ferguson classification) with an annual precipitation rate of 3,520 mm (Samsoedin et al. 2009). The highest and lowest average monthly temperatures are 27.4ºC and 24.3ºC respectively. The forest is dominated by dipterocarp species including Shorea spp. and Dipterocarpus spp. We use a growth period of 2 years ($\theta = 2$) because observations by (Krisnawati et al. 2008) were conducted in 1 and 2 years, and the authors found that the observation period of 2 years offered more reliable data for the increments of tree diameter and volume. We consider three species groups in the growth matrix with $i = 1$ for commercial dipterocarp, $i = 2$ for commercial non-dipterocarp, and $i = 3$ for non-commercial species. Each species group consists of 13 5-centimeter diameter classes ($j = 1$ for 10-14 cm, up to $j = 13$ for > 70 cm). [3] The growth matrices are presented in Appendix 4.1 (all Appendices can be found in the Supplementary Material). A short term validation of the growth model has been conducted by Krisnawati et al. (2008), who conclude that the predicted number of trees in each species and diameter class are not significantly different from the observed values. Following Martin Bollandsås et al. (2008), we conduct the long term validation by simulating the matrix growth model without harvesting for 1000 years starting from bare land. Figure 4.1 shows the development of basal areas of the forest. The climax forest is reached after approximately 300 years and has a basal area of 26.4 m^2/ha with a volume of 330 m^3/ha and 661 tons of CO_2 (180 tC) stored per ha in above-ground biomass. This predicted climax forest is similar to the basal area of 25 m^2/ha and the 214 tC/ha stored in above-ground biomass in the climax forest resulting from the growth matrix used in Boscolo and Buongiorno (1997) and Boscolo and Vincent (2000) and somewhat thinner than the virgin forest measured in Kalimantan by Sist, Picard, et al. (2003) and Sist, Sheil, et al. (2003), which has a basal area of ± 30 m^2/ha.

The dipterocarp species dominates the stand of the climax forest with a basal area of 19.4 m^2/ha (74%), whereas the basal areas of the commercial non-dipterocarp and non-commercial species are 5.8 m^2/ha (22%) and 1.1 m^2/ha (4%) respectively. The growth matrix of Krisnawati et al. (2008) was developed in a logged-over forest with high felling intensity. Since the growth rate of dipterocarp is faster than non-dipterocarp species (Vanclay 1994; Priyadi et al. 2007), the dipterocarp species dominate the stand composition of the climax forest.

[3] Diameters are measured at breast height (DBH).

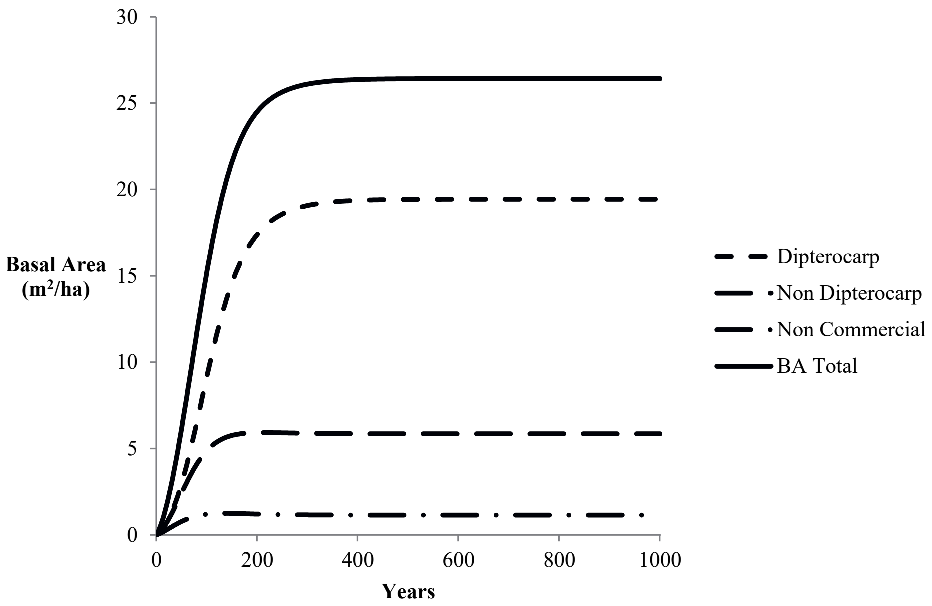

Figure 4.1. Predicted basal area (BA) of commercial dipterocarp, commercial non-dipterocarp and non-commercial species without harvest.

4.3.2. Harvest damage relation

Following the approach by Macpherson et al. (2010), the number of trees damaged through harvesting activities is $\mathbf{d}_{sT} = (\sum_i \sum_j h_{ijt})\mathbf{D}_s\mathbf{y}_t$, where $\mathbf{D}_s$, a damage matrix, is an $mn \times mn$ matrix where the diagonal contains the logging damage coefficients under logging practice s. The damage coefficients represent the proportion of trees killed per tree harvested within each species group i and size class j. Matrix $\mathbf{D}_s$ consists of damage coefficient matrices $\mathbf{E}_s$ and null matrices:

$$\mathbf{D}_s = \begin{bmatrix} \mathbf{E}_s & & 0 \\ & \mathbf{E}_s & \\ 0 & & \mathbf{E}_s \end{bmatrix}$$

Following the CIFOR data (Priyadi et al. 2007) we used to generate $\mathbf{D}_s$, RIL reduces damages per tree harvested as compared to conventional logging with 17% on average over all diameter classes, and with 25% on average for all trees of 50 cm diameter and larger. The matrices $\mathbf{E}_s$ are presented in Appendix 4.2. The data from Priyadi et al. (2007) come from experimental plots in Kalimantan, where different logging practices have been applied. In their study, the minimum-diameter harvested is 50 cm, based on the Indonesian selective logging system

(TPTI) that was applied until 2009. For our simulations we follow the new Indonesian selective logging system, effective since 2009 and set the minimum diameter for harvest at $\eta = 40$ cm (Ministry of Forestry 2009b). Larger trees are harvested only if it is commercially attractive to do so.

4.3.3. Economic parameters

We use production cost parameters reported by Dwiprabowo et al. (2002) for CL and RIL for a tropical forest concession on East-Kalimantan.[4] The investment and administration cost data were collected from a technical proposal of a company in East-Kalimantan (PT Sumalindo Lestari Jaya 2008).[5] The gross prices of timber per m^3 are based on standard prices determined by the Indonesian government in which commercial species are sorted into two groups: dipterocarp and non-dipterocarp.[6] We model both government managed and privately managed forests. The net price $\mathbf{v}_s$ is the gross price of timber per cubic meter minus the variable costs, fees, and taxes. However, for the government managed forest we exclude taxes.

Variable costs are slightly lower for RIL than for CL (46.4 USD/m^3 vs 44.8 USD/m^3) due to lower skidding costs (Dwiprabowo et al. 2002). For a government managed forest the resulting net price (price minus variable costs) is 89 USD/m^3 for dipterocarp and 55.2 USD/m^3 for non-dipterocarp for CL. For a privately managed forest taxes imply a lower net price of 59.4 USD/m^3 for dipterocarp and 32 USD/m^3 for non-dipterocarp for CL. Timber harvested under RIL has slightly higher net prices (1.5 USD/m^3) due to lower variable cost.

The fixed costs per harvest for RIL are substantially higher than those for CL (389 and 297 USD/ha per harvest respectively for a privately managed forest, including 9.98 USD/ha taxes that are excluded for the government managed forest). The fixed costs differ as a result of different machines used and additional pre-harvesting activities with RIL such as data checking and mapping, skid trail marking and checking, software purchasing, vine cutting, and improved timber inventory and contour survey (Dwiprabowo et al., 2002).

Our data are similar to data from Boltz et al. (2001) in that the variable costs are higher for CL but fixed costs are higher for RIL. The details of the cost parameters and taxes used in this study are presented in Appendix 4.1. We use a discount rate of 4% for a government

[4] We express values in USD of 2012, using an average inflation rate of 7.6% for 2002-2012 and an exchange rate of 1 USD = 9.387 IDR for 2012 (World Bank World Development Indicators).
[5] We express values in USD of 2012, using an average inflation rate of 4.9% for 2009-2012 and an exchange rate of 1 USD = 9.387 IDR for 2012 (World Bank World Development Indicators).
[6] Ministry of Trade Decree No 22/M-DAG/PER/4/2012. The dipterocarp species price used is 1.270.000 IDR/m^3 and the price for commercial non-dipterocarp is 953.000 IDR/m^3.

managed forest, based on the average real interest rate for Indonesia for the past 20 years.[7] For private forest management, we use a discount rate of 12% based on the interest rate used for companies in Indonesia (Hakim 2009; PT Bangun Alam Indonesia 2014; PT Borneo Subur Agro 2014).

4.3.4. Timber volume and carbon stored in tree biomass

We estimate timber volume using the formula developed by Enggelina (1998) for dipterocarp and non-dipterocarp species in Kalimantan. Because there are no data for timber volume estimation for non-commercial species, we assume that the formula for timber volume estimation for non-dipterocarp can also be applied for non-commercial species.

The amount of greenhouse gases stored in AGB is calculated as follows: $\boldsymbol{\chi} = \mathbf{AGB} \times \sigma \times 44/12$, where vector $\mathbf{AGB}$ is the vector of above-ground biomass weight, σ is the fraction of total weight stemming from carbon, and $44/12$ is the ratio of molecular mass of CO_2 to the atomic mass of carbon. Following Verified Carbon Standard, the largest existing voluntary carbon standard, we do not allow for credits for carbon stored in below-ground biomass. To estimate the amount of above-ground biomass for diameter class j of each species, we take the middle point of the respective diameter class and use the following allometric equation (Chave et al. 2005) where DBH refers to the diameter at breast height:

$$AGB_j = \rho \exp\left(\alpha_0 + \alpha_1 \ln\overline{DBH_j} + \alpha_2 \ln\overline{DBH_j}^2 + \alpha_3 \ln\overline{DBH_j}^3\right) \qquad (4.22)$$

where $\alpha_0, \alpha_1, \alpha_2,$ and α_3 are coefficients, $\overline{DBH_j}$ represents the middle point of the diameter values in diameter class j, and ρ represents the wood density.

Above-ground dry weight biomass is estimated using Equation (4.22) with parameter values α_0 = -1.499, α_1 = 2.148, α_2 = 0.207, α_3 = -0.0281(Chave et al. 2005), and ρ = 0.68 (Rahayu et al. 2006). In Equations (4.19) and (4.21), we take u_s equal to 0.262 and 0.462 for RIL and CL respectively (Sist and Saridan 1998). Wood processing efficiency ω is assumed to be 50% (Ministry of Forestry 2009a). Because wood from dipterocarp trees has a relatively high density (Basuki et al. 2009), end-use wood is assumed to be 100% for sawn wood. The proportion of EWP that is oxidized immediately $(1-\zeta)$ is 0.2 while the remainder oxidizes with an annual rate δ of 0.02 (Winjum et al. 1998). The proportion of carbon stored in tree biomass, σ, is 0.47 (IPCC 2006).

[7] Source: World Bank World Development Indicators.

4.3.5. Solving the model

We maximize LEV by changing the cutting cycle T, the number of the trees harvested $\mathbf{h}$, and the stock $\mathbf{y}$ simultaneously, with the restriction on $\mathbf{h}$ that the minimum DBH cutting limit is 40 cm. Depending on the context (maximize LEV from timber revenues only; include payments for carbon stored in AGB; include payments for carbon stored in EWP), we solve Equations (4.11), (4.19), or (4.21) with Equations (4.12) - (4.18) as constraints for $\gamma \in \{1,2,\ldots,51\}$ using the Excel Solver. We use the Generalized Reduced Gradient (GRG) nonlinear solving method, and find the value of γ that maximizes the land expectation value by non-linear programming. The solver uses a multi-start method using different starting points to avoid local optima.

4.4. Results and discussion

In this section, we first present the results of an optimal harvesting regime for conventional logging in the absence of carbon payments, our baseline case. Next, we introduce carbon pricing and determine the amount of carbon stored for different carbon prices when forest managers maximize their land expectation value. We conclude this section with a discussion of the carbon supply curves in the context of our steady state model.

4.4.1. Optimal forest management without carbon remuneration

Table 4.1 presents the key results for optimal forest management in the absence of carbon remuneration. The Land Expectation Values for private forest managers are lower than those for government forest managers due to the higher discount rate. Interestingly, in the absence of carbon pricing government forest managers prefer to use RIL whereas private forest managers prefer CL. The longer cutting cycle that results from the higher fixed costs makes RIL less attractive when a high discount rate is used. Indeed, CL is widely applied amongst private forest managers in Indonesia (see e.g. Dwiprabowo et al., 2002).

The cutting cycles for privately managed forests are shorter than those for government managed forests. Whereas higher fixed and variable costs as compared to a government managed forest induce a longer cutting cycle, the much higher discount rate more than offsets these effects. The optimal cutting cycles are shorter than 30 years, the rotation determined by the new Indonesian selective logging system introduced in 2009 (new TPTI).

The longer cutting cycle for RIL (for both privately and government managed forests) results in larger numbers of trees and larger basal areas, harvests, damages and volumes of carbon stored. The shorter cutting cycle for private forest managers results in a lower number of trees before harvest, lower basal area before harvest, and lower extracted volumes, damages and volumes of carbon stored.

The LEVs for CL in our study are lower than the maximum LEV of 702 USD reported by Boscolo and Buongiorno (1997) even though the cutting cycle is similar (20 years). Our damage matrix accounts for damages on all diameter classes (see Appendix 4.1), while in Boscolo and Buongiorno (1997) harvesting only causes damages to smaller trees. In addition, their climax forest is dominated by non-commercial trees, while the forest in our study is dominated by commercial trees, resulting in larger values of damages and opportunity costs of not initially harvesting the growing stock.

Table 4.1. Results for optimal management under CL and RIL without carbon remuneration

	Private		Government	
	CL	RIL	CL	RIL
Land Expectation Value (USD/ha)	32	29	481	492
Cutting cycle (years)	18	20	20	22
Total number of trees before harvest (trees/ha)	171	176	174	180
Total number of trees after harvest (trees/ha)	123	125	122	124
Basal Area before harvest (m^2/ha)	7	7.5	7.3	7.8
Basal Area after harvest (m^2/ha)	4.3	4.5	4.3	4.5
Extracted volume (m^3/ha)	11.8	14.2	13	15.5
Net harvest revenue (USD/ha)	512.4	637.9	860	1053.6
Volume damaged (m^3/ha)	17.1	18.5	19.4	20.7
Average amount of CO_2 stored in AGB (t/ha)	107.6	114.9	110.6	118.2
Average amount of CO_2 stored in EWP (t/ha)	4.1	6.7	4.5	7.2

4.4.2. Optimal forest management with carbon remuneration

We solve the model for prices for temporary (two-year) carbon credits of up to 5 USD/tCO_2. It is important to note that the value of a temporary credit expressed as the equivalent permanent credit differs for private and government forest managers due to their different discount rates. The formula $p_\infty = p\left((1+r)^\theta - 1\right)^{-1}$ shows the present value of an infinite stream of two-year credits, i.e. the value of the equivalent permanent credit. Since private forest managers use a higher discount rate, they assign a lower value to a temporary credit of a given value than government managers. The intuition behind this result is as follows. A temporary credit is issued every two years whereas a permanent credit is issued at the start of the planning horizon. Since private managers use a higher discount rate, they assign a lower present value to an infinite stream of two-year credits than the government managers. The price of 5 USD/tCO_2 is equivalent to a permanent credit price of 19.7 USD for a private forest manager and 61.3 USD for a government forest manager.[8] We set the results for conventional logging in which the LEV from timber revenues only is maximized (see Table 4.1) as our baseline. Forest managers only obtain credits for carbon stored in addition to the amount stored under the baseline.

4.4.3. Carbon payment from additional carbon in above-ground biomass

In this section, we analyze the effect of carbon payments on optimal management when I only consider carbon stored in above-ground biomass (AGB), i.e. when Equation (4.19) is the objective function. Table 4.2 presents the main results for the case of private forest management. More details can be found in Appendix 4.2. Under REDD+, managers of logged over forests may apply for carbon credits for carbon stored in addition to the amount stored under a baseline. Switching from CL to RIL at a zero carbon price increases the amount of carbon stored in above-ground biomass and end-use wood products by 9% (see Table 4.1). At a carbon price of 0.2 USD/tCO_2 it is optimal for a private forest manager to switch from CL (which does not qualify for carbon credits) to RIL since LEV increases to 34 USD/ha (not reported in the Table). The increase in LEV comes from the fact that with RIL more carbon is stored than under the baseline.

As the carbon price increases further, the cutting cycle increases to allow for more biomass accumulation and hence more carbon credits. This, in turn, allows for larger extracted volumes as can be seen from the amount of carbon stored in end-use wood products. At a credit price of 0.7 USD/tCO_2 (equivalent to the average 2015 price for EU emission allowances) carbon storage increases by 15% relative to the baseline. As the carbon price increases even further the cutting cycle never exceeds 32 years (at $p = 4.4$, not reported) since timber revenues are only obtained at the end of the cutting cycle and private forest managers have a high discount rate. Income from carbon credits, however, is received every two years and is hence less affected by discounting than timber revenues. For a two-year credit price of 4.5 USD or higher, private forest managers prefer not to harvest and only receive income from carbon

[8] The highest price observed in the EU ETS after the 2005-2007 pilot phase is 35 USD/tCO_2.

credits; in that case the optimal composition of the forest stand is the climax forest. The climax forest stores 661 tCO_2/ha (see section 4.3.1).

Table 4.2. Results for private forest management using RIL with carbon credits for carbon stored in AGB

Price temporary credit (USD/tCO_2)	0	1	2	3	4	5
Equivalent price permanent credit (USD/tCO_2)	0	3.93	7.86	11.79	15.72	19.65
LEV (USD/ha)	29	57	135	260	690	20,774
Cutting cycle (years)	20	26	26	28	30	-
Extracted volume (m^3/ha)	14	18	18	21	26	0
Volume of damaged trees (m^3/ha)	18	25	25	28	28	0
Average amount of CO_2 stored in AGB (tCO_2/ha)	115	125	140	166	302	661
Average amount of CO_2 stored in EWP (tCO_2/ha)	7	8	8	9	11	0

Table 4.3. Results for government management using RIL with carbon credits for carbon stored in AGB

Price temporary credit (USD/tCO_2)	0	1	2	3	4	5
Equivalent price permanent credit (USD/tCO_2)	0	12.25	24.51	36.76	49.02	61.27
LEV (USD/ha)	492	714	1634	32,750	49,211	65,672
Cutting cycle (years)	22	46	60	-	-	-
Extracted volume (m^3/ha)	16	31	45	0	0	0
Volume of damaged trees (m^3/ha)	21	50	62	0	0	0
Average amount of CO_2 stored in AGB (tCO_2/ha)	118	165	274	661	661	661
Average amount of CO_2 stored in EWP (tCO_2/ha)	7	12	15	0	0	0

As can be seen in Table 4.3, for a given price of a two-year credit, the cutting cycles for a government managed forest are much longer than those for a privately managed forest. Since government managers use a lower discount rate, their present value of a given stream of temporary credits, i.e. the equivalent price of a permanent credit, is larger than that for private managers. As the carbon price increases the cutting cycle increases stronger for a government manager than for a private forest manager because future carbon payments have more impact on the former. A longer cutting cycle implies a larger stock of carbon. At a credit price of 0.7 USD/tCO_2 carbon storage increases by 22%. At 2 USD/tCO_2 the amount of carbon stored in a government managed forest is twice as large as the amount stored under private management. The difference in discount rates between government and private management also drives the difference in the price at which it is optimal to switch to a “never harvest” regime. At the carbon price and corresponding cutting cycle where the forest manger is just indifferent to a ‘never harvest regime’, the present value of the gain in timber revenues from harvesting does just offset the present value of the loss in carbon revenues. For a private forest manager this is the case at $p = 4.5$ USD/tCO_2 for a two-year credit or 17.7 USD/tCO_2 for a permanent one, and a 32 years cutting cycle. If the private disount rate were then reduced, the manager would strictly prefer to harvest and lengthen the cutting cycle. For a 4% discount rate (and ignoring differences in taxes paid) this would lead to a switching point at a permanent price of 34.3 USD/t (2.8 USD/t for a two-year credit) and a cutting cycle of 60 years.

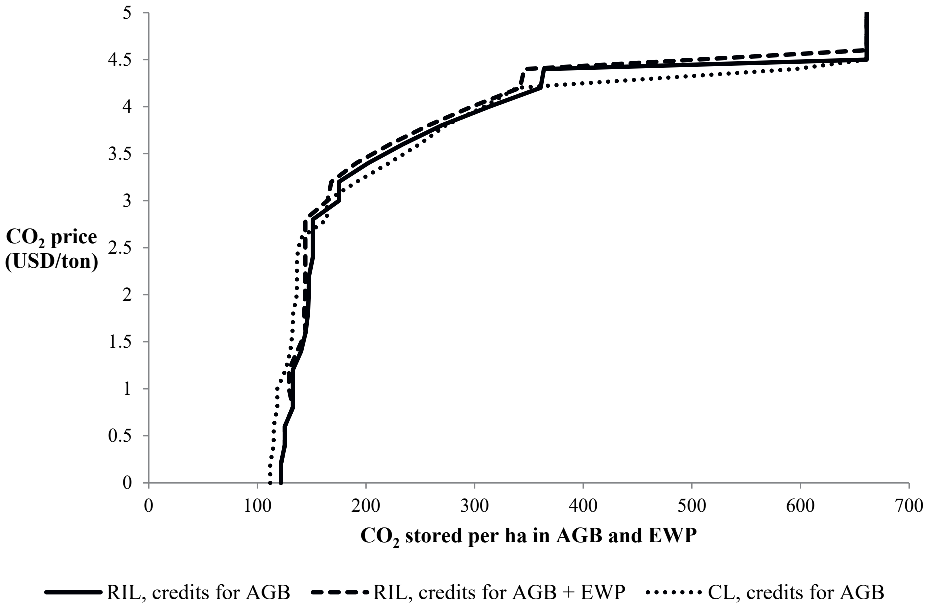

Figure 4.2. Private forest management: Supply curves for carbon storage for a managed tropical forest on Kalimantan, Indonesia, for RIL and CL

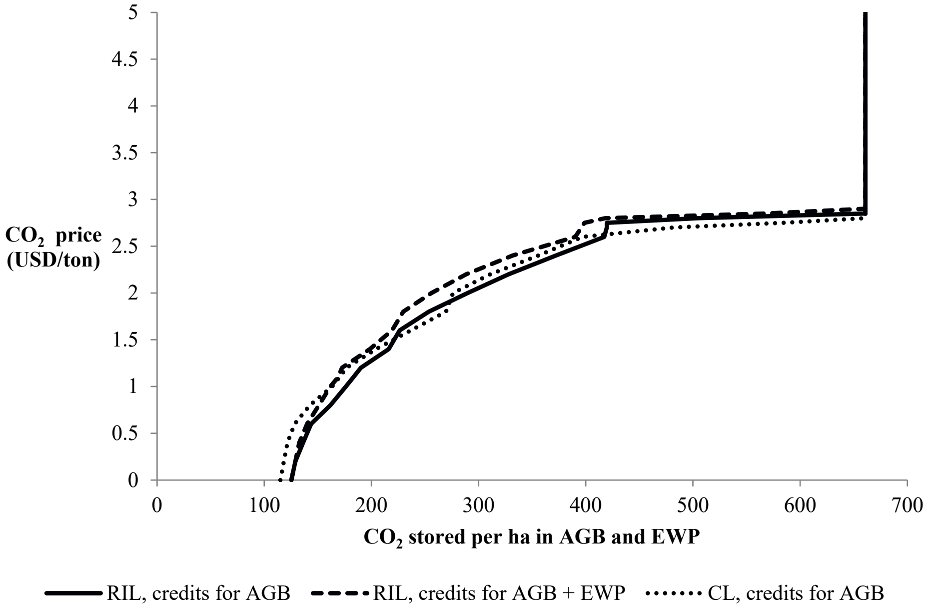

Figure 4.3. Government forest management: Supply curves for carbon storage for a managed tropical forest on Kalimantan, Indonesia, for RIL and CL

Figures 4.2 and 4.3 present supply curves for carbon storage for a hectare of managed tropical forest on Kalimantan, Indonesia. The solid lines represent the total amount of CO_2 stored under RIL when credits are issued for carbon stored in above-ground biomass. The curves in both Figures have a concave shape: as the price increases, progressively more carbon becomes stored since the cutting cycle becomes longer, even though damages increase as the CO_2 price increases up to 4 USD/tCO_2 for the privately managed forest (they decline between 4 and 4.5 USD) and 1.6 USD for the government managed forest. Extracted volume also increases up to a price of 4 USD/tCO_2 for the private case and 2.2 USD/tCO_2 for the government case, but while this increases the amount of carbon stored in EWP it decreases AGB. This concave shape is different from the convex supply curves presented by Boscolo et al. (1997) and Buongiorno et al. (2012). The reason is that we allow for profit maximizing behavior with endogenous adjustment of the cutting cycle as the carbon price increases. Boscolo et al. (1997) do not use a steady state model. They derive their supply curve from imposing exogenous restrictions on forest management, such as lengthening the cutting cycle. Buongiorno et al. (2012) use a steady state model with an endogenous steady state stand but keep the cutting cycle fixed: for a given cutting cycle it gets harder to store more carbon implying a convex shape of the supply curve.

As the carbon price (temporary, two-year credit) increases beyond 4.4 USD/tCO_2 for the private manager and 2.8 USD/tCO_2 for the government manager it is optimal for forest managers not to harvest and the climax forest is preferred[9]. The climax forest (see Figure 4.1) stores 661 tCO_2/ha independent of the carbon price. This marks the upper bound of the supply curves.

For comparison, Figures 4.2 and 4.3 and Appendix 4.2 include the results for various carbon prices when CL is used instead of RIL. Note that the use of conventional logging techniques may not qualify a forest stand for carbon payments under a REDD+ scheme as CL is not considered to be sustainable. Our baselines are the same as before: CL in the absence of carbon pricing, i.e. the results for CL in Table 4.1. For low carbon prices (up to around 3 USD/tCO_2 for the private forest manager and 1.5 USD/tCO_2 for the government manager), more carbon is stored in AGB per hectare under RIL than under CL because of the longer cutting cycle under RIL. However, for high carbon prices, more carbon is stored under CL. While the optimal cutting cycles for CL and RIL converge as the carbon price increases, fewer trees are harvested under CL leading to less damages and more AGB.

4.4.4. Carbon payments from additional carbon in above-ground biomass and wood products

In this section we present the results for optimal management when carbon payments are received for additional carbon stored in both AGB and end-use wood products, such as construction wood.

Table 4.4. Results for private forest management using RIL with carbon credits for carbon stored in AGB and EWP

Price temporary credit (USD/tCO_2)	0	1	2	3	4	5
Equivalent price permanent credit (USD/tCO_2)	0	3.93	7.86	11.79	15.72	19.65
LEV (USD/ha)	29	57	132	258	690	20,744
Cutting cycle (years)	20	24	24	22	30	-
Extracted volume (m^3/ha)	14	17	16	17	26	0
Volume of damaged trees (m^3/ha)	18	23	22	21	28	0
Average amount of CO_2 stored in AGB (tCO_2/ha)	115	121	137	157	302	661
Average amount of CO_2 stored in EWP (tCO_2/ha)	7	8	7	8	11	0

[9] For prices higher than 2.8 USD/tCO_2 and 4.4 USD/tCO_2 for the private and government case, respectively, we use Equation (4.20) instead of Equation (4.19) to calculate the LEV.

Table 4.5. Results for government management using RIL with carbon credits for carbon stored in AGB and EWP

Price temporary credit (USD/tCO_2)	0	1	2	3	4	5
Equivalent price permanent credit (USD/tCO_2)	0	12.25	24.51	36.76	49.02	61.27
LEV (USD/ha)	492	703	1600	32,750	49,211	65,672
Cutting cycle (years)	22	38	40	-	-	-
Extracted volume (m^3/ha)	16	26	33	0	0	0
Volume of damaged trees (m^3/ha)	21	40	41	0	0	0
Average amount of CO_2 stored in AGB (tCO_2/ha)	118	151	243	661	661	661
Average amount of CO_2 stored in EWP (tCO_2/ha)	7	10	13	0	0	0

Tables 4.4 and 4.5 present key results for credits for carbon stored in AGB and EWP for the case of private management and government management, respectively. The dashed lines in Figures 4.2 and 4.3 present the corresponding carbon supply curves. Interestingly, allowing for carbon credits for carbon stored in end-use wood products does not increase LEV and, at some prices, even reduces LEV, both for the private and the government forest manager. The forest manager only gets paid for carbon stored above the amount stored under the baseline. This effectively works as a lump sum tax equal to the present value of carbon stored under the baseline. With credits for carbon stored in EWP, this amount is larger than what she is able to earn through credits for EWP, despite her optimizing behaviour. That is, forest managers prefer not to receive compensation for carbon stored in final products; they are better off with a crediting scheme for carbon stored in AGB only.

Comparing the results in Tables 4.2 and 4.3 with those in Tables 4.4 and 4.5 shows that credits for carbon in EWP shorten the cutting cycle and reduce extracted volume per harvest at intermediate and higher carbon prices. There are several forces at work here. First, obtaining credits for carbon stored in EWP gives an incentive to shorten the cutting cycle. Since payment takes place at the instant of harvest, the payment can be obtained earlier when the cutting cycle is shorter; due to discounting, then, a shorter rotation is preferred (ceteris paribus). Second, there is an incentive to increase harvested volume to obtain credits for carbon stored in EWP. However, this is more than offset by foregone credits for carbon stored in the remaining stand: not only is the amount of carbon in AGB reduced by the increased harvest, it also decreases due to additional damage. Note also that one ton of carbon harvested leads to less than one ton stored in EWP due to losses from skidding, transportation, and a less than 100% recovery rate at the sawmill. Together with the shorter cutting cycle (which leads to less biomass accumulation between harvests) this results in a lower volume harvested when allowing for credits for carbon in EWP. As a result, payments for carbon stored in EWP never increase the amount of carbon stored but rather reduce it for most carbon prices. This is also shown in Figures 4.2 and 4.3.

Figures 4.2 and 4.3 present the carbon supply curves resulting from maximizing the LEV in Equation (4.19) or (4.21). However, these results are local optima in the sense that we did not compare the LEV for a positive harvest with the LEV of not harvesting for each carbon price (maximizing Equation (4.20)). Now we turn to this comparison in order to ensure a global optimum is obtained.

4.4.5. To harvest or not to harvest?

Since our analysis employs a steady state model that determines the maximum LEV by considering marginal changes in the stand before harvest, volume harvested and the length of the cutting cycle, we need to check whether the optimal regime with positive harvest is preferred to not harvesting. For a given carbon price, a small increase in this price might lead to an increase in the length of the cutting cycle and the LEV from timber and carbon revenues after re-optimization (Equations (4.19) and (4.21)). However, it might be optimal to switch to a 'no harvest' regime instead (Equation (4.20)). Table 4.6 reports LEVs for a no harvest regime and compares them with LEVs from locally optimal cutting cycles.

Table 4.6. LEV of 'harvest' and 'no harvest' scenario for RIL and CL with and without carbon credits for carbon stored in end-use wood products for government and concessionaire case

Private management						
Price temporary credit (USD/tCO_2)	0	1	2	3	4	5
Equivalent price permanent credit (USD/tCO_2)	0	3.93	7.86	11.79	15.72	19.65
LEV no harvest (USD/ha)	-11,045	- 4,682	1,682	8,046	14,410	20,774
LEV with harvest (USD/ha) of RIL without EWP	29	57	135	260	690	20,774
LEV with harvest (USD/ha) of RIL with EWP	29	57	132	258	690	20,774
Government management						
Price temporary credit (USD/tCO_2)	0	1	2	3	4	5
Equivalent price permanent credit (USD/tCO_2)	0	12.25	24.51	36.76	49.02	61.27
LEV no harvest (USD/ha)	-16,632	-171	16,290	32,750	49,211	65,672
LEV with harvest (USD/ha) of RIL without EWP	492	714	1,634	32,750	49,211	65,672
LEV with harvest (USD/ha) of RIL with EWP	492	703	1,600	32,750	49,211	65,672

Table 4.6 shows that at low carbon prices it is optimal to harvest as it gives a higher LEV than managing a climax forest. In contrast, LEVs are higher in the "no harvest" scenario starting from a carbon price of 2.0 USD/tCO_2 for private management and 1.2 USD/tCO_2 for government management. These prices are lower than the 4.5 and 2.9 USD/tCO_2 found in section 4.4.2. Figures 4.4 and 4.5 present the corresponding carbon storage supply curves. To understand the difference between Figures 4.2 and 4.3 on the one hand and Figures 4.4 and 4.5 on the other, notice that the supply curves of Figures 4.2 and 4.3 take the perspective of a forest manager with an infinite planning horizon who considers small adjustments in forest management when the carbon price changes marginally. In this case adjustments to the steady state forest stand and the management practices will be marginal.

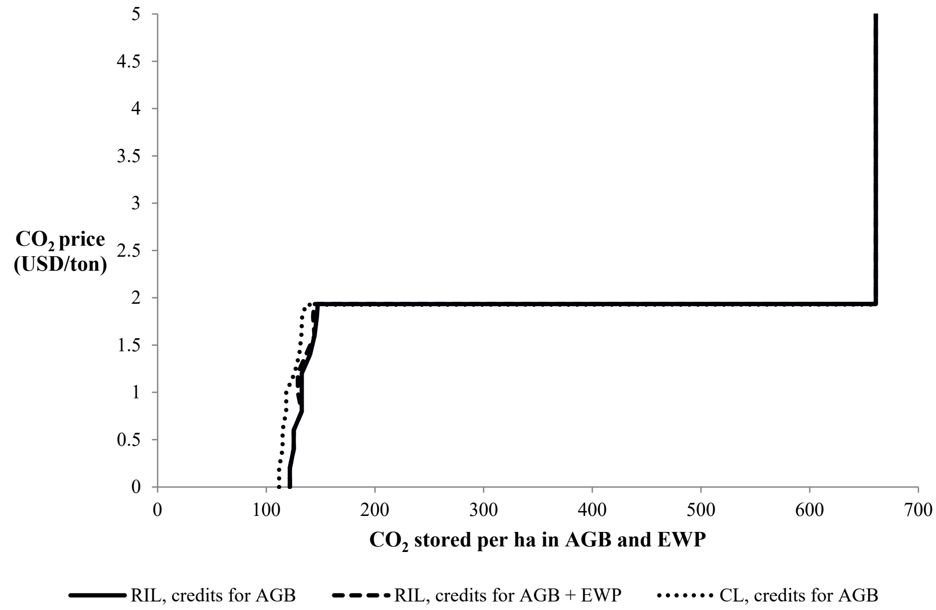

Figure 4.4. Supply curves for carbon storage for a managed tropical forest on Kalimantan, Indonesia, for RIL and CL: global solutions (private case)

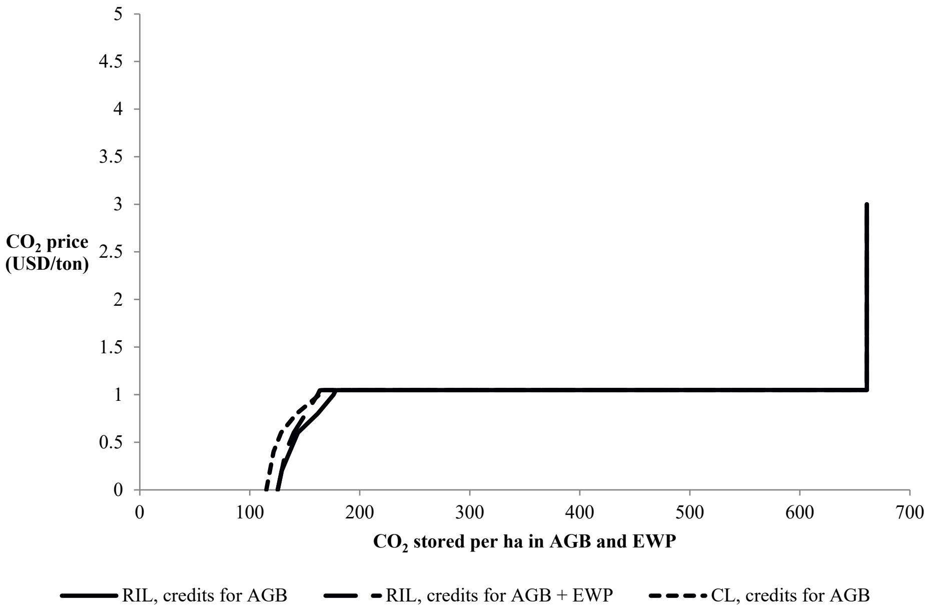

Figure 4.5. Supply curves for carbon storage for a managed tropical forest on Kalimantan, Indonesia, for RIL and CL: global solutions (government case)

By contrast the supply curves for forest carbon storage in Figures 4.4 and 4.5 come from the perspective of a forest manager with an infinite planning horizon who can chose an optimal steady state forest stand and adopt the associated harvest and management schedule.

Hence, the difference between the carbon supply curves in Figures 4.2-3 and 4.4-5 is a direct result of the fact that we use a steady state model and do not consider the transition phase from one forest stand before harvest to another when the carbon price changes. Extending the Buongiorno and Michie (1980) framework with a transition phase for simulating forest carbon supply curves is an important line of future research.

4.5. Conclusions

We have applied a Hartman model to a tropical forest considering timber values and benefits of carbon sequestration from sustainable forest management (REDD+) for both privately managed and government managed forests. In the latter case, the discount rate is lower and no taxes have to be paid. We have used detailed data from Kalimantan, Indonesia, and presented supply curves for forest carbon sequestration in the context of REDD+, representing conditions when carbon credits are awarded only for carbon stored in above-ground biomass and when credits are also awarded for carbon end-use wood products. Our main conclusions are as follows.

First, if carbon credits are valued at 0.7 USD/tCO_2 for two-year credits (equivalent to the average 2015 price of permanent credits in the EU ETS), the total amount of CO_2 (implicitly) stored per ha in AGB and EWP for a production forest with selective logging on Kalimantan could increase by 15.8%.[10] It should be noted that this analysis applies at the level of one hectare. Carbon crediting schemes may require a forest manager to set-aside part of her land for conservation purposes. Hence our results regarding LEV and the carbon price at which it becomes optimal to switch from CL to RIL do not carry over to the landscape level. Indeed, if such a requirement were included in a carbon credit scheme, at the landscape level the average LEV for an accredited forest would be lower and the carbon price at which it is optimal for a private manager to switch from CL to RIL and accept the crediting scheme would be higher.

Second, the extracted volume of timber increases with the carbon price up to a price of 1.2 USD/tCO_2 (4.7 USD/ tCO_2 for permanent credits) for privately managed forests and up to 2.2 USD/tCO_2 (27 USD/ tCO_2 for permanent credits) for government managed forests. This shows that sustainable forest management, forest carbon sequestration and production of commercial timber – important for employment in the sawmill and manufacturing industries – go hand in hand for low carbon prices but become substitutes at higher prices.

Third, remuneration for carbon stored in end-use wood products (EWP) has a negative effect on land expectation value. The forest manager only gets paid for carbon stored above the amount stored under the baseline. This effectively works as a lump sum tax equal to the present value of carbon stored under the baseline. With credits for carbon stored in EWP, this amount is larger than the earnings that can be obtained through credits for EWP, despite the optimizing behaviour. That is, forest managers are better off with a crediting scheme for carbon stored in AGB only.

Fourth, credits for carbon stored in EWP do not increase the amount of carbon stored as carbon stored in end-use products incentivizes cutting and goes at the expense of carbon stored in trees. Cutting more trees for timber also increases damages on the remaining stand, and carbon is lost to the atmosphere due to inefficiencies during transport and timber processing.

[10] 95.8% of managed tropical forest on Kalimantan is privately managed (Hutan-Aceh, 2014). We assume that all privately managed forest is currently managed using CL, cf. our results in Table 4.1, and all government managed forest is currently managed using RIL.

Fifth, the exact shapes of the carbon supply curves depend on the interpretation of our steady state model. If it is assumed that forest managers can immediately adjust the stand of their forest into the climax forest, then it is optimal to switch to a no-harvest policy already at lower prices (2.0 USD/tCO_2 for the private case and 1.2 USD/tCO_2 for the government case) than if the model is interpreted as representing marginal changes (in which case switching prices are 4.5 and 2.9 USD/tCO_2 respectively).

An interesting line for future research is to extend the current model with a transition phase from an existing initial stand to a new steady state forest and derive supply curves for forest carbon sequestration for the transition phase and for the steady state.

Appendix 4.1. Data for the forest growth model

$$A_1 = \begin{bmatrix}
0.80 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.16 & 0.79 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.17 & 0.79 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.18 & 0.78 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.19 & 0.78 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.19 & 0.78 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.20 & 0.78 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.19 & 0.79 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.19 & 0.79 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.18 & 0.80 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.17 & 0.81 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.16 & 0.82 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.14 & 0.95
\end{bmatrix}$$

$$A_2 = \begin{bmatrix}
0.84 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.14 & 0.84 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.13 & 0.84 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.13 & 0.83 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.12 & 0.83 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.11 & 0.83 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.11 & 0.82 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.10 & 0.82 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.09 & 0.81 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.08 & 0.80 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.07 & 0.79 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.06 & 0.78 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.05 & 0.81
\end{bmatrix}$$

$$A_3 = \begin{bmatrix}
0.81 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.13 & 0.81 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.13 & 0.81 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.12 & 0.81 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.12 & 0.81 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.11 & 0.81 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.11 & 0.81 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.10 & 0.81 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.10 & 0.81 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.09 & 0.81 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.09 & 0.81 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.08 & 0.80 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.08 & 0.88
\end{bmatrix}$$

The ingrowth matrices $\mathbf{R}_{ik}$ only contain nonzero values on the first row. For the sake of brevity, we omit the remaining rows.

$$\mathbf{R}_{11} = \begin{bmatrix} 0.0103 & 0.0102 & 0.0099 & 0.0097 & 0.0093 & 0.0090 & 0.0085 & 0.0080 & 0.0075 & 0.0069 & 0.0062 & 0.0055 & 0.0047 \end{bmatrix}$$

$$\mathbf{R}_{12} = \begin{bmatrix} -0.0002 & -0.0003 & -0.0006 & -0.0008 & -0.0012 & -0.0015 & -0.0020 & -0.0025 & -0.0030 & -0.0036 & -0.0043 & -0.0050 & -0.0058 \end{bmatrix}$$

$$\mathbf{R}_{13} = \begin{bmatrix} -0.0002 & -0.0003 & -0.0006 & -0.0008 & -0.0012 & -0.0015 & -0.0020 & -0.0025 & -0.0030 & -0.0036 & -0.0043 & -0.0050 & -0.0058 \end{bmatrix}$$

$$\mathbf{R}_{21} = \begin{bmatrix} -0.0002 & -0.0003 & -0.0006 & -0.0008 & -0.0012 & -0.0015 & -0.0020 & -0.0025 & -0.0030 & -0.0036 & -0.0043 & -0.0050 & -0.0058 \end{bmatrix}$$

$$\mathbf{R}_{22} = \begin{bmatrix} 0.0103 & 0.0102 & 0.0099 & 0.0097 & 0.0093 & 0.0090 & 0.0085 & 0.0080 & 0.0075 & 0.0069 & 0.0062 & 0.0055 & 0.0047 \end{bmatrix}$$

$$\mathbf{R}_{23} = \begin{bmatrix} -0.0002 & -0.0003 & -0.0006 & -0.0008 & -0.0012 & -0.0015 & -0.0020 & -0.0025 & -0.0030 & -0.0036 & -0.0043 & -0.0050 & -0.0058 \end{bmatrix}$$

$$\mathbf{R}_{31} = \begin{bmatrix} -0.0002 & -0.0003 & -0.0006 & -0.0008 & -0.0012 & -0.0015 & -0.0020 & -0.0025 & -0.0030 & -0.0036 & -0.0043 & -0.0050 & -0.0058 \end{bmatrix}$$

$$\mathbf{R}_{32} = \begin{bmatrix} -0.0002 & -0.0003 & -0.0006 & -0.0008 & -0.0012 & -0.0015 & -0.0020 & -0.0025 & -0.0030 & -0.0036 & -0.0043 & -0.0050 & -0.0058 \end{bmatrix}$$

$$\mathbf{R}_{33} = \begin{bmatrix} 0.0103 & 0.0102 & 0.0099 & 0.0097 & 0.0093 & 0.0090 & 0.0085 & 0.0080 & 0.0075 & 0.0069 & 0.0062 & 0.0055 & 0.0047 \end{bmatrix}$$

$$\boldsymbol{c}_1' = [3.89\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0]$$

$$\boldsymbol{c}_2' = [3.88\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0]$$

$$\boldsymbol{c}_3' = [1.87\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0]$$

$$\mathbf{E}_{CL} = \begin{bmatrix} 0.043 &&&&&&&&&&&& \\ & 0.043 &&&&&&&&&&& \\ && 0.043 &&&&&&&&&& \\ &&& 0.043 &&&&&&&&& \\ &&&& 0.046 &&&&&&&& \\ &&&&& 0.046 &&&&&&& \\ &&&&&& 0.046 &&&&&& \\ &&&&&&& 0.046 &&&&& \\ &&&&&&&& 0.051 &&&& \\ &&&&&&&&& 0.051 &&& \\ &&&&&&&&&& 0.045 && \\ &&&&&&&&&&& 0.045 & \\ &&&&&&&&&&&& 0.029 \end{bmatrix}$$

$$\mathbf{E}_{RIL} = \begin{bmatrix} 0.039 &&&&&&&&&&&& \\ & 0.039 &&&&&&&&&&& \\ && 0.039 &&&&&&&&&& \\ &&& 0.039 &&&&&&&&& \\ &&&& 0.034 &&&&&&&& \\ &&&&& 0.034 &&&&&&& \\ &&&&&& 0.044 &&&&&& \\ &&&&&&& 0.044 &&&&& \\ &&&&&&&& 0.036 &&&& \\ &&&&&&&&& 0.036 &&& \\ &&&&&&&&&& 0.034 && \\ &&&&&&&&&&& 0.034 & \\ &&&&&&&&&&&& 0.024 \end{bmatrix}$$

Appendix 4.2. Additional Tables

Table A4.2.1. Economic parameters, all values in 2012 US dollars.

	CL	RIL	Source
Fixed costs (in USD/ha)			
Administration and investment			PT Sumalindo Lestari Jaya (2008)
Environmental Impact Assessment (EIA)	0.37	0.37	
Technical Proposal	0.12	0.12	
Working area Definition	0.12	0.12	
Recommendation from Bupati/Gubernur	0.37	0.37	
Building	22.77	22.77	
Forest protection	3.96	3.96	
Transportation	17.76	17.76	
Machineries	218.08	304.19	
Office	2.88	2.88	
Supporting equipment	9.38	9.38	
Pre harvesting			Dwiprabowo et al. (2002)
Timber inventory and contour survey	10.06	13.92	
Data entry and block mapping	1.00	1.31	
Data checking and mapping		0.44	
Skidtrail marking and checking		0.95	
ROADENG software purchase		0.23	
Vine cutting		0.81	
Tax			
Concession license fee (IUPHHK)	5.34	5.34	
Building tax	4.64	4.64	
Total	**297**	**390**	
Variable costs (in USD/m^3)			
Production			
Training		0.47	Dwiprabowo et al. (2002)
Supervision	0.12	0.24	
Felling	0.42	0.42	
Skidding	6.09	4.41	
Log landing opening	0.11	0.08	
Road construction and maintenance	7.90	7.90	
Log transport	31.80	31.80	
Total	**46.4**	**44.8**	

(Table continues on next page)

Table A4.2.1. Economic parameters, all values in 2012 US dollars (continued).

	CL	RIL	Source
Taxes and prices			
Royalty Tax Dipterocarp*	13.7	13.7	Gov't Regulation No 51/1998
Royalty Tax non Dipterocarp*	10.3	10.3	Gov't Regulation No 51/1998
Reforestation Fund (DR) Dipterocarp	16	16	Presidential Decree No 40/1993
Reforestation Fund (DR) non Dipterocarp	13	13	Presidential Decree No 40/1993
Price Dipterocarp (USD/m^3)	137	137	Min. of Trade Decree No 22/2012
Price non Dipterocarp (USD/m^3)	103	103	Min. of Trade Decree No 22/2012
Net price Dipterocarp (USD/m^3)**	60	61	
Net price Non- Dipterocarp (USD/m^3)**	32	34	
Discount rate	4%	4%	

* Ministry of Trade Decree No 22/2012 (royalty tax is 10% of the standard price determined by the government).

** Price after taxes and variable costs; elements of $\mathbf{v}_s$.

Table A4.2.2. Predicted stand state in the steady state condition with no harvest

Diameter (cm)	N/ha			Total
	Dipterocarp	Non Dipterocarp	Non Commercial	
10-14	24.85	28.84	9.69	63.4
15-19	18.71	24.57	6.81	50.1
20-24	14.94	20.03	4.60	39.6
25-29	12.47	15.43	2.97	30.9
30-34	10.77	11.09	1.84	23.7
35-39	9.53	7.33	1.09	17.9
40-44	8.57	4.39	0.62	13.6
45-49	7.78	2.35	0.33	10.5
50-54	7.07	1.10	0.17	8.3
55-59	6.39	0.44	0.08	6.9
60-64	5.69	0.15	0.04	5.9
65-69	4.93	0.04	0.02	5.0
≥ 70	14.77	0.01	0.01	14.8
Population (N/ha)	146.4	115.8	28.3	290.5
Basal Area (m^2/ha)	19.4	5.8	1.1	26.4
Volume (m^3/ha)	270	51	9	330
Carbon stored in biomass (ton/ha)	196.02	46.34	8.65	251

Table A4.2.3. Predicted above ground biomass, root biomass, and carbon stored in biomass in dipterocarp, non-dipterocarp and non-commercial species

Diameter (cm)	Dipterocarp		Non Dipterocarp		Non-commercial	
	AGB (ton /tree)	C stock (ton /tree)	AGB (ton /tree)	C stock (ton /tree)	AGB (ton /tree)	C stock (ton /tree)
10-14	0.082	0.039	0.082	0.039	0.082	0.039
15-19	0.200	0.094	0.200	0.094	0.200	0.094
20-24	0.388	0.183	0.388	0.183	0.388	0.183
25-29	0.655	0.308	0.655	0.308	0.655	0.308
30-34	1.009	0.474	1.009	0.474	1.009	0.474
35-39	1.454	0.683	1.454	0.683	1.454	0.683
40-44	1.995	0.938	1.995	0.938	1.995	0.938
45-49	2.636	1.239	2.636	1.239	2.636	1.239
50-54	3.378	1.587	3.378	1.587	3.378	1.587
55-59	4.222	1.984	4.222	1.984	4.222	1.984
60-64	5.171	2.430	5.171	2.430	5.171	2.430
65-69	6.223	2.925	6.223	2.925	6.223	2.925
≥ 70	7.380	3.469	7.380	3.469	7.380	3.469

Table A4.2.4. Estimated wood volume and basal area of dipterocarp, non-dipterocarp and non-commercial species

Diameter (cm)	Dipterocarp		Non Dipterocarp		Non-commercial	
	Volume (m^3/tree)	Basal Area (m^2/tree)	Volume (m^3/tree)	Basal Area (m^2/tree)	Volume (m^3/tree)	Basal Area (m^2/tree)
10-14	0.17	0.012	0.06	0.012	0.06	0.012
15-19	0.25	0.024	0.13	0.024	0.13	0.024
20-24	0.41	0.040	0.28	0.040	0.28	0.040
25-29	0.64	0.059	0.49	0.059	0.49	0.059
30-34	0.96	0.083	0.76	0.083	0.76	0.083
35-39	1.35	0.110	1.11	0.110	1.11	0.110
40-44	1.82	0.142	1.51	0.142	1.51	0.142
45-49	2.37	0.177	1.99	0.177	1.99	0.177
50-54	3.00	0.217	2.53	0.217	2.53	0.217
55-59	3.70	0.260	3.13	0.260	3.13	0.260
60-64	4.49	0.307	3.81	0.307	3.81	0.307
65-69	5.35	0.358	4.54	0.358	4.54	0.358
≥ 70	6.29	0.413	5.35	0.413	5.35	0.413

Table A4.2.5. Value of trees in each species and diameter class

Diameter (cm)	Value of trees					
	Dipterocarp		Non Dipterocarp		Non-commercial	
	CL (USD/tree)	RIL (USD/tree)	CL (USD/tree)	RIL (USD/tree)	CL (USD/tree)	RIL (USD/tree)
10-14	0	0	0	0	0	0
15-19	0	0	0	0	0	0
20-24	0	0	0	0	0	0
25-29	0	0	0	0	0	0
30-34	0	0	0	0	0	0
35-39	0	0	0	0	0	0
40-44	87	89	39	41	0	0
45-49	113	116	51	54	0	0
50-54	143	147	65	68	0	0
55-59	176	181	81	85	0	0
60-64	214	219	98	103	0	0
65-69	255	262	117	123	0	0
≥ 70	299	308	137	144	0	0

CHAPTER 5

5

Chapter 5. Logging Damage and Injured Tree Mortality in Tropical Forest Management[1]

Abstract

Using insights from the forest ecology literature, we analyze the effect of injured trees on stand composition and carbon stored in above-ground biomass, and the implications for forest management decisions. Results from a Faustmann model with data for a tropical forest on Kalimantan show that up to 50% of the basal area of the stand before harvest can consist of injured trees. Considering injured trees leads to an increase in the amount of carbon in above-ground biomass of up to 165%. These effects are larger under reduced impact logging than under conventional logging. The effects on land expectation value and cutting cycle are relatively small. The results suggest that considering injured trees in models for tropical forest management is important for the correct assessment of the potential of financial programs to store carbon and conserve forest ecosystem services in managed tropical forests, such as REDD+ and Payment for Ecosystem Services.

Keywords: bioeconomic model, age-structured model, logging damage, tree mortality, Faustmann, Kalimantan, sustainable forest management, reduced impact logging, conventional logging, tropical forest

5.1. Introduction

Limiting global warming to no more than 2°C, and preferably below 1.5°C, has become the target for global climate policy. To achieve this target, it will be necessary to utilize carbon sinks, including forests as natural sinks (Rogelj et al. 2015). The extraction of wood from tropical forests using selective logging causes forest degradation, especially through the resulting damage on the remaining stand (Medjibe and Putz 2012) and thereby a reduction in the pool of stored carbon. This is particularly the case when conventional logging (CL) techniques are used as workers start cutting ill-trained and ill-prepared. Carbon losses can be reduced with the use of reduced-impact logging (RIL), i.e., “intensively planned and carefully

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controlled timber harvesting conducted by trained workers in ways that minimize the deleterious impacts of logging" (Putz et al. 2008). Although uniform guidelines for RIL do not exist (Putz et al. 2008), common RIL practices include pre-harvest planning (block layout, inventory, vine cutting, data processing, map-making), harvest planning (tree marking, road planning, log deck planning), infrastructure development (road construction, log deck construction, skidtrail layout), directional felling and low stumps (Dykstra and Heinrich 1996; Holmes et al. 2002). Estimates for the fraction of the remaining stand that gets damaged during harvest range from 48% to 65% for CL and from 28% to 38% for RIL (Pinard and Putz 1996; Bertault and Sist 1997; Sist, Sheil, et al. 2003). Still, a large fraction of damaged trees does not die but rather gets injured (e.g., crown or bark injury) where the survival rate for damaged trees is higher for RIL (54-62%) than for CL (39-52%) (Pinard and Putz 1996; Bertault and Sist 1997; Sist, Sheil, et al. 2003). Contrary to decayed dead trees, injured trees contribute to the stock of carbon, yet they negatively affect the development of young trees as they take away light and nutrients.

The economic literature on the optimal management of managed tropical forests has dealt with harvest damages in various ways. Some papers ignore damages altogether (e.g., Ingram and Buongiorno (1996)), some assume logging affects only smaller diameter classes (Boscolo and Buongiorno 1997; Boscolo et al. 1997; Boscolo and Vincent 2000), whereas others have a detailed representation of the harvest-damage relation (Indrajaya et al. 2016). Importantly, all papers assume that all damaged trees (whether they are dead or only injured) decay quickly and do not affect the remaining stand. Surprisingly, none of these papers takes the indirect costs of injured trees into account, despite the fact that these trees negatively affect the growth of the rest of the stand – notably the ingrowth of new trees. Ignoring the role of injured trees leads to gross underestimates of the amount of carbon stored in managed tropical forests, and affects recommendations regarding optimal management decisions such as harvest rates and cutting cycle.

In this chapter, we explicitly take the role of harvest damages and the biophysical and economic effects of the presence of injured trees into account when analyzing the optimal management of a tropical forest. Using findings from the forest ecology literature, we allow for a large fraction of damaged trees to remain on the stand after harvest and thereby to contribute to the carbon pool while negatively affecting the ingrowth of new trees. We use the detailed harvest-damage relation modeled in Indrajaya et al. (2016) together with detailed data on forest growth and management costs for a forest on Kalimantan in a Faustmann model. We use a scenario in which logging does not cause any damages as a point of reference to analyze the effects of different assumptions about the role of injured trees (both regarding their presence and their mortality rate) on stand composition, carbon stored in above-ground biomass, and economic decision variables such as the cutting cycle. Among other things, we find that ignoring the role of injured trees can lead to underestimates of the amount of carbon stored in above-ground biomass of up to 109% with conventional logging and up to 165% with reduced impact logging.

The remainder of this chapter is organized as follows. In the next section, we first describe the economic optimization model and the forest growth model. We subsequently present the scenarios and parameters used for our analysis. We present our results in section 5.3 and perform a sensitivity analysis in section 5.4. We conclude in section 5.5.

5.2. Study methods and materials

Our model builds on the matrix stand growth model developed by Buongiorno and Michie (1980) and has previously been applied in Indrajaya et al. (2016). We use one hectare of forest stand as our unit of analysis.

5.2.1. Economic and forest growth models

5.2.1.1. Forest growth and damage model

Let l indicate the number of species groups. Each species group has a healthy variety and an injured variety. To make a distinction between the healthy varieties and injured varieties of a species group, we order species groups such that the first $l = m/2$ species varieties indicate healthy varieties; that is, $i, k \in [1, \ldots, l]$ indicate healthy varieties and $i, k \in [l+1, \ldots, m]$ indicate injured varieties of the same species groups.

Forest growth can be described as

$$\mathbf{y}_{T+\theta} = \mathbf{G}_x \mathbf{z}_T + \mathbf{c}; \mathbf{y}_{t+\theta\gamma} = \mathbf{G}_x\big(\mathbf{y}_{t+\theta(\gamma-1)}\big) + \mathbf{c}, \tag{5.1}$$

where vector $\mathbf{y}_t = [y_{ijt}]$ is a column vector and y_{ijt} is the number of the trees per ha of species variety i and diameter class $j \in [1, \ldots, n]$ at time t. Parameter θ represents the growth period in years and γ is the number of growth periods θ within the harvesting cycle (T). Vector $\mathbf{z}_T = [z_{ijT}]$ denotes the residual stand after harvest. Matrix $\mathbf{G}_x$ is the $nm \times nm$ forest growth matrix where x indicates the scenario at hand. It consists of an upgrowth matrix and an ingrowth matrix:

$$\mathbf{G}_x = \mathbf{A}_x + \mathbf{R}_x. \tag{5.2}$$

Matrix $\mathbf{A}_x$ is an upgrowth matrix representing the probabilities of a tree in each species group and diameter class to stay in the same diameter class (a_{ij}), die ($o_{x,ij}$), or move to a larger diameter class ($b_{x,ij} = 1 - a_{ij} - o_{xij}$). Among other things, we analyze the effect of a higher mortality rate for injured varieties while keeping the probability of an injured tree to stay in the same diameter class constant. Hence, the mortality rate o_{xij} and the probability to move to a larger diameter class b_{xij} depend on the scenario at hand, x:

$$\mathbf{A}_x = \begin{bmatrix} \mathbf{A}_{x,1} & 0 & \dots & 0 \\ 0 & \mathbf{A}_{x,2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \mathbf{A}_{x,m} \end{bmatrix}; \ \mathbf{A}_{xi} = \begin{bmatrix} a_{i1} & 0 & \dots & 0 \\ b_{x,i2} & a_{i2} & \dots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \dots & b_{x,in} & a_{in} \end{bmatrix}. \tag{5.3}$$

Matrix $\mathbf{R}_x$ represents the effects of the stand state on ingrowth. It is based on the hypothesis that ingrowth for a species is positively affected by the number of trees of that species, and negatively affected by the total stand density (Buongiorno and Michie 1980; Lu and Buongiorno 1993; Buongiorno et al. 1995). In Section 5.2.2, we develop scenarios with different assumptions about the impact of injured trees on ingrowth into the healthy variety of the own species group. We assume that there is no ingrowth in injured species varieties: trees enter these varieties only when being injured after harvest. That is,

$$\mathbf{R}_x = \begin{bmatrix} \mathbf{R}_{x,11} & \mathbf{R}_{x,12} & \dots & \mathbf{R}_{x,1m} \\ \mathbf{R}_{x,21} & \mathbf{R}_{x,22} & \dots & \mathbf{R}_{x,2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{R}_{x,m1} & \mathbf{R}_{x,m2} & \dots & \mathbf{R}_{x,mm} \end{bmatrix}; \ \mathbf{R}_{xik} = \begin{bmatrix} e_{x,ik1} & e_{x,ik2} & \dots & e_{x,ikn} \\ 0 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 \end{bmatrix} \text{ for } i \le l;$$

$$\mathbf{R}_{x,ik} = \mathbf{0} \text{ for } i > l. \tag{5.4}$$

Furthermore, ingrowth is positively affected by trees from the own species group due to the presence of seedlings ($e_{x,ikj} > 0$ for $i = k$) but negatively affected by trees from other species groups due to competition for light and nutrients ($e_{x,ikj} < 0$ for $i \neq k$), and $e_{x,ikj} = e_{x,kij}$ for $i \neq k$.

Finally, vector $\mathbf{c}$ contains the ingrowth constants representing the number of trees exogenously entering the smallest diameter class for each variety. There is no exogenous ingrowth in injured species varieties:

$$\mathbf{c} = \begin{bmatrix} \mathbf{c}_1 \\ \mathbf{c}_2 \\ \vdots \\ \mathbf{c}_m \end{bmatrix}; \mathbf{c}_i = \begin{bmatrix} \beta_{i0} \\ 0 \\ \vdots \\ 0 \end{bmatrix} \text{ for } i \le l; \mathbf{c}_i = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \text{ for } i > l. \tag{5.5}$$

Harvest at the end of the cutting cycle is represented by vector $\mathbf{h}_T = [h_{ijT}]$, where h_{ijT} is the number of trees harvested of variety i and DBH (diameter at breast height) class j. The damage to the residual stand $\mathbf{d}_{xsT}$ is a function of overall logging intensity and this function depends on the scenario at hand, x, and the harvesting practice $s \in \{CL, RIL\}$. We will provide more details in Section 2.2. Equation (5.6) represents the stand immediately after harvest:

$$\mathbf{z}_T = \mathbf{y}_T - \mathbf{h}_T - \mathbf{\Gamma}_{xs}\mathbf{d}_{xsT}. \tag{5.6}$$

A novelty in our model is the introduction of matrix $\mathbf{\Gamma}_{xs}$. After harvest, this transition matrix moves a fraction of the trees that got damaged during harvest from 'healthy' species varieties to 'injured' species varieties. The rest of the damaged trees are considered dead and are assumed to decay sufficiently fast such that they no longer affect the ingrowth of new trees. The exact design of this matrix depends on the scenario at hand and will be explained in Section 2.2. Note that the transition matrix differs for the two logging techniques: following Pinard and Putz (1996), Bertault and Sist (1997), and Sist, Sheil, et al. (2003), we assume that reduced impact logging leads to a smaller fraction of injured trees after harvest than conventional logging.

5.2.1.2. Economic model

Optimal management of a multi-age multi-species tropical forest concerns the choice of three variables: (i) type of logging practice (CL or RIL), (ii) length of the cutting cycle T, and (iii) harvest intensity $\mathbf{h}_T$ (i.e., number of trees harvested for each variety and diameter class per ha). The economic model for maximizing land expectation value (LEV) over an infinite horizon subject to logging damage, harvest and steady state equilibrium constraints for a given cutting cycle and logging practice looks as follows:

$$\max_{\mathbf{y}_T,\mathbf{h}_T} LEV = \frac{\mathbf{v}_s{}'\,\mathbf{h}_T - F_s}{(1+r)^T - 1} - \mathbf{v}_s{}'\mathbf{z}_T \tag{5.7}$$

subject to Equations (5.1), (5.6) and

$$\mathbf{y}_T \geq \mathbf{h}_T + \mathbf{d}_{xsT} \tag{5.8}$$

$$\mathbf{h}_T, \mathbf{y}_T, \mathbf{z}_T \geq 0 \tag{5.9}$$

$$h_{ij} = 0 \text{ for all } j < \eta \tag{5.10}$$

$$\mathbf{y}_t = \mathbf{y}_{t+T} \text{ for all } t = 1, \dots, \infty. \tag{5.11}$$

Vector $\mathbf{v}_s$ denotes the net revenue per tree (i.e., price minus variable costs and taxes) under logging practice s, F_s represents the fixed costs per ha of harvesting using logging practice s and r represents the discount rate. Equations (5.8) and (5.9) are the harvest and non-negativity constraints. Equation (5.10) represents the minimum diameter harvested, where η is the minimum diameter harvested as restricted by government regulation. Equation (5.11) shows the equilibrium steady state constraint. The harvesting cycle in years T is the product of the growth period of the forest growth model, θ, and the number of growth periods within one harvesting cycle, γ. We solve the model for different values of γ and then find the value of γ that maximizes the land expectation value.

5.2.2. Scenarios

Our focus in this chapter is on the effects of introducing a more realistic representation of the role of injured trees in a model for optimal tropical forest management as compared to existing literature. We are especially interested in the effects on stand density and composition, the amount of carbon stored in above-ground biomass and optimal management decisions (harvest intensity and cutting cycle). We proceed to describe our scenarios. For each scenario, we make assumptions on the following model characteristics:

A: The effect of harvesting on the stand through damages: $\mathbf{d}_{xsT}$;

B: The effect of damages on stand composition, i.e., whether some damaged trees move from healthy species varieties to injured species varieties: $\mathbf{\Gamma}_{xs}$;

C: The effect of injured trees on the ingrowth of healthy trees: $\mathbf{R}_{xik}$;

D: The growth parameter and mortality rate for injured trees for $i > l$: b_{xij} and o_{xij}.

5.2.2.1 Scenario A: No damage

Our first scenario is a reference scenario in which we make the extreme assumption that logging does not result in damages and, consequently, there are no injured or dead trees (e.g., Buongiorno et al. (2012), Ingram and Buongiorno (1996)). This allows us to examine the effects of the differences in fixed and variable costs for RIL and CL on the corresponding LEV and optimal cutting cycle and establish a baseline quantity of carbon stored in above-ground biomass. In subsequent scenarios, we will introduce more realistic assumptions about damaged trees.

We denote this scenario *Scenario A*, i.e., $x = A$ in which we assume

$$\mathbf{d}_{AsT} = \mathbf{0} \tag{5.12}$$

and since no trees need to be moved from healthy to injured species varieties

$$\mathbf{\Gamma}_{As} = \mathbf{I}_{nm\times nm}. \tag{5.13}$$

Furthermore, since there is no distinction between healthy and injured trees,

$$o_{Aij} = o_{ij}. \tag{5.14}$$

5.2.2.2. Scenario B: Damage occurs but does not affect growth of the remaining stand

For *Scenario B,* we follow Macpherson et al. (2010) and Indrajaya et al. (2016) and assume that harvest intensity and stand composition affect damages in the following way:

$$\mathbf{d}_{BsT} = \left(\sum_i \sum_j h_{ijT}\right)\mathbf{D}_s\mathbf{y}_T, \quad (5.12')$$

where $\mathbf{D}_s$ is an $mn \times mn$ damage matrix the diagonal of which contains the logging damage coefficients under logging practice s (damage coefficients are lower for reduced impact logging than for conventional logging). The damage coefficients represent the proportion of trees damaged per tree harvested within each species group i and diameter class j. Matrix $\mathbf{D}_s$ consists of damage coefficient matrices $\mathbf{E}_s$ and null matrices:

$$\mathbf{D}_s = \begin{bmatrix} \mathbf{E}_s & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{E}_s & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{E}_s \end{bmatrix}. \quad (5.15)$$

In this scenario, we assume that all damaged trees decay sufficiently fast such that they do not affect the growth of the remaining stand, irrespective of their physical condition: injured but still alive (for example due to a bark or crown injury) or dead (for example due to a broken trunk). This is a common assumption in the literature on the optimal management of multi-age forests (e.g., Boscolo et al. (1997), Boscolo and Vincent (2000), Boscolo and Vincent (2003), Indrajaya et al. (2016), Tahvonen (2009)). As a result, as in *Scenario A*, no trees need to be moved from healthy to injured species varieties so,

$$\mathbf{\Gamma}_{Bs} = \mathbf{I}_{nm\times nm} \quad (5.13')$$

and

$$o_{Bij} = o_{ij}. \quad (5.14')$$

Comparing the results of this scenario with those of *Scenario A* allows us to disentangle the effects of differences in costs and the effects of differences in damages between CL and RIL on various variables.

5.2.2.3. Scenario C: Damage occurs and injured trees affect growth

In *Scenario C* we assume harvest causes damages to the remaining stand, as in *Scenario B*:

$$\mathbf{d}_{CsT} = \left(\sum_i \sum_j h_{ijT}\right)\mathbf{D}_s\mathbf{y}_T. \quad (5.12'')$$

However, in the current scenario we divide damaged trees into two groups: injured trees and dead trees. We follow the existing literature in assuming that dead trees decay sufficiently fast not to affect the growth rate of the other trees or the carbon pool (Ingram and Buongiorno (1996), Boscolo and Buongiorno (1997), Boscolo et al. (1997), Boscolo and Vincent (2000), Indrajaya et al. (2016)). This assumption can be justified using insights from the literature on the decomposition of woody debris in the tropical forest of South-East Asia. Yoneda et al. (1977) and Yoneda et al. (1990) found that the half time of litter in these forests ranges from less than one to 2.5 years. Mori et al. (2014) found half times of litter ranging from less than one year to almost 28 years, with most species having a half time of less than five years and a third of the species having a half time of less than two years. None of these studies explicitly looks at the effects of litter on other trees. Given that the decay rates of most species appear to be rather high, and given that our growth model has two-year growth steps, we assume that dead trees do not affect the growth of other trees. Note that this is not the same as assuming that dead trees fully decay in two years.

Crucially, we differ from the literature by assuming that injured trees stay on the plot. Mathematically, for each species group and each diameter class a fraction of the damaged trees that disappeared after harvest in *Scenario B* now stays on the plot and moves from the 'healthy' species variety to the corresponding 'injured' species variety. Let $\omega_{i,j,s}$ denote the proportion of damaged trees in diameter class j of 'healthy' species variety $i \leq l$ that moves to diameter class j of its corresponding 'injured' species variety $k > l$ after harvest. This proportion depends on s, the logging technique used. In *Scenario C* we assume

$$\mathbf{\Gamma}_{Cs} = \begin{bmatrix} \mathbf{\Gamma}_{1,1,s} & \cdots & \mathbf{\Gamma}_{1,m,s} \\ \vdots & \ddots & \vdots \\ \mathbf{\Gamma}_{m,1,s} & \cdots & \mathbf{\Gamma}_{m,m,s} \end{bmatrix} \tag{5.13''}$$

where $\mathbf{\Gamma}_{i,k,s} = \mathbf{I}_{nl \times nl}$ for $i, k \leq l$ so all previously healthy trees that got damaged during harvest move out of the 'healthy' species variety; $\mathbf{\Gamma}_{i,k,s} = \mathbf{0}$ for $i \leq l$ and $k > l$ as after harvest previously injured trees do not suddenly become healthy; $\mathbf{\Gamma}_{i,k,s} = -\mathbf{I}_{nl \times nl}\boldsymbol{\omega}_s$ for $i > l$ and $k \leq l$ where $\boldsymbol{\omega}_s = [\boldsymbol{\omega}_{1,s} \cdots \boldsymbol{\omega}_{l,s}]'$ and $\boldsymbol{\omega}_{i,s} = [\omega_{i,1,s} \cdots \omega_{i,n,s}]'$ – that is, a fraction $\omega_{i,j,s}$ of previously healthy trees in diameter class j that got damaged during harvest moves to the injured variety while the remainder dies; and $\mathbf{\Gamma}_{i,k,s} = \mathbf{I}_{nl \times nl} - \boldsymbol{\omega}_s \mathbf{I}_{nl \times nl}$ for $i, k > l$ (i.e., some trees that were previously injured, and therefore have zero commercial value, get damaged again).

In our growth model, the ingrowth of new trees is positively affected by the basal area of the own species group and negatively affected by the basal area of other species groups. Injured trees negatively affect the ingrowth of trees from other species. Regarding the effect of injured trees on ingrowth of the own species, however, we compare two different assumptions regarding ingrowth matrix **R**. First, we assume that injured trees still carry seedlings and thereby positively contribute to ingrowth of healthy trees of the own species, just like healthy trees: $e_{iij} > 0$. We denote this case '*Sub-scenario Positive*'. We subsequently analyze the effects of assuming that injured trees do not carry seedlings but do require nutrients and light and thereby negatively affect the ingrowth of healthy trees of the own species, just like healthy trees negatively affect the ingrowth of trees in other species groups: $e_{iij} < 0$. We denote this case '*Sub-scenario Negative*'.

As in *Scenario B*, we assume that injured trees and healthy trees have the same growth and mortality rates:

$$o_{Cij} = o_{ij} \text{ for all } i. \tag{5.14''}$$

Comparing the results for this scenario with those for *Scenario B* allows us to analyze the effect of the presence of injured trees that have zero commercial value but negatively affect the ingrowth of new trees from other species groups (and possibly of the own species group) due to competition for light and nutrients.

5.2.2.4. Scenario D: Damage occurs and injured trees have higher mortality rate

For *Scenario D,* we make the same assumptions regarding damages and injured species varieties as in *Scenario C*:

$$\mathbf{d}_{DsT} = \left(\sum_{\mathrm{i}} \sum_{\mathrm{j}} \mathrm{h}_{\mathrm{ijT}}\right)\mathbf{D}_{s}\mathbf{y}_{\mathrm{T}} \tag{5.12'''}$$

and

$$\mathbf{\Gamma}_{Ds} = \begin{bmatrix} \mathbf{\Gamma}_{1,1,s} & \cdots & \mathbf{\Gamma}_{1,m,s} \\ \vdots & \ddots & \vdots \\ \mathbf{\Gamma}_{m,1,s} & \cdots & \mathbf{\Gamma}_{m,m,s} \end{bmatrix}. \tag{5.13'''}$$

As in *Scenario C*, we also compare two different assumptions regarding the effect of injured trees on ingrowth of the own species (*Sub-scenarios Positive* and *Negative*).

In *Scenario D,* we assume that injured trees have a higher mortality rate than trees that are undamaged:

$$o_{Dij} = o_{ij} + \xi \text{ for } i > l. \tag{5.14'''}$$

That is, injured trees have a higher mortality rate, and a smaller fraction of injured trees move up to a larger diameter class than for healthy trees. Hence, with this scenario, we can assess the effect of higher tree mortality of injured trees.

5.2.3. Parameterization of the model

5.2.3.1. Forest growth parameters

We apply the forest growth model described in Indrajaya et al. (2016), which is based on the growth matrix developed by Krisnawati et al. (2008) for lowland dipterocarp forest in Central Kalimantan. The forest is dominated by dipterocarp species, including *Shorea* spp. and *Dipterocarpus* spp. We use a growth period θ of 2 years. There are three (healthy) species groups i in the growth matrix with $i = 1$ for commercial dipterocarp, $i = 2$ for commercial non-dipterocarp, and $i = 3$ for non-commercial species. Correspondingly, $i \in \{4, 5, 6\}$ indicates the respective injured variety of each species group. Each species group consists of 13 five-centimeter diameter classes ($j = 1$ for 10-14 cm DBH, and $j = 13$ for > 70 cm DBH). Since the growth matrix is empirically calibrated, trees entering the smallest diameter class are not seedlings but rather the number of trees that have reached a diameter of at least 10 cm DBH. Note that, in our model, trees are classified according to diameter class, not age in years. Furthermore, it is important to note that a cutting cycle of T years does not mean that harvested trees are T years old. Hence, ignoring trees with < 10 cm DBH does not affect the cutting cycle as long as the ingrowth into the 10-14 cm class is empirically calibrated, as it is in our model. Following current Indonesian policy, we apply a diameter cutting limit of 40 cm (i.e., $\eta = 40$). Which diameter classes above this DBH limit are being harvested is endogenously determined in the model through harvest intensity $\mathbf{h}_T$ (i.e., number of trees harvested for each variety and diameter class per ha) – see Equation (5.7): trees are only harvested when it is commercially attractive to do so. The complete growth matrices and model validation are presented in Indrajaya et al. (2016).

Damage parameters of matrix $\mathbf{D}_s$ in *Scenarios B-D* are as in Indrajaya et al. (2016) and are based on Priyadi et al. (2007). Parameter values are such that the lower the DBH class, the larger the number of damaged trees. Furthermore, CL causes more damages to the remaining stand than RIL: the latter reduces damages per tree harvested by 17% on average over all diameter classes and by 25% on average for trees of 50 cm diameter and larger relative to CL.

Damaged trees can further be classified into dead trees and injured trees. Bertault and Sist (1997) and Sist et al. (2003) compare tree injuries and mortalities after harvests based on conventional logging techniques with those after harvests based on reduced impact logging techniques in East Kalimantan, and Pinard and Putz (1996) do so for Sabah, Malaysia. From these papers, we calculate the average fraction (over all diameter classes over all three papers) of damaged trees that die after harvest to be 53% for CL and 43% for RIL. In Pinard and Putz (1996) these numbers are 61% and 46%, respectively. This is the only paper from which we can derive these parameters for different diameter classes while differentiating between CL and RIL. Our growth model has five-centimeter DBH classes, with the largest class being 60-70 cm. Pinard and Putz (1996) only report numbers for a fraction of damaged trees that dies or gets injured for the DBH classes 10-20, 20-40, and 40-60 cm; hence we assume that all five-centimeter classes *within* each of the broader 10-20, 20-40 and 40-60 DBH classes have the same fraction of damaged trees that dies after harvest. Furthermore, we assume that the numbers for the 60-70 cm class are the same as for the 40-60 cm class. This can be justified based on the findings by Bertault and Sist (1997), who report combined data for CL and RIL. We scale the numbers for the 10-20, 20-40 and 40-60 cm DBH classes as reported in Pinard and Putz [1996] down using the average fractions presented above and the fractions reported in Pinard and Putz [1996] which results in ratios 53/61 and 43/46 for CL and RIL respectively. These steps result in the parameters $\omega_{i,j,s}$ of transition matrix $\mathbf{\Gamma}_{xs}$, i.e. the proportion of damaged trees in diameter class j of 'healthy' species variety $i \leq l$ that moves to diameter class j of its corresponding 'injured' species variety $k > l$ after harvest, for *Scenarios C* and *D*. The values are presented in Table 5.1. Note that the remaining fraction $1 - \omega_{i,j,s}$ dies after harvest.

Table 5.1. The values for $\boldsymbol{\omega_{i,j,s}}$ for CL and RIL per DBH category

DBH (cm)	CL	RIL
10-14	0.45	0.50
15-19	0.45	0.50
20-24	0.50	0.73
25-29	0.50	0.73
30-34	0.50	0.73
35-39	0.50	0.73
40-44	0.60	0.79
45-49	0.60	0.79
50-54	0.60	0.79
55-60	0.60	0.79
60-64	0.60	0.79
65-69	0.60	0.79
>70	0.60	0.79

In *Scenario D* we use an increased mortality rate for injured trees as compared to healthy trees. To our knowledge, only one paper has analyzed the mortality of injured trees. We increase the annualized mortality rate of injured trees by 3.1 percentage points relative to that of healthy trees, based on the mean mortality rates of 1.8% and 4.9% for undamaged and injured trees, respectively, found by Sist and Nguyen-Thé (2002). Since our model is based on two-year growth periods we use $\xi = 0.059923$ which roughly implies a doubling of the mortality rate as compared to healthy trees.[2] Sist and Nguyen-Thé (2002) report that four years

[2] $\xi = (1 - (1 - 0.049)^2) - (1 - (1 - 0.018)^2) = 0.059923$.

after harvest they do not find statistically significant differences between mortality rates of the two groups, but the authors admit that "[t]his decrease of mortality in comparison to that recorded 2 years after logging was likely to be the result of the removal of the most badly damaged stems [through cutting or poisoning], eliminating by this way the most vulnerable trees in terms of survival." (p.89). As it is rather expensive, removal of badly damaged stems is usually not applied in managed tropical forests. In *Scenario D* we assume that the increase in mortality rate for injured trees is permanent. While this is a rather extreme assumption, it can be compared against the other extreme of no increase in mortality rate for injured trees which is assumed in *Scenario C*.

We estimate the weight of Above Ground Biomass (AGB) in metric tonnes per tree with the allometric equation developed by Chave et al. (2005): $AGB_j = \rho \times \exp\left(-1.499 + 2.148 \ln \overline{DBH}_j + 0.207 \ln \overline{DBH}_j^{\,2} - 0.0281 \ln \overline{DBH}_j^{\,3}\right)/1000$, where $\overline{DBH}_j$ represents the middle point of the diameter values in diameter class j, and ρ represents the wood density (i.e., 0.68 based on Rahayu et al. (2006)). The proportion of carbon stored in forest biomass is 0.47 (IPCC (2006)). The amount of carbon stored in AGB at time t is $\boldsymbol{\chi_t} = \mathbf{AGB'y_t}$. The average amount of carbon stored in AGB in one cutting cycle is therefore: $\bar{\boldsymbol{\chi}} = \sum_{t=\theta}^{T} \boldsymbol{\chi_t} / \gamma$, where γ is the number of growth periods within a cutting cycle.

5.2.3.2. Economic parameters

The production cost parameters for CL and RIL used in our study are those reported by Dwiprabowo et al. (2002) for a forest concession on East-Kalimantan and used in Indrajaya et al. (2016).[3] We use the investment and administration costs data from a technical proposal of a company in Kalimantan (PT Sumalindo Lestari Jaya 2008). The standard prices determined by the Indonesian government are used for gross prices of timber per m^3, in which commercial species are sorted into two groups: dipterocarp and non-dipterocarp.[4] The net price $\mathbf{v}_s$ is the gross price of timber minus the variable costs and taxes per cubic meter and is positive for healthy trees and zero for injured trees. The latter assumption is based on the observation that, in Indonesia, commercial trees from tropical forests are only used for construction, which requires high-quality timber, and not for pulp. Total variable costs are slightly lower for RIL than for CL (46.4 USD/m^3 vs. 44.8 USD/m^3), whereas the fixed costs per harvest for RIL are

[3] We express monetary values in USD of 2012 throughout the chapter.

[4] Ministry of Trade Decree No 22/M-DAG/PER/4/2012. The dipterocarp species price used is 1.270.000 IDR/m^3 and the price for commercial non-dipterocarp is 953.000 IDR/m^3.

substantially higher than those for CL (389 and 297 USD/ha per harvest, respectively). The different machines used and additional pre-harvesting activities with RIL such as data checking and mapping, skidtrail marking and checking, software purchasing, vine cutting, and improved timber inventory and contour survey cause higher fixed costs for RIL (Dwiprabowo et al. 2002). Our data are similar to data from Boltz et al. (2001) in that the variable costs are higher for CL than that for RIL and the fixed costs are higher for RIL than those for CL. Regarding variable costs, additional activities with RIL, such as training and supervision, also imply higher costs. However, this is more than offset by higher skidding costs with CL (Dwiprabowo et al. 2002). The resulting net price (standard price minus variable costs) is 59 USD/m^3 for dipterocarp and 32 USD/m^3 for non-dipterocarp in CL and 61 USD/m^3 for dipterocarp and 34 USD/m^3 for non-dipterocarp in RIL.

Since 96% of managed tropical forests in Indonesia are managed by private companies (Hutan-Aceh 2014), we use a discount rate of 12% for our main analyses. For sensitivity analysis, we use a discount rate of 4% based on the average real interest rate for Indonesia for the past 20 years.[5] In addition, we analyze the case of a fixed 30-year cutting cycle, which is prescribed by Indonesian policy.

5.3. Results

5.3.1. Results for optimal management with conventional logging techniques

The results for all scenarios for the case of conventional logging are presented in Table 5.2, where '*Pos.*' and '*Neg.*' indicate the positive and negative effect of damaged trees on the ingrowth of trees from the own species group, respectively.

[5] Source: World Bank World Development Indicators.

Table 5.2. Results for optimal management with conventional logging

Scenario	*A*	*B*	*C*	*C*	*D*	*D*
Sub-scenario			*Pos.*	*Neg.*	*Pos.*	*Neg.*
Land Expectation Value (USD/ha)	305	32	35	31	35	32
Cutting cycle (years)	10	18	16	18	18	18
BA healthy trees before harvest (m^2/ha)	11.2	7.0	7.1	6.9	7.4	7.0
BA healthy trees after harvest (m^2/ha)	9.3	4.3	4.6	4.2	4.5	4.3
BA injured trees before harvest (m^2/ha)	0.0	0.0	4.2	3.8	0.9	0.8
BA injured trees after harvest (m^2/ha)	0.0	0.0	4.6	4.3	1.8	1.6
Total BA before harvest (m^2/ha)	11.2	7.0	11.3	10.7	8.3	7.8
Total BA after harvest (m^2/ha)	9.3	4.3	9.2	8.5	6.3	5.9
Extracted volume (m^3/ha)	23.2	11.8	11.0	11.8	12.2	11.8
Volume damaged (m^3/ha)	0.0	17.1	28.8	28.5	21.5	19.5
Net harvest revenue (USD/ha)	938	512	477	505	528	511
Average amount of C stored in AGB (t/ha)	54.9	29.3	61.2	57.2	38.6	36.1

In *Scenario A*, we assume that logging activities do not cause damage to the residual stand. As a result, basal area and Land Expectation Value (LEV) are the largest and the cutting cycle the shortest over all scenarios. The optimal cutting cycle is 10 years, which is twice as long as in Ingram and Buongiorno (1996), in which damages are ignored as well, probably because the diameter cutting limit in that study is lower than in ours (30 cm vs. 40 cm). Basal area is 11.2 m^2/ha before harvest and 9.3 m^2/ha after harvest, and the average amount of carbon in AGB is 54.9 tonnes per ha. It should be noted that these basal areas are the equilibrium (i.e., steady state) basal areas with repeated harvests by a commercial company. Hence these numbers need not be comparable with the results found on experimental plots as these typically have not been harvested repeatedly and harvested volumes need not result from commercial decisions. Basal areas found on Kalimantan after logging of experimental plots range from 10 to 28.3 m^2/ha (e.g., Johns (1988), Sist and Nguyen-Thé (2002)). The climax forest that results from our growth model, that is, the forest that would result from our growth model if it were never harvested, has a basal area of 26.4 m^2/ha, which is somewhat thinner than the 31.3-35 m^2/ha found in primary forests on Kalimantan (Johns 1988; Cannon et al. 1994; Brearley et al. 2004).

In *Scenario B*, damages to the remaining stand impose an additional implicit harvesting cost relative to *Scenario A*, which increases the cutting cycle from 10 to 18 years and reduces basal area. Basal area after harvest decreases by more than 50% and carbon in AGB (average over the cutting cycle) by almost 50% (from 54.9 tC/ha to 29.3 tC/ha) as compared to the case of no damages. Lower harvest revenue combined with a longer cutting cycle (and hence more discounting) implies that LEV in *Scenario B* is much lower than in *Scenario A*.

In both *Scenario C Positive* (‘*Pos.*’ in Table 5.2) and *Scenario C Negative* (‘*Neg.*’ in Table 5.2) total basal area before harvest increases by more than 50% relative to *Scenario B* (62% with *C Pos.* and 53% with *C Neg.*) while basal area after harvest roughly doubles. Indeed, in *Scenario C Positive* basal area before and after harvest is comparable to the case in which damages are completely ignored (*Scenario A*). Furthermore, the average amount of carbon stored in AGB over the cutting cycle roughly doubles relative to *Scenario B* (to 61.2 tC/ha in *Scenario C Pos.* and 57.2 tC/ha in *C neg.*) and is for both Sub-scenarios even higher than in *Scenario A*. Injured trees make 50% of the basal area after harvest, which reduces to 36-37% just before harvest due to ingrowth of new healthy trees.

These results show the importance of including injured trees with zero commercial value in economic models for the optimal management of tropical forests: ignoring them leads to strong underestimates of the potential of such forests to store carbon in the context of REDD+ and payment for ecosystem services (PES) programs.

There is little difference in the basal area of healthy trees between *Scenarios B* and *C*, for which there are two reasons. First, in our model, injured trees negatively affect the ingrowth of new trees but do not affect the upgrowth of existing trees. Second, the stand composition is different between the two scenarios, with a larger share of trees belonging to the fast-growing commercial dipterocarp species in *Scenario C*. The latter also explains why extracted volume does not differ much between the scenarios. Indeed, volume harvested and cutting cycles are the same for *Scenarios B* and *C Negative*. The cutting cycle in the sub-scenario in which injured trees still carry seedlings is shorter than that of the one in which they do not because harvest damages in the former scenario have a smaller impact on future growth. As opportunity costs of harvesting in *Sub-scenario Positive* are lower, the average growth rate is higher (due to injured trees producing seedlings) and the cutting cycle is shorter than in *C Negative*, which results in less discounting and a higher LEV.

In *Scenario D*, the higher mortality rate for injured trees causes basal area and carbon stored in AGB to be lower than in *Scenario C* but still higher than in *Scenario B*. As expected, the higher mortality rate for injured trees leads to a smaller share of injured trees in the basal area as well as a smaller total basal area as compared to *Scenario C*. Basal area before harvest is still 11-19% larger and average amount of carbon stored is still 23-32% higher than in *Scenario B*. These results show that even in the extreme case that the mortality rate of injured trees is permanently higher than that of healthy trees, ignoring the presence of injured trees on the plot in economic models of optimal tropical forest management leads to underestimates of the amounts of carbon stored in such forests.

5.3.2. Results for optimal management with reduced impact logging techniques

Reduced impact logging not only leads to less damages after harvest as compared to conventional logging, but within the group of damaged trees also to a smaller fraction of dead trees. In *Scenario A*, we assume that logging activities do not cause damage to the residual stand. When harvests do not cause damage to the residual stand, the only difference between CL and RIL is in their costs, with CL having higher variable costs but RIL having higher fixed costs. Comparing the results for *Scenario A* in Table 5.3 with those in Table 5.2 shows that the stand state of the forest and volumes harvested are the same for CL and RIL. With lower variable cost per m^3 timber harvested, RIL gives higher net harvest revenue and LEV than CL does. However, the lower variable cost cannot offset the much higher fixed costs in RIL, so LEV is higher in CL than in RIL. Hence, in the reference scenario, in which logging does not result in damages, profit-maximizing forest managers prefer CL over RIL. The cutting cycle for CL and RIL is 10 years. The difference in fixed costs is not sufficiently large to induce a longer cutting cycle for RIL.[6]

Comparing the LEV of each scenario for RIL with that for CL shows that a commercial forest manager (i.e. with a 12% discount rate) prefers to apply CL as it gives a higher LEV irrespective the role of damaged trees. However, the environmental services provided with RIL may be much larger than with CL as basal areas and volumes of carbon stored in AGB are higher with the use of more sustainable logging techniques.

[6] Note that our model uses a growth period of two years. The current difference in fixed costs is probably sufficient to induce a difference in cutting cycles of one year but this cannot be shown with our model. As a check we have run the model with larger differences in fixed costs and find that when fixed costs for RIL are increased from 389 to 425 USD/ha, the cutting cycle for RIL increases from 10 to 12 years.

Table 5.3. Results for optimal management with reduced impact logging

Scenario	*A*	*B*	*C*	*C*	*D*	*D*
Sub-scenario			*Pos.*	*Neg.*	*Pos.*	*Neg.*
Land Expectation Value (USD/ha)	274	29	32	27	31	28
Cutting cycle (years)	10	20	18	20	20	20
BA healthy trees before harvest (m^2/ha)	11.2	7.5	7.7	7.3	8.0	7.4
BA healthy trees after harvest (m^2/ha)	9.3	4.5	4.8	4.4	4.7	4.5
BA injured trees before harvest (m^2/ha)	0.0	0.0	6.6	5.7	1.3	1.1
BA injured trees after harvest (m^2/ha)	0.0	0.0	7.6	6.7	2.6	2.3
Total BA before harvest (m^2/ha)	11.2	7.5	14.3	13.0	9.2	8.6
Total BA after harvest (m^2/ha)	9.3	4.5	12.3	11.1	7.4	6.8
Extracted volume (m^3/ha)	23.2	14.2	13.6	14.2	14.8	14.2
Net harvest revenue (USD/ha)	967	638	605	625	662	634
Volume damaged (m^3/ha)	0.0	18.5	37.0	34.4	24.2	21.6
Average amount of C stored in AGB (t/ha)	54.9	31.4	83.2	74.8	44.5	41.1

With RIL, the effects of the various assumptions regarding injured trees are qualitatively the same as with CL, but the effects on basal area and carbon stored are even stronger.[7] Indeed, basal area before harvest is larger for both *Scenarios C Positive* and *C Negative* as compared to *Scenario A*, while it increases by 91% and 74%, respectively, as compared to *Scenario B*. Relative to this scenario, the average amount of carbon stored in AGB increases by 165% and 139% in *Scenarios C Positive* and *C Negative*, respectively. Hence, the role of injured trees in calculating the amount of carbon stored in AGB is even stronger in case of reduced impact logging.

5.4. Sensitivity analysis

In Table 5.4, we present results for a sensitivity analysis in which we use discount rates of 4% (e.g., for a government forest manager rather than a commercial one). In *Scenario A*, in which only costs differ between CL and RIL, CL is still the preferred logging practice, as with a 12% discount rate. However, the cutting cycle is now longer with RIL than with CL, as the

[7] The difference in cutting cycle between *Scenarios A* and *B* is 10 years for RIL and 8 years for CL. This is the result of rounding with the two-year growth period in our model. See previous footnote. If we increase fixed costs for RIL to 425 USD/ha the cutting cycle for RIL is 12 years under *Scenario A* and 22 years under *Scenario B*, i.e. a difference of 10 years as with CL. Hence, the increase in difference in cutting cycle between CL and RIL appears to be an artefact of the two-year instead of one-year growth period.

difference in fixed costs is sufficiently large to induce a longer cutting cycle for RIL. For all other scenarios, the LEV is higher for RIL than for CL, contrary to the case of a 12% discount rate: in the presence of harvest damages, a non-commercial forest manager may prefer RIL over CL.

Cutting cycles are much longer than with a 12% discount rate. As this allows for more harvestable volume, the costs of having large damages are higher, and reduced impact logging becomes more attractive as compared to the case with a high discount rate.

Conclusions regarding the effect of different assumptions about the role of damaged trees are qualitatively the same as in the previous section: accounting for damaged trees on the stand implies considerably larger basal areas and volumes of carbon stored. Again, these effects are even stronger for RIL.

Table 5.5 presents the results for the case of an exogenous cutting cycle of 30 years, which is in line with Indonesian forestry policies. We use a 12% discount rate. Again, the effects on basal area and carbon stored are qualitatively similar to the findings in Section 3. As with the 4% discount rate, the long cutting cycle goes with more harvestable volume and higher costs of having large damages, and for all scenarios with damages, RIL is more attractive than CL.

Table 5.4. Results for optimal management under CL and RIL at 4% discount rate

	Scenario A		*Scenario B*		*Scenario C*				*Scenario D*			
					Positive		*Negative*		*Positive*		*Negative*	
	CL	RIL	CL	RIL	CL	RIL	CL	RIL	CL	RIL	CL	RIL
Land Expectation Value (USD/ha)	1429	1380	239	248	254	270	236	243	251	264	238	247
Cutting cycle (years)	16	18	26	30	26	28	26	30	24	28	24	30
BA healthy trees before harvest (m2/ha)	12.4	12.7	8.2	9.0	8.7	9.3	8.1	8.8	8.3	9.2	7.8	8.9
BA healthy trees after harvest (m2/ha)	9.4	9.4	4.3	4.4	4.4	4.7	4.2	4.4	4.5	4.7	4.3	4.4
BA injured trees before harvest (m2/ha)	0.0	0.0	0.0	0.0	4.5	6.7	4.0	5.7	0.9	1.1	0.8	1.0
BA injured trees after harvest (m2/ha)	0.0	0.0	0.0	0.0	5.4	8.4	4.8	7.4	2.1	3.2	1.9	3.0
Total BA before harvest (m2/ha)	12.4	12.7	8.2	9.0	13.1	16.0	12.0	14.5	9.2	10.4	8.6	9.9
Total BA after harvest (m2/ha)	9.4	9.4	4.3	4.4	9.8	13.1	9.0	11.7	6.6	7.8	6.2	7.4
Extracted volume (m3/ha)	37.6	42.5	16.4	20.8	17.0	20.4	16.3	20.6	15.8	20.2	15.3	20.7
Net harvest revenue (USD/ha)	1544	1804	721	945	748	928	716	935	690	916	668	943
Volume damaged (m3/ha)	0.0	0.0	26.7	30.2	48.0	56.6	42.0	50.8	29.7	34.9	27.0	33.7
Average amount of C stored in AGB (t/ha)	58.9	60.3	32.6	35.7	69.5	91.6	63.4	82.3	42.0	49.2	39.3	46.7

Table 5.5. Results for CL and RIL with exogenous cutting cycle of 30 years

	Scenario A		*Scenario B*		*Scenario C*				*Scenario D*			
					Positive		*Negative*		*Positive*		*Negative*	
	CL	RIL	CL	RIL	CL	RIL	CL	RIL	CL	RIL	CL	RIL
Land Expectation Value (USD/ha)	95	95	18	19	19	19	17	18	18	19	17	19
Cutting cycle (years)	30	30	30	30	30	30	30	30	30	30	30	30
BA healthy trees before harvest (m2/ha)	14.9	14.9	8.8	9.0	9.3	9.4	8.6	8.8	9.2	9.5	8.6	8.9
BA healthy trees after harvest (m2/ha)	9.4	9.4	4.2	4.4	4.4	4.5	4.1	4.3	4.4	4.6	4.1	4.4
BA injured trees before harvest (m2/ha)	0.0	0.0	0.0	0.0	4.5	6.7	4.0	5.7	0.8	1.1	0.7	1.0
BA injured trees after harvest (m2/ha)	0.0	0.0	0.0	0.0	5.6	8.6	5.0	7.4	2.4	3.3	2.2	3.0
Total BA before harvest (m2/ha)	14.9	14.9	8.8	9.0	13.8	16.2	12.6	14.5	10.1	10.6	9.4	9.9
Total BA after harvest (m2/ha)	9.4	9.4	4.2	4.4	10.0	13.0	9.1	11.7	6.8	7.9	6.3	7.4
Extracted volume (m3/ha)	71.8	71.8	18.7	20.8	19.3	21.6	18.6	20.6	19.2	21.6	18.7	20.7
Net harvest revenue (USD/ha)	3040	3040	819	945	849	936	799	933	843	968	798	942
Volume damaged (m3/ha)	0.0	0.0	31.9	30.2	55.6	62.4	49.2	50.8	38.3	37.8	35.1	33.8
Average amount of C stored in AGB (t/ha)	68.3	68.3	34.3	35.7	72.6	92.5	65.8	82.3	45.3	50.1	41.8	46.7

5.5. Conclusions

In this chapter we analyzed four scenarios to identify the effects of various assumptions regarding injured trees on land expectation value (LEV), cutting cycle, basal areas and carbon stored in above-ground biomass (AGB). We find that allowing injured trees to stay on the plot leads to much larger basal areas and much more carbon stored in AGB. This effect is stronger for RIL than for CL: with reduced impact logging the average amount of carbon stored can increase by up to 165% as compared to the case where injured trees are assumed to decay so fast that they do not affect ingrowth or the composition of the stand, just like dead trees. In managed tropical forests biodiversity and ecosystem services are positively correlated with basal area. The potential of managed tropical forests to store carbon and provide ecosystem services in response to programs – such as payments for ecosystem services and Reducing Emissions from Deforestation and forest Degradation and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries (REDD+) – may hence be grossly underestimated when ignoring injured trees in the analysis.

An important area of future research would be to assess the role of damages when injured trees do not only affect the ingrowth of new trees but also the upgrowth of (small) existing trees. A lower growth rate would, ceteris paribus, imply smaller effects of the presence of injured trees on basal area and carbon stored, though this would be partly offset by a longer cutting cycle. The effect on the choice between CL and RIL (in terms of LEV) is a priori unclear. Such an analysis would require a more advanced forest growth model. Second, the modelling of the decomposition of dead trees can be improved by allowing for almost full decomposition to take more than two years, although it should be noted that the literature on the decomposition of woody debris in the tropical forests of South-East Asia presents a wide range of estimates of half time rates. Furthermore, the economic model can be improved by allowing for non-repetitive cutting cycles. Notwithstanding these drawbacks of the model used in this chapter, we have shown that including damaged trees can have large effects on the potential of managed tropical forests to store carbon.

CHAPTER 6

Chapter 6. Synthesis

6.1. Societal problem and research objective

Forests, which cover about a third of the Earth's land surface and are home to a major part of the world's terrestrial biodiversity (Betts et al. 2017), play a vital role in the global carbon cycle (Parrotta et al. 2012). FAO (2020) reports that the rate of net forest loss decreased significantly between 1990 and 2020, owing to reduced deforestation in some countries and increases in forest area in others due to afforestation and natural forest growth. Deforestation and forest degradation have significant detrimental impacts on terrestrial biodiversity (Parrotta et al. 2012; Vijay et al. 2016; Giam 2017).

In Indonesia, the extent and rate of deforestation have increased significantly as the timber industry has grown since the 1970s (FAO 1990). Sunderlin and Pradnja Resosudarmo (1996) reported the progression of annual deforestation estimates as follows: In the 1970s, 300,000 ha were deforested annually; in the 1980s, 600,000 ha were deforested annually; and in 1990, one million ha were deforested annually. Ministry of Environment and Forestry (2021) reported that Indonesia has calculated levels of deforestation periodically since 1990. The highest levels of deforestation rates were recorded from 1996 to 2000, at 3.51 million hectares per year. In the subsequent period, from 2002 to 2014, the rate of deforestation declined, along with the decline in incidences of forest and land fires, and some of the excesses of decentralized forest management have been reined. After 2015, the deforestation rate decreased to an average of < 1 million ha, and in 2019 it was 0.46 Mha. Thus, deforestation has been and still is a major contributor to Indonesian GHG emissions. The deforestation rate in Indonesia and CO_2 emissions are presented in Figure 6.1.

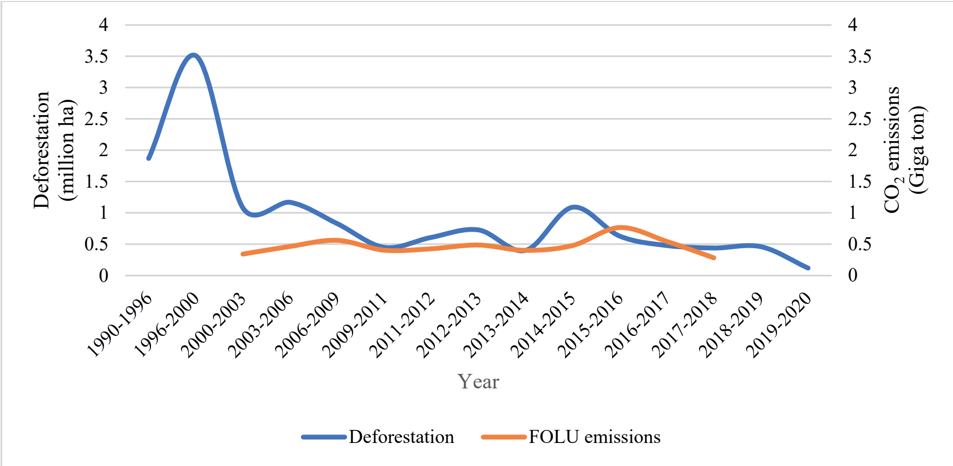

Figure 6.1. Deforestation and FOLU emissions in Indonesia
Source: (Ministry of Environment and Forestry 2021)

Indonesia has pledged to contribute to climate change mitigation and adaptation to balance present and future development and poverty reduction goals (Government of Indonesia 2016). According to the country's Second National Communication from 2010, Indonesia's national greenhouse gas (GHG) emissions were estimated to be 1.8 Gt CO_2e in 2005. This is an increase of 0.4 Gt CO_2e compared to 2000. Most emissions (63%) come from land-use change and peat and forest fires, while fossil fuel combustion accounts for around 19% of total emissions. According to Indonesia's First Biennial Update Report (BUR) submitted to the UNFCCC in January 2016, national greenhouse gas (GHG) emissions in 2012 were 1.453 $GtCO_2e$, an increase of 0.452 $GtCO_2e$ from 2000 emissions. LUCF, including peat fires (47.8%), and energy were the main contributors (34.9%). The 2nd BUR reported a slight increase in emissions to 1.457 Gt CO_2e in 2016, with emissions from LUCF, including peat fires accounting for 43.59% and energy accounting for 36.91%, respectively. Since voluntarily pledging to reduce emissions by 26% on its own efforts and up to 41% with international support, compared to the business as usual scenario by 2020, Indonesia has promulgated relevant legal and policy instruments, including the national action plan on GHG emissions reduction and GHG inventory as stipulated in Presidential Decree No. 61/2011(Government of Indonesia 2011). In December 2015, the UNFCCC Secretariat received a Forest Reference Emission Level (FREL) for REDD+, which covered deforestation, forest degradation, and peat decomposition. The FREL was set at 0.568 Gt CO2e per year (AGB) using the 1990–2012 reference period and is used as a benchmark for reporting actual emissions from 2013 to 2020.

After 2020, Indonesia intends to go beyond its present carbon reduction promise. Based on the country's most recent emission level assessment, Indonesia has set an unconditional reduction target of 29% and a conditional reduction target of up to 41% of the business as usual scenario by 2030.

Given Indonesia's climate change mitigation regime, this thesis investigates the best management practices for plantation forests (with monoculture and sylvicultural systems of clear-cutting and artificial regeneration) and multi-age, multi-species forests (selective harvesting and natural regeneration sylvicultural system). Being one of the world's largest emitters of greenhouse gases (GHGs) from Land Use, Land Use Change, and Forestry (LULUCF) activities (Baumert et al. 2005), Indonesia focuses on LULUCF operations to reduce GHG emissions by minimizing emissions from forests and peat by reducing deforestation and improving forest management. In order to contribute to Indonesia's CO_2 abatement efforts, this thesis examines how to manage production forests best (i.e., forests allocated for wood production) when remuneration for carbon storage becomes available. Numerical optimization tools based on detailed data are employed in this research.

6.2. Overview of results and discussion

Chapter 2 answers the first research question, "How would the incentives for carbon storage change the optimal forest management of a short-rotation plantation in Indonesia? How efficient is the Verified Carbon Standard (VCS) remuneration scheme incentivizing forest managers to lengthen the rotation?". Chapter 2 calculates the minimum carbon payment required to incentivize the *Acacia mangium* (one of the short rotation species) plantation forest managers in Indonesia to extend the forest rotation and, as a result, sequester more carbon under two remuneration schemes. I compare the cost-effectiveness of Verified Carbon Standard (VCS), which is based on average additional carbon storage over a rotation period, to that of an ideal remuneration scheme developed from Hartman's (1976) model of optimal forest management with non-timber benefits. Carbon remunerations in the latter scheme are calculated based on the annual additional current carbon stock (i.e., 'current carbon' accounting). The amount of carbon stored under an optimal rotation of forest managed solely for timber production is used to determine the additionality for both schemes. Carbon that is stored at the baseline level is not eligible for compensation (lack of additionality). Chapter 2 finds that, compared to the current carbon model, the VCS model, one of the most used schemes in the voluntary carbon market, is less cost-effective. The inefficiencies of VCS are more pronounced for longer rotation or storing more carbon in forest biomass. To increase the average amount of CO_2 stored by 26% (33 tons, i.e., a nine-year rotation), for example, the current carbon approach requires a payment of USD 449 per hectare, whereas VCS requires a payment of USD 502 per hectare. This represents a 12% difference in payments and demonstrates the lower cost-effectiveness of the VCS average accounting scheme compared to the current accounting scheme. The biggest difference in payments between the two schemes is for the 17-year rotation and the climax forest, where payments under VCS are nearly double of those under current carbon accounting. This is because the current carbon scheme's payments are more closely connected with forest carbon fluxes than VCS's carbon payments. Furthermore, Chapter 2 describes that the cost-effectiveness difference is more pronounced for lower discount rates. The price of VCS forestry and land use credits in 2021, i.e., 3.56 USD/ton CO_2 (Ecosystem Marketplace 2021), is insufficient to encourage Indonesian *A. mangium* forest managers to extend the cycle.

Chapter 3 answers the second research question, "How do multiple uses affect the optimal forest management decisions in plantation forests with different soil conditions?". Chapter 3 investigates the optimal management of multiple-use forests for several site conditions. The current price of VCS forestry and land use credits in 2021 (i.e., 3.56 USD/ton CO_2) (Ecosystem Marketplace 2021) incentivizes forest managers to extend the rotation of Indonesian pine forests by 1-2 years, resulting in an 8-17 percent increase in CO_2 storage. This finding is different from that in the case of *A. mangium* in Chapter 2. With slower growth, longer rotation, and higher wood value than *A. mangium* forest, the pine forest is more cost-effective. This is in line with the findings of West et al. (2019) that *A. mangium* which has a short rotation and is the least valuable wood, has the lowest cost-effectiveness compared to *Tectona sp.*, *Pinus sp.*, and *Eucalyptus sp.* that have higher wood values and longer rotations.

This chapter finds that resin production in the pine forest lengthens the rotation and supports carbon storage. This is in line with the finding of Wang et al. (2006) that the inclusion of resin production in the pine forests in China lengthens the optimal rotation age. Better site conditions mean faster timber growth and thus a shorter rotation for timber production only. Additional income from resin production will lengthen the rotation, with a more pronounced effect on rotation at the lower site qualities. At lower site qualities and at the same age, the number of trees is higher than that at higher site quality. Therefore, resin production of pine forest is somewhat larger in the lower site qualities (Sukarno et al. 2012). Without carbon compensation, resin production may help to store 8-26% more carbon compared to a forest that only produces timber. The additional revenue from carbon and resin has increased the amount of CO_2 stored in pine forest biomass by 16-42%.

Chapter 4 answers the third research question of this thesis "How do incentives from REDD+ affect the optimal management of multi-age multi-species in Indonesia?". In Chapter 4, I examine the potential of REDD+ to induce carbon sequestration and present supply curves for carbon storage in a tropical multi-age, multi-species forest; that is, I show the amount of carbon stored in above-ground biomass for a range of carbon credit prices. I do so in the context of both private and public forest management, which differ in terms of tax liability and discount rate. Chapter 4 finds that the total quantity of CO_2 stored per ha in above-ground biomass and end-use wood products (EWP) for a production forest with selective logging on Kalimantan may grow by 15.8% at 0.7 USD/tCO_2 for two-year credits (similar to the average 2015 price of permanent credits in the EU ETS). The volume of timber harvested rises in lockstep with the carbon price until a threshold price is reached, i.e., 1.2 USD/tCO_2 (4.7 USD/ tCO_2 for permanent credits) for privately managed forests and up to 2.2 USD/tCO_2 (27 USD/ tCO_2 for permanent credits) for government-managed forests. This demonstrates that, at low carbon prices, sustainable forest management, forest carbon sequestration, and commercial timber production – all of which are crucial for employment in the sawmill and manufacturing industries – go hand in hand, but at higher prices, they become alternatives.

The land expectation value is negatively impacted by compensation for the carbon stored in EWP. This is in line with the findings from Zhou and Gao (2016) that the LEV is negatively affected by the EWP for the short rotation plantation forest in China. The forest manager is only compensated for the carbon stored above the baseline level (additionality principle). This is effectively a one-time tax equivalent to the current amount of carbon stored under the baseline. Carbon credits for EWP do not enhance the quantity of carbon stored since carbon stored in end-use items encourages cutting and depletes carbon stored in trees. Cutting down more trees for timber causes more damage to the remaining forest, and carbon is lost to the atmosphere due to inefficiencies in transportation and processing. In chapter 4, it is assumed that all damaged trees (whether they are dead or only injured) decay quickly and do not affect the remaining stand. Later in Chapter 5, I explain how dead and injured trees affect the remaining stand.

The steady-state model applied in Chapter 4 determines the shape of the carbon supply curves based on marginal changes in the stand before harvest, volume harvested, and the length of the cutting cycle. Looking at marginal changes only may lead to a locally optimal solution (in terms of the stand before harvest, volume harvested, and the length of the cutting cycle).

For a global solution, these results need to be compared with the case where forest managers would (immediately) convert their forest stand to the climax forest. In that case, switching to a no-harvest policy occurs at lower prices of a 2-year credit (2.0 USD/tCO_2 for the private case and 1.2 USD/tCO_2 for the government case) as compared to the case of marginal changes (in which case switching to a no-harvest strategy occurs at 4.5 and 2.9 USD/tCO_2, respectively). The no-harvest decision lowers dissolved organic content and subsequently lowers C inputs in the mineral soil in the tropics (Fujii et al. 2009).

Chapter 5 addresses the fourth research question, "How do logging damage and injured trees in the selective logging system affect stand composition, carbon stored in aboveground biomass, and ultimately optimal management decisions?" The results show that allowing damaged trees to remain on the plot results in significantly higher basal areas and carbon storage in aboveground biomass (AGB) compared to the situation where damaged trees are assumed to decay sufficiently fast that they do not affect ingrowth or stand composition. This effect is larger for reduced impact logging (RIL) than for conventional logging (CL): with reduced impact logging, the average quantity of carbon retained can increase by up to 165%, compared to the situation where damaged trees are left to decay similar to dead trees. Biodiversity and ecosystem services are favourably associated with the basal area in managed tropical forests. The ability of managed tropical forests to store carbon and provide ecosystem services in response to programs – such as payments for ecosystem services, conservation, sustainable forest management, and enhancement of forest carbon stocks in developing countries (REDD+) – may thus be grossly underestimated.

6.3. Limitations and future research

The economic models used in this thesis are stylized Faustmann models that have some drawbacks. The Faustmann model makes several key assumptions, including that the same stumpage price, stand volume, regeneration/planting costs, and interest rate will repeat from harvest to harvest. However, casual observations of actual management situations indicate that these assumptions are often not appropriate (Chang 1998; Müller and Hanewinkel 2018). Stumpage prices are rarely, if ever, constant from harvest to harvest. Price fluctuations are the norm, not the exception (Gould Jr 1960). The harvest age would increase with the current stumpage price. A higher future stumpage price level would result in a younger current timber harvest age (Chang 1998; Penttinen 2006).

Moreover, Chang (1998) argues that a higher interest rate on the current timber crop would shorten its harvest age. This effect is the same as that under the classic Faustmann model. Due to changing soil conditions and weather, two consecutive stands would be hard-pressed to produce the same volume, let alone multiple harvests (Chang 1998; Willassen 1998). With global warming, climate conditions will lead to changes in forest growth and hence in timber production. In addition, active management efforts, such as the creation of genetically improved seeds, may improve future yield . On the other hand, careless management may result in unfavourable outcomes such as a loss of forest productivity due to soil compaction and nutrient depletion, thus significantly reducing future stand yield. Under stochastic forest growth (i.e., considering a model that explicitly recognizes uncertainty in the future values of trees), Willassen (1998) and Alvarez (2004) suggest using the impulse control theory to solve economic optimization problems. Impulse controls can be used to analyze at least two broad categories of economic problems (Chu et al. 2015). In the first category, policymakers choose to implement cyclical policies, in which controls are activated at the start of a cycle. The second type of impulse control is intended to deal with uncertainties and determine when and how to apply impulse controls in response to an unexpected disturbance in the state variable(s). Policy responses that may occur following a catastrophic event, such as an earthquake or hurricane, or what could be the best investment or spending option following an unfortunate financial event, are examples of practical decisions.

Simultaneously, improved techniques and evolving technologies have a continuous impact on the cost of regeneration. Moreover, the analysis of the optimal forest management under the carbon project regime in this thesis is simplified by ignoring transaction and monitoring costs. Transaction costs are very important for a successful land-use-based carbon project because they affect the commodity's (certified carbon) price (Galik et al. 2012; Cacho et al. 2013; Pearson et al. 2014).

Future studies could use the generalized Faustmann model as proposed by Chang (1998), which considers the changes in stumpage prices (Müller and Hanewinkel 2018), stand volume (Chang 1998), regeneration costs, and interest rate (Buongiorno and Zhou 2011) both in the even-aged and uneven-aged forest (Chang and Gadow 2010; Xabadia and Goetz 2010). With one exception, the results are the same as the classic Faustmann model (Chang 1984). With the generalized Faustmann model solved with the backward recursive method, the land expectation value varies between timber crops. Current market conditions, government policies, regeneration technology, management practices, and forest stand growth can alter the land expectation value. In this way, the optimal harvest age for any given tree depends on its stand value and the land expectation value after harvest. Current stand value and increment plus land expectation value at the start of the next crop determine the optimal harvest age. The generalized Faustmann model has also been used to analyze carbon sequestration services in uneven-aged forests (Parajuli and Chang 2012). Under the generalized Faustmann model, carbon benefits could not significantly alter the optimum management regimes of uneven-aged loblolly pine stands when managed jointly with timber production (Parajuli and Chang 2012). Stumpage prices and future land values were less important for optimum joint management regimes.

Future studies could extend the current model to include a transition phase from an existing initial stand of natural forest to a managed steady-state forest and calculate supply curves for forest carbon sequestration in both the transition phase and the steady state. The structures of many stands in the natural tropical forests differ from the desired stocking and diameter distribution conditions. Some silvicultural management decisions (including the cutting cycle, number of trees harvested, and logging techniques) are considered in order to determine the appropriate cutting schedule during the transition period. The stand is brought from its current, irregular state to the desired stable state. As with sustainable distributions, numerous harvesting schedules can be used to achieve the desired transition from given initial to desired stand conditions, depending on the length of the transition period and management objectives. Optimal paths of development can be determined for both even-aged or uneven-aged forest systems based on a matrix transition model (Tahvonen 2009). Tahvonen (2009) found that density dependency reduces tree growth, tree regeneration options, discount rate, and other economic criteria such as timber price and replanting costs are critical considerations in determining the optimal management option. Future studies also could be conducted to analyze the shift from monoculture plantation forest to continuous cover forestry with mixed-species (Tahvonen et al. 2019).

The role of damage when injured trees affect not only the ingrowth of young trees but also the upgrowth of (small) existing trees would be an interesting subject of future research. A reduced growth rate due to ignoring the role of damaged trees would, in theory, mean that the presence of injured trees would have a smaller impact on basal area and carbon storage, albeit this would be partially offset by a longer cutting cycle. A priori, the impact on the decision between CL and RIL (in terms of LEV) is unknown. A more complex forest growth model would be required for such a study. Furthermore, by allowing almost full decomposition to take more than two years, the modelling of the decomposition of dead trees could be improved, though it should be noted that the literature on the decomposition of woody debris in tropical forests of Southeast Asia presents a wide range of estimates of half-time rates. Finally, allowing for non-constant cutting cycles (transition phase) can strengthen the economic model. Despite the limitations of the model used in Chapter 5, I have demonstrated that incorporating injured trees can significantly impact the capacity of managed tropical forests to store carbon.

Regarding the inclusion of End-use Wood Product (EWP) in the optimization problem, future studies could simulate the role of EWP in LEV when the wood use efficiency is improved. In my research (Chapter 4), the wood use efficiency is relatively low because wood waste due to logging, transportation, and wood processing is relatively high. Improved technology (whether in logging, transportation, and wood processing activities) to reduce wood waste can increase wood use efficiency that may affect the impact of EWP on LEV.

6.4. Implications for policy makers and forest managers

Based on the overall conclusions drawn in the previous section, some policy recommendations can be formulated. This thesis is based on data from forest areas designated by the government as permanent forests and managed by the Ministry of Environment and Forestry/MoEF. Therefore, the policy recommendations only apply to these forest areas. First, the government may issue regulations for plantation forest concessions that are mainly focused on wood production to include incentives for carbon sequestration. New regulations would determine how forest concession managers manage their forests for joint wood production and carbon sequestration. The different site conditions give forest managers a broad alternative for managing plantation forests, including the choice of balancing the production of wood and non-wood products. By this regulation, the plantation forest managers or concession holders have a legal option to sell the carbon credits to the market.

Second, the cutting cycles for selective logging regimes in the multi-aged multi-species forest should not be fixed by the regulations but should be based on the growth data, economic considerations, harvesting techniques, and products that vary among natural forests in Indonesia. This fixed cutting cycle may give suboptimal management for forest managers and thus not maximum profit. The existing regulation on the silvicultural system in multi-aged multi-species forest in Indonesia uses a 30-years cutting cycle. However, based on the results presented here, the cutting cycle can be less than 30 years to obtain the maximum profit from timber only.

The results presented here reveal that the carbon price of VCS in 2021 (i.e., 3.56 USD/ton CO_2) is insufficient to incentivize forest managers to store more carbon in short-rotation plantation forests, e.g., *A. mangium*. However, it is sufficient to incentivize extending the rotation for slower-growing (longer rotation) species, e.g., *Pinus merkusii*. The total area of industrial plantation forest in Indonesia in 2020 is 11.19 million ha (Ministry of Environment and Forestry 2021), and the area for *A. mangium* is about 1.6 million ha (Hardie et al. 2018). At the carbon price of 30 USD/ton CO_2, the additional CO_2 per ha of Acacia plantation under the VCS FOLU scheme is 72 tons CO_2/ha (Chapter 2), or approximately 115 million tons of CO_2. This contributes about 23% of the target emission reduction for the AFOLU sector in countermeasure 1 (without international support), i.e., 494 million tons CO_2, or about 17% of the target of countermeasure 2 (with the international support), i.e., 692 million tons CO_2. The total pine forest area in Indonesia is approximately 1.5 million ha (Imanuddin et al. 2020). At the carbon price of 30 USD/ton CO_2 in the pine forest, it is optimal to make a "no harvest" decision with the additional amount of CO_2 of more than 324 tons CO_2/ha or more than 484 million tons CO_2. With the VCS FOLU remuneration scheme at this carbon price, *Acacia mangium* and pine forests in Indonesia can significantly reduce the emission by 599 million tons of CO_2, surpassing the AFOLU target under the countermeasure 1 (i.e., 494 million tons CO_2) and almost reach the emission reduction target of AFOLU sectors in 2030, i.e., 695 tons of CO_2 under countermeasure 2.

Regarding emissions from the forestry sector and peatlands, the average annual level of emissions from 2000 to 2018 was 439.8 Mton CO_2e per year (Ministry of Environment and Forestry 2021). If peat fire emissions are excluded, the average annual level of emissions is 214 Mton CO_2e. Mitigation measures in peatlands by the 3R approach (rewetting, revegetation, and revitalisation of local livelihood) have reduced emissions, particularly emissions from peat fires. Following El Nino, the emissions from peat fires fell to 90.3 Mton CO_2e in 2016 from 822.7 Mton CO_2e in 2015. The emissions from peat fires fell further in 2017, to 12.5 Mton CO_2e. The government of Indonesia has set the goal of restoring the peatlands area of 2 million ha by 2030 by 3R (Government of Indonesia 2021).

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Summary

Forests play an important role in the global carbon cycle and are home to a significant portion of the world's terrestrial biodiversity. Global concerns about climate change forces governments to mitigate climate change by reducing greenhouse gases in the atmosphere, including the contribution from the forestry sector. One of the greenhouse gas mitigation strategies of the forestry sector is reducing the rate of deforestation and forest degradation and increasing forest carbon stocks. As part of the global community, Indonesia is committed to contributing to climate change mitigation by reducing deforestation and forest degradation and increasing forest carbon stocks by improving forest management. This thesis focuses on optimal forest management for climate change mitigation in Indonesia in the even-aged forest (plantation forest) and uneven-aged forest (natural forest). I use the Faustmann approach to analyze the optimal forest management with additional income from carbon credit. This thesis consists of six chapters.

Chapter 1 introduces the research presented in this dissertation. It provides an overview of the importance of forests in climate change mitigation and the potential role of remunerations for improving carbon stock. It describes the optimal forest management when the additional income from carbon credits is considered. The chapter introduces briefly the case studies of plantation forests (i.e., monoculture with clear-felling and artificial regeneration) and of multi-age multi-species forests (i.e., polyculture with selective cutting and natural regeneration) that are analyzed with numerical models in this thesis.

Chapter 2 elaborates the cost-effectiveness of forest carbon remuneration by comparing a theoretically correct model, i.e., the current carbon approach, with the most used voluntary carbon schemes, i.e., the Verified Carbon Standard (VCS) for *Acacia mangium* in Indonesia. The global accord on climate change mitigation (Paris Agreement), which specifically includes REDD+ (Reducing Emissions from Deforestation and forest Degradation and fostering conservation, sustainable management of forests, and enhancing forest carbon stocks) as part of the agreement, has the potential to promote carbon sequestration in plantation forests by extending forest rotation. Voluntary carbon payment systems have recently issued a greater proportion of carbon credits than compliance schemes. VCS is the most prominent of the voluntary carbon remuneration systems. The cost-effectiveness of using VCS in Indonesian short-rotation plantation forests is investigated. We can provide recommendations to forest plantation managers who want to improve forest management to make it "climate-smart."

Chapter 3 analyzes how resin production and carbon sequestration individually and jointly affect the optimal management of pine forests in Indonesia. Plantation forests are used to produce wood and non-timber forest products (NTFPs), such as resin. In comparison to a forest where timber is the only source of income, additional income from NTFP – here I am looking at resin and carbon services – may change the optimal management of a plantation forest. In order to achieve optimal forest management, different site types that influence pine forest growth are researched and discussed. Forest managers may have more options to maximize profit from some income sources from pine forest timber and NTFP.

Chapter 4 analyzes the optimal management of multi-age, multi-species forests under REDD+ in Indonesia. REDD+ can encourage carbon sequestration in Indonesia's multi-age, multi-species forests which are primarily logged with conventional methods (CL). Reduced-impact logging (RIL) reduces the damage to the residual stand by carefully planning and controlling timber harvesting by trained workers. As a result, the amount of carbon stored in forest biomass increases. The REDD+ scheme has the potential to fund the implementation of RIL that reduces forest degradation by incentivizing "improved forest management." The REDD+ potential for tropical forest management can be better understood by answering this research question through a systematic study. Furthermore, tropical forest managers would make a huge profit by switching from CL to RIL logging. Finally, Chapter 4 estimates a carbon supply curve for REDD carbon sequestration for Kalimantan, Indonesia.

Chapter 5 takes this a step further by studying the effect of logging damage and tree mortality in tropical forest management. Selective logging in the tropical forest damages the residual stand and reduces the amount of carbon stored. Conventional logging (CL) causes more extensive damage and injured trees in the residual stand than RIL. The latter, however, needs better trained workers and careful preparation of felling operations. Forest growth, stand composition, and carbon stored in aboveground biomass are all influenced by harvest damage and injured trees. The model that explicitly considers harvest damage and the biophysical and economic effects of the presence of injured trees will provide a better explanation for determining optimal forest management practices such as harvesting intensity and cutting cycle.

Samenvatting

Bossen spelen een belangrijke rol in de wereldwijde koolstofcyclus en herbergen een aanzienlijk deel van 's werelds terrestrische biodiversiteit. Wereldwijde bezorgdheid over klimaatverandering dwingt regeringen om klimaatverandering te matigen door broeikasgassen in de atmosfeer te verminderen, inclusief de bijdrage van de bosbouwsector. Een van de strategieën om de klimaatverandering door de bosbouwsector te verminderen, is het verminderen van de ontbossing en de aantasting van bossen en het vergroten van de koolstofvoorraden in de bossen. Als onderdeel van de wereldwijde gemeenschap zet Indonesië zich in om bij te dragen aan de beperking van de klimaatverandering door ontbossing en bosdegradatie te verminderen en de koolstofvoorraad in bossen te vergroten door het bosbeheer te verbeteren. Dit proefschrift richt zich op optimaal bosbeheer voor het tegengaan van klimaatverandering in Indonesië in het even-aged forest (plantagebos) en ongelijk-aged forest (natuurlijk bos). Ik gebruik de gestileerde Faustmann om het optimale bosbeheer te analyseren met extra inkomsten uit koolstofkrediet. Dit proefschrift bestaat uit zes hoofdstukken..

Hoofdstuk 1 introduceert het onderzoek dat in dit proefschrift wordt gepresenteerd. Het geeft een overzicht van het belang van bossen bij het tegengaan van klimaatverandering met de REDD+. Het beschrijft ook het optimale bosbeheer wanneer rekening wordt gehouden met de extra inkomsten uit koolstofkrediet. Het numerieke voorbeeld met casestudies van plantagebos (d.w.z. monocultuur met kap en kunstmatige regeneratie) en multi-age multi-species (d.w.z. polycultuur met selectief kappen en natuurlijke regeneratie)

Hoofdstuk 2 gaat in op de kosteneffectiviteit van koolstofcompensatie in bossen door het theoretisch correcte model, d.w.z. de huidige koolstofbenadering, te vergelijken met de meest gebruikte vrijwillige koolstofschema's, d.w.z. de Verified Carbon Standard (VCS) voor Acacia mangium in Indonesië. Het recente wereldwijde akkoord over mitigatie van klimaatverandering (Overeenkomst van Parijs), waarin REDD+ specifiek als onderdeel van de overeenkomst is opgenomen, heeft het potentieel om koolstofvastlegging in aangeplante bossen te bevorderen door de bosrotatie uit te breiden. Vrijwillige CO_2-betalingssystemen hebben onlangs een groter deel van de CO_2-credits uitgegeven dan nalevingsregelingen. VCS is de meest prominente van de vrijwillige CO_2-vergoedingssystemen. De kosteneffectiviteit van het gebruik van VCS in Indonesische plantagebossen met korte omlooptijd wordt onderzocht. We kunnen aanbevelingen doen aan bosplantagebeheerders die het bosbeheer willen verbeteren om het 'klimaatslim' te maken.

Hoofdstuk 3 analyseert hoe harsproductie en koolstofvastlegging het optimale beheer van dennenbossen in Indonesië beïnvloeden. Aanplantingsbossen worden gebruikt voor de productie van hout en niet-hout bosproducten (NTFP's), zoals hars. In vergelijking met een bos waar hout de enige bron van inkomsten is, kunnen extra inkomsten uit NTFP – hier heb ik het over hars- en koolstofdiensten – het optimale beheer van een plantagebos veranderen. Om tot een optimaal bosbeheer te komen, worden verschillende soorten terreinen die de groei van dennenbossen beïnvloeden onderzocht en besproken. Bosbeheerders hebben mogelijk meer mogelijkheden om de winst uit sommige inkomstenbronnen uit dennenbos en NTFP te maximaliseren.

Hoofdstuk 4 analyseert het optimale bosbeheer van multi-age multi-species onder REDD+ in Indonesië. REDD+ kan koolstofvastlegging aanmoedigen in Indonesië's meerjarige bos met meerdere soorten, dat voornamelijk wordt gekapt met conventionele methoden (CL). Reduced-impact logging (RIL) vermindert de schade aan de resterende opstand door zorgvuldige planning en controle van de houtoogst door getrainde werknemers. Als gevolg hiervan neemt de hoeveelheid koolstof die is opgeslagen in bosbiomassa toe. De REDD+-regeling heeft het potentieel om de implementatie van RIL te financieren die de aantasting van bossen vermindert door "verbeterd bosbeheer" te stimuleren. Het REDD+ potentieel voor tropisch bosbeheer kan beter worden begrepen door deze onderzoeksvraag te beantwoorden door middel van een systematische studie. Bovendien zouden tropische bosbeheerders een enorme winst maken door over te stappen van CL- naar RIL-kap. Er is ook een koolstofaanbodcurve voor REDD-koolstofvastlegging voor Kalimantan, Indonesië.

Hoofdstuk 5 gaat een stap verder door het effect van kapschade en boomsterfte in tropisch bosbeheer te bestuderen. Selectieve houtkap in het tropische bos beschadigt de resterende stand en vermindert de hoeveelheid opgeslagen koolstof. Wanneer werknemers geen training en voorbereiding hebben, veroorzaakt conventionele houtkap (CL) meer uitgebreide schade en gewonde bomen in de reststand dan RIL. Bosgroei, standsamenstelling en koolstof opgeslagen in bovengrondse biomassa worden allemaal beïnvloed door oogstschade en gewonde bomen. Het model dat expliciet rekening houdt met oogstschade en de biofysische en economische effecten van de aanwezigheid van gewonde bomen, zal een betere verklaring bieden voor het bepalen van optimale bosbeheerpraktijken zoals oogstintensiteit en kapcyclus.

Biography

Yonky Indrajaya was born on June 13, 1976, in Purwokerto, Central Java, Indonesia. He finished school in 1994 and started to study forestry in the Faculty of Forestry at Gadjah Mada University, Yogyakarta, in 1995. He obtained his diploma in 2000 and after that started to work as a researcher in the Watershed Management Technology Center (WMTC), Forestry Research and Development Agency (FORDA) under the Ministry of Forestry of the Republic of Indonesia in Surakarta. In 2004, he started his master degree at the Institute of Technology Bandung and the University of Groningen, which was completed in 2006 with the thesis "The Application of Sustainability Concepts in the Watershed Management."

In June 2007, he moved to Agroforestry Technology Center in Ciamis, West Java. In May 2009, Yonky started as an external PhD candidate at Environmental Economics and Natural Resources group at the Wageningen University and Research sponsored by Tropenbos International Indonesia Programme (TBI). During his PhD, he attended and presented his work at international conferences held in Indonesia.

In June 2020, Yonky moved back to Watershed Management Technology Center in Surakarta. Starting from March 1, 2022, he works in the National Research and Innovation Agency (BRIN). His current interests are forest management, forest economics, and general forestry.

List of Publications (selection)

1. Imanuddin, R.; Hidayat, A.; Rachmat, H.H.; Turjaman, M.; Pratiwi; Nurfatriani, F.; Indrajaya, Y.; Susilowati, A. Reforestation and Sustainable Management of Pinus merkusii Forest Plantation in Indonesia: A Review. *Forests* **2020**, *11*, doi:https://doi.org/10.3390/f11121235.
2. Siarudin, M.; Rahman, S.A.; Artati, Y.; Indrajaya, Y.; Narulita, S.; Ardha, M.J.; Larjavaara, M. Carbon Sequestration Potential of Agroforestry Systems in Degraded Landscapes in West Java, Indonesia. *Forests* **2021**, *12*, doi:https://doi.org/10.3390/f12060714.
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Yonky Indrajaya
Wageningen School of Social Sciences (WASS)
Completed Training and Supervision Plan

Name of the learning activity	Department/Institute	Year	ECTS*
A) Project related competences			
REDD+ Science and Governance: Opportunities and Challenges	ENP/WUR	2012	1.5
'The Effects of Carbon Payment on Optimal Rotation of Mangium Forest Plantation in Indonesia'	The International Symposium on Bioeconomics of Natural Resource Utilization	2017	1
'Joint production of wood, resin, and carbon from pine plantation forest in Java'	5th International Conference of Indonesia Forestry Researchers (INAFOR)	2019	1
B) General research related competences			
Mansholt Introduction course	MGS	2009	1.5
Advanced Microeconomics, UEC51806	WUR	2009	6
Advanced Macroeconomics, DEC53806	WUR	2009	6
Economics and Management of Natural Resources, ENR31306	WUR	2010	6
Econometrics, AEP 21306	WUR	2010	6
Advanced Econometrics, YSS34306	WUR	2010	6
C) Career related competences/personal development			
Information Literacy, including introduction Endnote	WGS	2009	0.8
Interpersonal Communication for PhD students	WGS	2009	0.6
Effective Behaviour in your personal surroundings	WGS	2009	0.5
Total			**36.9**

*One credit according to ECTS is on average equivalent to 28 hours of study load

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