Selective Logging and Silvicultural Treatments in Rainforests of the Neotropics: Consequences for Sustainability, Economics and Carbon Balance

Dissertation

to obtain the academic degree

Doctor rerum naturalium (Dr. rer. nat.)

at the Faculty of Mathematics, Informatics and Natural Sciences

Department of Biology

of Universität Hamburg

Submitted by

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from Dresden

Hamburg, 2020

Day of oral defence:	26 March 2021
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Selective Logging and Silvicultural Treatments in Rainforests of the Neotropics: Consequences for Sustainability, Economics and Carbon Balance
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Susan J. Ortloff, October 14, 2020

Declaration on oath

(Eidesstattliche Versicherung)

I hereby declare, on oath, that I have written the present dissertation by my own and have not used other than the acknowledged resources and aids.

(Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.)

Hamburg, 18 October 2020 ……………………….....

Gunter Sebastian Gräfe

Acknowledgements

I would like to thank Prof. Dr. Michael Köhl for giving me the opportunity to conduct the studies, for the supervision of this dissertation and for the continuous support and fruitful discussions throughout the whole duration of the work.

I also want to express my gratitude to Prof. Dr. Marco Marchetti and Prof. Dr. Dieter Pelz for their willingness to assess this thesis.

Furthermore, I would like to thank all co-authors of the articles for their magnificent input and all efforts made during the establishment of the studies, the field work and the writing process.

I especially thank Dr. Claus-Martin Eckelmann for his coordination, support and guidance during the field work in Belize, Guyana, Suriname, and Trinidad and Tobago.

Furthermore, I would like to thank the whole World Forestry team for providing a brilliant working atmosphere.

Finally, I would like to thank my wife Anna for their strong emotional support and backing during the time of writing this dissertation.

Abstract

Forests cover about 31 percent of the global land area. Tropical forests account for almost half of the total forest area and are a major terrestrial carbon pool. Since they act as both carbon source and sink, they contribute significantly to the global carbon cycle. Although the rate of deforestation has been declining over the last three decades, deforestation and forest degradation continue at a high rate. Despite the positive trends at global level, forest loss and degradation continue especially in tropical countries, which account for 10-15 percent of anthropogenic carbon emissions. Commercial logging is the main cause of forest degradation in the tropics. At present, tropical forests are mainly managed through selective logging. Over the past 30 years, the concept of sustainability has increasingly been incorporated into tropical forest management. The concept of sustainable forest management (SFM) attempts to reconcile ecological, socio-cultural and economic management objectives with the Forest Principles adopted at the United Nations Conference on Environment and Development (UNCED) in 1992. In addition to Reduced Impact Logging (RIL), SFM measures also include silvicultural treatments. In 2005, the negotiations on the United Nations Framework Convention on Climate Change (UNFCCC) launched a discussion on the link between climate change and forest loss, which led to the concept of Reducing Emissions from Deforestation and Forest Degradation (REDD). By integrating the conservation of forest carbon stocks, sustainable forest management and the enhancement of forest carbon stocks, the REDD scheme was expanded to REDD+. Although the concept of SFM is widespread and strongly promoted, it remains unclear to what extent SFM contributes to the sustainable use of tropical forests and to what extent SFM measures contribute to reducing carbon emissions from forests and thus to REDD+. The three scientific papers constituting this cumulative dissertation examine the contribution of SFM to sustainability in tropical forest management. They also analyse silvicultural treatments in terms of their impact on economic added value and the carbon balance of tropical forests.

The first part of the comprehensive summary presents the thematic context of the three papers. The thematic context provides an introduction to the relevance and status of tropical forests and their contribution to the global climate, followed by brief introductions to timber exploitation, sustainable forest management in the tropics and the REDD+ concept. Uncertainties in sustainable forest management in the tropics and in the implementation of REDD+ are discussed and conflicts of interest in the implementation of REDD+ are briefly presented. After the thematic framework has been established, the main objectives of this thesis are presented. The main objectives are "sustainability of selective logging", "profitability of future crop tree release treatments" and "impacts of silvicultural treatments as REDD+ mitigation benefits". The second part of the comprehensive summary integrates the three papers into the thematic framework of the current cumulative dissertation.

The first paper focuses on the analysis of recovery times and sustainability in tropical forest management using the example of four forest tenure types in Central and South America: large scale concession, private forests, forests managed under the periodic block system and community managed forests. As an indicator of sustainable timber production, the recovery times expected under the initial conditions of the stands were calculated and discussed with the regard to currently practiced cutting cycles. The findings show that general harvesting codes do not guarantee sustainable forest management in the tropics. Local stand conditions must always be one of the guiding principles of sustainable timber production. The application of rigid rules that do not take into account the current conditions of the stands carries the long-term risk of forest degradation. With these results, the currently practiced, generalized production methods for tropical forests are questioned and the necessity of a paradigm shift towards an ecologically sound, sustainable forest management is justified.

The second paper examines the economic aspects of silvicultural release treatments and considers the growth of the remaining stand and the timber prices that should be achieved at the end of the rotation period to make a treatment profitable. In this context, release treatments are considered as an investment that must be amortised by the additional growth of the remaining forest stand by the end of the rotation period. The treatment costs were derived from time studies carried out in four tropical countries during the treatment. A reverse approach was used to determine the additional growth that must be generated by the released trees by the end of the 30-year felling cycle to cover the treatment costs. The paper shows that the expected improvement in tree growth alone is not sufficient to justify the application of silvicultural treatments. While the treatment costs are known at the time when the decision to implement the measures is taken, future timber prices and harvesting costs as well as the additional growth actually achieved are subject to uncertainty. These uncertainties have a significant impact on the assessment of the economic risk, which is reflected in the choice of internal interest rates. The paper shows that investments in silvicultural treatments involve a considerable financial risk and that the decision to invest in silvicultural treatments should always be the subject of a detailed investment calculation.

The third paper examines the extent to which silvicultural treatments affect the carbon balance of the forest stand and whether refinancing through any profits generated from carbon sequestration payments would be possible. As in the second paper, this paper investigates silvicultural release treatments used to increase the growth of selected trees by felling competing trees in their immediate vicinity. The felling of competing trees leads to a reduction in a forest's carbon stock and thus represents a carbon loss. The paper estimates the time needed for the released trees to compensate for the carbon loss through felling competitor trees by increased growth. By using a recursive approach, it was examined whether the treatment costs could be offset by the financial carbon benefits achieved. The paper shows that silvicultural release treatments do not guarantee for an increase in forest carbon stocks. Furthermore, it is shown that refinancing of treatment costs is problematic and that silvicultural release treatments as a sustainable forest management measure are not suitable as REDD+ activities.

Based on the results derived in the papers and their discussion in the thematic context, conclusions are drawn with regard to the main objectives presented above. The complete versions of the three papers that, together with the comprehensive summary, constitute this cumulative dissertation and a short explanation of the personal contribution of the author to the papers are attached in the Annex.

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Acronyms and abbreviations

AGB *Above ground biomass*

CBD *Convention on Biological Diversity*

CL *Conventional logging*

CM *Community managed forest*

DBH *Diameter at breast height (1.3 m)*

FAO *Food and Agricultural Organisation of the United Nations*

FCT *Future crop tree*

FCTR *Future crop tree release*

FOB *Free on board*

FSC *Forest Stewardship Council*

HFLD *High-forest cover/low-deforestation*

ITTO *International Tropical Timber Organization*

LSC *Large scale concession*

MHD *Minimum harvesting diameter*

MR *Mortality rate*

NPV *Net present value*

PBS *Periodic block system*

PEFC *Programme for the Endorsement of Forest Certification*

PR *Private forests*

REDD+ *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*

RIL *Reduced impact logging*

SFM *Sustainable Forest Management*

SMF *Sustainable management of forests*

UNCED *United Nations Conference on Environment and Development*

UNFCCC *United Nations Framework Convention on Climate Change*

PART 1: THEMATIC CONTEXT

1 Structure of this thesis

The present work consists of two parts. The first part forms the thematic framework of the thesis. The theoretical background of the topic is presented and the relevance of tropical forests and their contribution to the global climate is discussed. Management of tropical forests and the REDD+ concept for reducing and avoiding carbon emissions from forests are briefly presented. Furthermore, uncertainties regarding SFM in the tropics and conflicts of interest in the implementation of REDD+ are addressed. Subsequently, the core issues of this thesis, which result from the theoretical background, are presented. These form the thematic context of three peer-reviewed publications of which this thesis consists. The individual papers are briefly summarized and will be discussed in the thematic context in the second part of this thesis. These papers are:

1) Gräfe, S.; Eckelmann, C.-M.; Playfair, M.; Oatham, M.; Pacheco, R.; Bremner, Q.; Köhl, M. (2020). Recovery Times and Sustainability in Logged-Over Natural Forests in the Caribbean. *Forests*. 11. 256. Published on 26 February 2020.
2) Gräfe, S.; Eckelmann, C.-M.; Playfair, M.; Oatham, M.; Pacheco, R.; Bremner, Q.; Köhl, M. (2020). Future crop tree release treatments in Neotropical forests – an empirical study on the sensitivity of the economic profitability. *Forest Economics and Policy*. 121. 102329. Published on 13 October 2020.
3) Gräfe, S.; Köhl, M. (2020). Impacts of future crop tree release treatments on forest carbon as REDD+ mitigation benefits. *Land*. 9. Accepted for publication on 16 October 2020.

2 Background

2.1 Relevance and state of tropical forests

With an area of 4.06 billion hectares, forests cover about 31% of the global land area. Tropical forests account for 45% of the total forest area (FAO 2020). Forests are home to the majority of the world's biodiversity and about 60% of all plant species are found in tropical forests (FAO and UNEP 2020). In addition to their diverse ecosystem services, such as water regulation and soil stabilization, forests provide the basis of life for a large number of people. The livelihoods and incomes of more than 410 million people depend on forests. Another estimated 1.6 billion people depend indirectly on forest goods and services for their livelihoods (Munang et al. 2011; World Bank 2004; World Resources

Institute et al. 2005). At the local level, communities benefit from access to forest products such as wood, medicines and firewood. At the regional level, forests provide important ecosystem services such as water regulation, soil stability, flood protection and air quality. At the global level, forests make an important contribution to economic development, biodiversity and climate regulation. Timber and processed forest products contribute more than US$ 450 billion to the global economy each year, and the annual value of internationally traded forest products is between US$ 150 and US$ 200 billion (Munang et al. 2011).

Forests contain large amounts of sequestered carbon and act both as a source and sink of carbon (Butarbutar et al. 2019; FAO 2020). They thus contribute significantly to the global carbon cycle (Lugo and Brown 1992; Soepadmo 1993; Pan et al. 2011). The carbon stocks of tropical forest ecosystems alone are estimated to be 306-324 billion tons of C, of which about 49-53% are bound in tropical primary forests[1]. Primary forests cover 32% of the tropical forest area. Each year, tropical forests sequester between 0.47 and 1.3 billion tons of C, which corresponds to 8-13% of annual anthropogenic CO_2 emissions (Mackey et al. 2020).

Although the rate of deforestation has decreased over the past three decades, deforestation and forest degradation continue to occur at an alarming rate (FAO 2010, 2015, 2020). Since 1990, an estimated 420 million hectares of forest have disappeared through conversion to other land uses. Between 2015 and 2020, the rate of deforestation has decreased from 16 million hectares per year in the 1990s to 10 million hectares per year (FAO 2015; FAO and UNEP 2020). Despite the positive trends at the global level, forest loss and forest degradation continue in tropical countries. Forest gain occurs at higher latitudes and in richer countries, while forest loss continues in poorer tropical countries. Africa had the highest net loss of forest cover, with a loss of 3.94 million hectares per year between 2010 and 2020, while South America experienced a decline in forest cover of 2.6 million hectares per year during this period (FAO and UNEP 2020). Deforestation in the tropics is responsible for 10-15% of anthropogenic carbon emissions (Houghton 2013; Pearson et al. 2014; Pearson et al. 2017; Munang et al. 2011). Some middle-income tropical countries are in transition to forest gain. This forest gain is the result of forest management reforms and improvements in agricultural practices on the one hand, and a significant expansion of forest plantations and tree plantations on the other. Artificial

[1] According to the FAO (2010) three categories of forests are distinguished: (1) Primary forests - naturally regenerated forests of native species in which there are no clearly visible signs of human activity and the ecological processes are not significantly disturbed; (2) production forests - forests used for industrial logging, where there is clearly visible evidence of human activity, but where the forests are dependent on natural regeneration processes; and (3) plantation forests - planted forests, consisting mainly of trees resulting from the planting or deliberate seeding of commercial species.

forest plantations account for 25-100% of forest gains in tropical countries (Sloan and Sayer 2015). Despite international attention and measures against deforestation and forest degradation, primary forests are declining rapidly due to ongoing land use interventions (Mackey et al. 2015).

The primary driver of global forest loss is commercial agriculture (Skutsch and Turnhout 2020; DeFries et al. 2010; Busch and Ferretti-Gallon 2017; McAlpine et al. 2009; Rudel 2007; Rudel et al. 2009; Leblois et al. 2017; Pendrill et al. 2019; Jayathilake et al. 2020). It is responsible for 80% of deforestation in the tropics (Kissinger et al. 2012). Commercial logging is the main cause of forest degradation in Latin America and South-East Asia, while firewood and charcoal production are the main causes of degradation in Africa. Besides the direct causes of deforestation, indirect causes will become more important in the future. Indirect causes include global population and economic growth and the associated increase in demand for primary raw materials, agricultural products, wood products and minerals (Kissinger et al. 2012; Boucher et al. 2011; Hosonuma et al. 2012; Geist and Lambin 2001).

Several international initiatives and programs have been launched to combat deforestation and forest degradation. Within the framework of the UNCED[2], 179 countries signed the Agenda 21 and declared their intention to combat deforestation (Norman and Carr 2009). Forest certification systems such as the PEFC[3] or the FSC[4] promote sustainable forest management practices at the local level in order to prevent forest degradation. The Convention on Biological Diversity (CBD) adopted the strategic plan for biological diversity 2011-2020, which includes measures to reduce forest degradation. The United Nations Framework Convention on Climate Change (UNFCCC) developed a mechanism to reduce carbon emissions from deforestation and forest degradation (REDD).

2.2 Timber exploitation and sustainable forest management in the tropics

Currently, tropical forests are mainly managed through selective logging (Asner et al. 2005; Putz et al. 2012; Blanc et al. 2009; Blaser and ITTO 2011). Selective logging is used to extract selected trees of economically relevant species for timber production. The removal is often controlled by a felling cycle, a diameter limit and an annual production quota[5] (Fredericksen 1998). Annual logging takes place in one or more compartments, depending on the length of the logging cycle and the total area of the forest. In the tropics, felling cycles of between 15 and 40 years are typical (Hawthorne et al. 2011; Keller et al. 2007). Selective logging is usually performed as conventional logging (CL) or reduced impact logging (RIL). While RIL is based on a 100% inventory of all commercial timber

[2] UNCED stands for the United Nations Conference on Environment and Development.

[3] PEFC stands for the Programme for the Endorsement of Forest Certification.

[4] FSC stands for the Forest Stewardship Council.

[5] Annual allowable cut.

trees with a certain minimum diameter, CL is based on harvesting operations without any prior logging planning. Marketable logs are identified and felled during harvesting in the forest and later searched for and extracted by skidders. Due to the lack of planning, CL leads to considerable damage to the remaining stand (Boltz et al. 2003; Rivero et al. 2008). CL refrains from measures such as pre-harvest inventory, skid trail planning or directional felling. The loggers are usually paid by piece rate, which provokes quick work with little care for the remaining stock. The skidding crews usually lack the necessary information to locate the felled trees exactly. This leads to a high inefficiency of the skidding process and thus to major skidding damage to the remaining stand (Holmes et al. 2002).

Over the past 30 years, the concept of sustainability has increasingly found its way into tropical forest management. The concept of sustainable forest management (SFM) attempts to bring ecological, socio-cultural and economic management goals into harmony with the forest principles adopted at the UNCED in 1992. Techniques for minimizing the ecological impact of tropical timber harvesting were tested in the 1990s and are now standard techniques in tropical forest management under the term RIL (van der Hout and van Leersum 1998; Putz et al. 2008; Holmes 2020). RIL is the intensively planned and carefully controlled execution of logging operations to minimize the environmental impact on forest stands and soils. RIL includes a number of measures, such as pre-harvest inventories, skid trail planning, cutting of lianas, protection of sensitive areas and buffer zones, use of directional felling, use of a winch to pull logs to the skid trail, post-harvest assessments, etc. (Dykstra 2001, 2002; Sist 2000).

2.3 Silvicultural treatments

Silviculture is defined as the theory and practice of controlling the establishment, structure, condition and growth of forests (Ford-Robertson 1971). Silviculture in the tropics in recent decades has been concerned mainly with two concepts: artificial regeneration, for example through enrichment plantings, and natural regeneration and improvement of existing forest stands, for example through thinning treatments (Bertault et al. 1995; Putz).

In enrichment planting, the stands are enriched with valuable tree species by planting them after the harvest. The enrichment requires permanent care to ensure the survival and establishment of the planted trees (Schwartz et al. 2013; Schwartz et al. 2017; Navarro-Cerrillo et al. 2011). Since the requirements for the necessary careful planning and the considerable amount of work involved were rarely met, the goal of the enrichment plantings was often missed (Bertault et al. 1995; dos Santos and Ferreira 2020; Neves et al. 2019).

The concepts for natural regeneration and stand improvement aim to promote certain existing tree species in the stand. Thinning can reduce the proportion of undesirable tree species in the stand and concentrate available resources on the remaining stand. One form of an intermediate thinning is future crop tree release (FCTR) which is directed toward the elimination of competitors from larger trees to favour selected immature trees of promising commercial value (Smith 1997; Dawkins 1955; Wadsworth and Zweede 2006; Wadsworth 1997). Individual tree measures, such as the selective removal of climbers and lianas, can lead to an increase in the growth of desired individual trees (Graaf et al. 1999; Villegas et al. 2009; Peña-Claros et al. 2008; Wadsworth and Zweede 2006; Mills et al. 2019).

2.4 REDD+

In 2005, the negotiations on the United Nations Framework Convention on Climate Change (UNFCCC) launched a discussion on the link between climate change and forest loss, which resulted in the concept of REDD (UNFCCC 2006, 2008). The REDD mechanism creates a financial value for the carbon stored in forests by providing financial incentives to developing countries to reduce emissions from forests (Fischer et al. 2016; Seymour and Busch 2016). The payments are results-based, i.e. linked to proof of a measurable reduction in carbon emissions (Angelsen et al. 2018; Voigt and Ferreira 2015). The concept of REDD was later expanded to REDD+ and supplemented with the conservation of forest carbon stocks, sustainable forest management and the enhancement of forest carbon stocks (UNFCCC 2011). After extensive negotiations, the technical guidance for REDD+ was completed at the end of 2013 (EFI and Proforest 2014). The guideline includes the definition of reference levels, appropriate protection frameworks and approaches for monitoring, measurement, reporting and verification (UNFCCC 2014). The question of the long-term financing of REDD+ has not been finally clarified. In addition to financing through public funds, the plan is also to finance REDD+ through trading in emission credits, which means that REDD+ will be self-financing in future under market conditions (Karsenty 2012).

2.5 Uncertainties related to SFM in the tropics

2.5.1 Understanding of SFM

Despite the widespread use of SFM and the integration of SFM into the REDD+ mechanism, there is no uniform definition. The debate on what activities should be eligible for incentives under a REDD+ instrument is confused by the lack of a common understanding of SFM and the term "sustainable management of forests" (SMF) used by the UNFCCC (FAO 2009). One of the most widely accepted definitions of SFM is that of the ITTO[6] (2005): "The process of managing forest to achieve one or more clearly specified objectives of management with regard to the production of a continuous flow of desired forest products and services without undue reduction of its inherent values and future

[6] ITTO stands for the International Tropical Timber Organization.

productivity and without undue undesirable effects on the physical and social environment". For the World Commission on Forests and Sustainable Development, SFM must be "a flexible concept that accepts changes in the mix of goods and services produced or maintained over long periods of time and according to changing values signalled by various stakeholders" and that SFM should be "seen as a process that can be continuously adapted according to changing values, resources, institutions and technologies" (Salim and Ullstein 2000; Sist et al. 2014). SFM aims not only to ensure the flow of goods and services, but also to keep forest processes intact, including the preservation of the range of functional species that provide these goods and services (Thompson et al. 2014). SFM considers forests both in terms of time and space. Therefore, SFM represents a balance between the conservation and production of forest goods and services for humans and must operate within the capacity of the forest to restore and maintain its functions (Sist et al. 2014). The FAO definition of SMF refers to "application of forest management practices for the primary purpose of sustaining constant levels of carbon stocks over time" (Contreras-Hermosilla 1999). Thus, SMF would not require the sustainable conservation of other forest values such as biodiversity, timber production, watershed protection, etc. (Zimmerman and Kormos 2012). The two terms SMF and SFM and the lack of a common definition of SFM create confusion and potential for conflict in the debates (FAO 2009). Furthermore, they offer forest managers the opportunity to choose between different concepts and definitions, thus allowing them to decide which forest values are to be sustainably preserved (Zimmerman and Kormos 2012).

2.5.2 Post-harvest recovery and rotation cycles

Tropical forest management focuses mainly on timber production, with the main objective of sustained timber yield. Trees above a certain minimum diameter are removed from the stand, which is then expected to recover over a period of 30 to 40 years (Keller et al. 2007). The crucial question is how much the timber stock will increase during a 30 to 40 year rotation cycle. Sustainability is achieved when the same amount of wood is harvested in each felling cycle as is regenerated over the next 30 to 40 years. From an environmental point of view, SFM requires that by the end of the rotation cycle, the stock must have returned to the state it was in before harvest. This means that forests should have the same structure, timber volume, biodiversity, biomass and ecological processes as before harvesting (Sist et al. 2014). However, studies investigating the influence of logging on the recovery of some of these variables (timber volume, biomass and tree species diversity) in tropical forests show that only 50% of the original timber volume can be recovered within a rotation cycle of 30 to 40 years (Putz et al. 2012).

2.5.3 Impact of selective logging and fixed harvest regulations

Usually, during selective logging in the tropics, the most valuable and marketable tree species are harvested selectively first. When the most valuable species in an area have been exhausted, the next most valuable tree species is used. This high-grading leads to an impoverishment of species diversity and a consequent reduction in the value of the stand. The impact of selective logging on the forest depends mainly on the harvest intensity, measured in the number of trees harvested or extracted cubic metres per hectare. With increasing harvest intensity, the damage to the remaining stand increases (Zimmerman and Kormos 2012).

Harvest regulations such as minimum cutting cycle, minimum felling diameter, maximum harvest intensity or seed-tree retention rate are partly specified by the authorities. Minimum cutting cycles of 25-35 years or minimum harvesting diameter of 50 cm are common. Various studies have investigated and questioned cutting cycles and harvest intensities in tropical South America (e.g. Macpherson et al. (2012), Piponiot et al. (2019), ter Steege et al. (2002)), whereby the common consensus calls into question the sustainability of current management. Several studies have shown that such rigid regulations do not ensure sustainable management (Huth and Ditzer 2001; Kammesheidt et al. 2001; Hall et al. 2003; Sist et al. 2003; Dauber et al. 2005; Zimmerman and Kormos 2012). If a harvest intensity of eight trees per hectare or 25-30 m^3 ha^{-1} is applied, cutting cycles of 25-35 years are not sufficient for a complete regeneration of the stand. High harvest intensities usually lead to a strong opening of the canopy, which provokes a strong growth of pioneer vegetation. The fast growing pioneer species prevent the slow growing, shade-tolerant hardwood species from regeneration. Within a cutting cycle of 25-35 years such a stand will not regenerate. If the minimum felling diameter is used as the only restriction, 50 cm is too small to ensure a stable population of reproductive individuals (Zimmerman and Kormos 2012).

2.5.4 Effects of silvicultural treatments

Silvicultural treatments are a common tool used to increase the timber production and thus shorten the time until the next harvest. In addition to enrichment plantings, removal of lianas or girdling of unwanted trees, liberation felling is one of the silvicultural treatments that have been studied in the tropics. Future crop tree release (FCTR) is mainly used in North America and Europe to positively influence the growth of so-called future crop trees (FCTs) identified in the early stages of stand development (Abetz 1990; Abetz and Klädtke 2002; Burschel and Huss 2003). By eliminating crown competition from neighbouring trees, the FCTs are provided with more growing space. FCTR supports the concentration of growth factors of a forest site on a small number of selected trees. The increased growing space provides more light, water and nutrients for the released tree. This promotes their diameter and volume growth rates and shortens the time until the final harvest diameter is reached (Dawkins 1955; Wadsworth and Zweede 2006; Smith 1997). The positive stimulation of tree growth by release treatments in temperate forests has been confirmed by numerous studies (e.g. Hein et al. (2007a), Hein et al. (2008), Hein et al. (2007b), Herbstritt et al. (2006), Mäkinen and Isomäki (2004)). Several studies examined the effect of silvicultural treatments in tropical forests, where growth increases from 20 to 60% were observed (Wadsworth and Zweede 2006; Villegas et al. 2009; Peña-Claros et al. 2008; Kuusipalo et al. 1997; Werger 2011). Graaf et al. (1999) have carried out silvicultural treatments in Suriname since 1965. They reduced the basal area of non-marketable species from 20 m^2 ha^{-1} to 6 m^2 ha^{-1} and the total basal area to 10 m^2 ha^{-1}. The effects of these treatments lasted for less than 10 years and even with short cutting cycles of 20-30 years, the treatments were only effective if they were repeated. The mortality rate increased as the intensity of the treatments increased. David et al. (2019) found that the strength of the liberation effect on the remaining stand depends strongly on the tree species. Kuusipalo et al. (1996) investigated the effect of deforestation and crown liberation on the population dynamics of tree seedlings. They showed that canopy release apparently favours the recruitment of seedlings from light-demanding pioneer species rather than promoting the regrowth of the desired timber stock. Kübler et al. (2020) showed that the topographical position of a tree in tropical mountain forests is more relevant for growth than the application of silvicultural measures.

2.6 Uncertainties in the implementation of REDD+

The three major challenges often mentioned in connection with REDD+ are leakage, permanence and additionality (Agrawal et al. 2011). Leakage refers to the relocation of economically destructive activities to another site as a result of a REDD+ project. Therefore, national REDD+ programmes are targeted, as they could reduce the risk of leakage within a country. Permanence refers to the risk that carbon is only temporarily stored in forests. There is no guarantee that this stored carbon will not be emitted in the future due to economic destructive activities or natural disasters. Additionality refers to the risk that reduced carbon emissions would have occurred anyway even without REDD+ payments (Agrawal et al. 2011; Ghazoul et al. 2010; Atmadja and Verchot 2012; van Oosterzee et al. 2012).

Redd+ payments are linked to proof of a measurable reduction in carbon emissions. Currently, most of the funding comes from public funds from governments and international organisations. In the future, REDD+ is expected to become self-financing mainly through trading in carbon credits under market conditions. The emission reductions must be measurable and verifiable. Such measurement of emission reductions requires the creation of a reference scenario. The reduction of emissions from deforestation and forest degradation or the increase in sequestration due to improved forest management or the increase in carbon stock in forests is often measured by forest reference levels or forest reference emission levels. Forest reference (emission) levels set a benchmark for mitigation activities by providing a reference point against which current and actual efforts over a predetermined period can be compared (Chagas et al. 2013). However, since the emission reduction for REDD+ always refers to a hypothetical alternative scenario, the reference scenario for the REDD+ measure, verifiability is not given (Kill 2016). The hypothetical scenario, without REDD+ measure, does not occur as soon as the REDD+

measure is implemented. The marketed CO_2 credits do not represent a physical product or newly sequestered carbon, but only the intention to avoid emissions from forest degradation or deforestation over the REDD+ project period (Kill 2015).

REDD+ should provide financial support to forest communities that traditionally manage their forests and whose use does not pose a threat to the forest (Sobrevila 2008; Bayrak and Marafa 2016). In order to benefit from REDD+, forest communities would have to present their traditional forest use as a threat to the forest, since without evidence of a hypothetical deforestation risk, there can be no hypothetical emissions from deforestation that can be avoided (Kill 2016). Therefore, forest communities cannot prove that REDD+ measures have contributed to reducing emissions, which means that REDD+ payments are not possible.

Due to the complexity and dynamics of forest ecosystems in the tropics, the determination of carbon sequestered in forests is highly error-prone and unreliable. A uniform methodology is still lacking. Thus, an accurate and reliable calculation of the supposed emission reduction is not possible. Reference values for deforestation in the hypothetical case without REDD+ project could be set too high, which would lead to excessive avoided emissions and thus generate too many emission credits (Karsenty 2008; Griscom et al. 2009; Dezécache et al. 2018). Besides the benefits for forest communities, it is also unclear how so-called high-forest cover/low-deforestation (HFLD[7]) countries can benefit from REDD+ (Köhl et al. 2020; da Fonseca et al. 2007). If payments were based solely on emission reductions, developing countries with historically low forest emission rates (HFLD countries) would have little incentive to participate in REDD+. Instead, they could be induced to accept offers from forest-based industries which would come under pressure in other REDD+ countries to operate in their (HFLD) forests, leading to a carbon leakage rather than a reduction, thus invalidating the REDD+ credits of the non-HFLD country (Overman et al. 2018; Strassburg et al. 2009).

3 Core issues of forest management for the thesis

3.1 Sustainability of selective logging

As mentioned in the previous chapters, tropical forests are currently managed mainly through selective logging. Usually the most valuable and marketable tree species are harvested first. When the populations of the most valuable species in an area are exhausted, the next most valuable tree species is harvested. This high-grading leads to an

[7] HFLD was defined by da Fonseca et al. (2007) to identify a group of countries at risk of being excluded from a new framework for reducing emissions from deforestation - countries with high forest cover (>50% of land area in 2005) and low deforestation rates (below the global average of 0.22% in 1990-2000).

impoverishment of species diversity and thus to a reduction in the value of the stand. In order to control timber exploitation, many tropical countries have adopted general harvesting codecs with fixed harvesting regulations, such as fixed harvesting cycles and a maximum allowable cutting rate (e.g. van der Hout (2011), GFC (2014), etc.). However, it is unclear to what extent harvesting codecs contribute to sustainability in tropical forest management.

The first paper of this cumulative dissertation studies the question of sustainability under four different forest tenure types, also critically analysing the fixed harvesting rules in tropical forest management.

3.2 Profitability of future crop tree release treatments

The decision whether or not to apply silvicultural treatments is usually based on the expected increase in the growth of the remaining stand. Numerous studies exist which investigate the effects of silvicultural treatments on the growth and mortality of the remaining stand in the tropics. However, silvicultural treatments also represent a financial investment which must be amortised in order to be profitable. The success of the treatment and its profitability are subject to various factors and risks which must be taken into account when deciding for or against the implementation of a silvicultural treatment in order to avoid financial damage. While the cost of the treatment is known at the time of the decision, future timber prices and harvesting costs as well as the additional growth actually achieved are subject to uncertainty. In addition, investments in silvicultural treatments are usually subject to long maturities, so the choice of discount rate has a significant impact on profitability.

The second paper of this thesis examines silvicultural treatments from an economic point of view. The costs of a silvicultural treatment were determined on the basis of empirical data and public data of the project region. The paper examines the additional growth required and the timber prices that would have to be achieved in order for a silvicultural treatment to be profitable. Furthermore, the sensitivity of profitability to the factors growth, timber price, harvesting costs and discount rate is examined.

3.3 Impacts of silvicultural treatments on forest carbon as REDD+ mitigation benefits

The five activities of REDD+ that contribute to mitigation measures in the forest sector include increasing the carbon stocks of forests and sustainable forest management (UNFCCC 2011). Silvicultural treatments are SFM tools used to increase the volume growth of commercial tree species in forests. While the effects on the mortality and growth of treated trees have been investigated in numerous studies, there have been few studies on the effects on the carbon stock of forests.

The third paper of this dissertation examines silvicultural release treatments, which aim at increasing the growth of selected trees by felling competing trees in their immediate vicinity. The felling of competing trees leads to a reduction of a forest's carbon stocks and thus represents a carbon loss. The paper estimates the time needed for the trees released to compensate for the carbon loss through increased growth. Using a recursive approach, the paper further examines whether the treatment costs can be offset by the financial carbon benefits achieved.

PART 2: INTEGRATION OF THE STUDIES INTO THE THEMATIC CONTEXT

Part I shows that, despite the widespread and strong promotion of sustainable forest management (SFM), uncertainties remain concerning the sustainability of tropical forest management. As part of SFM, silvicultural treatments are part of the activities currently under discussion in tropical forest management. However, there are still large uncertainties about the economic profitability of such treatments in tropical forests. Since SFM has become part of REDD+, potential possibilities can be discussed to what extent investments in silvicultural treatments could be financed with REDD+ payments. However, the question of the impact of silvicultural treatments on the C-stock of the forest stand and whether they qualify as REDD+ mitigation benefits must be answered first.

These core questions are the overarching theme of the three papers that make up this thesis. In the following the summaries of the individual papers are provided. The summaries[8] presented are more detailed than the original summaries of the papers, primarily to better illustrate the methods. However, for reasons of easy readability, only short summaries are presented. The methods and results are described in detail in the papers. After each summary, a discussion of the paper is presented to highlight the relevance to the thematic context presented in Part I.

1 Gräfe et al. (2020)[9]: "Recovery times and sustainability in logged-over natural forests in the Caribbean"

The first paper of the cumulative dissertation was written by Sebastian Gräfe, Claus-Martin Eckelmann, Maureen Playfair, Mike Oatham, Ramon Pacheco, Quacy Bremner and Michael Köhl, and published online with open access in the peer-reviewed MDPI journal "Forests" on 26 February 2020.

1.1 Summary

The paper critically analyses the sustainability of timber production by comparing common forestry practices in four tropical countries of Central and South America: Belize, Guyana, Suriname, and Trinidad and Tobago (Figure 1). As an indicator of sustainable timber production, the recovery times expected under the initial condition of stands and their status 30 years after previous logging activities were calculated.

[8] Contain partial citations from the papers.

[9] Gräfe, S.; Eckelmann, C.-M.; Playfair, M.; Oatham, M. P.; Pacheco, R.; Bremner, Q.; Köhl, M. (2020b): Recovery Times and Sustainability in Logged-Over Natural Forests in the Caribbean. In Forests 11 (3), p. 256. DOI: 10.3390/f11030256.

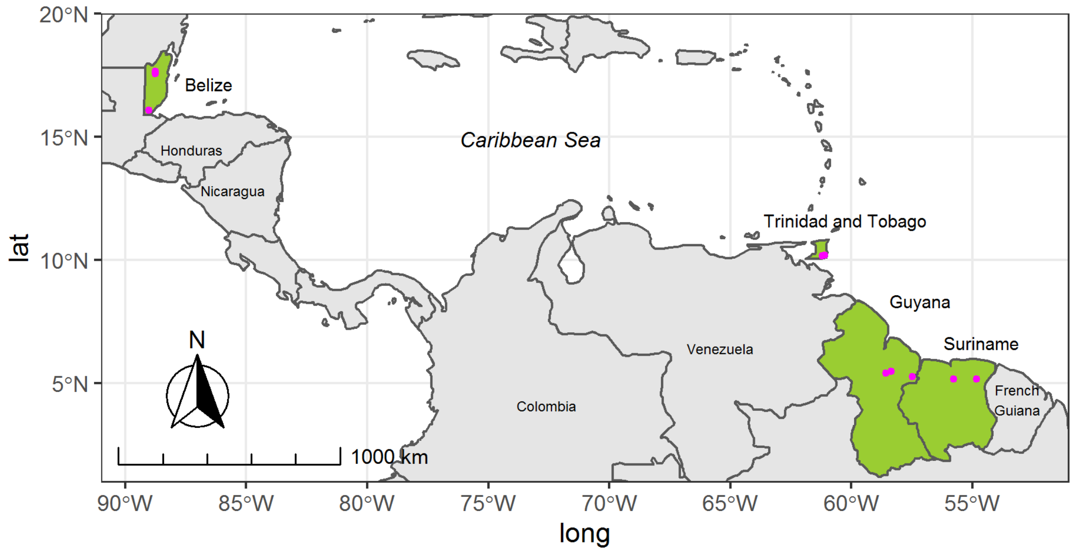

Figure 1. Study countries (green) and experimental sites (magenta) (from Gräfe and Köhl (2020))

The approach of sustainable forest management has become an essential part of tropical forest management (ITTO 2015; Blaser and ITTO 2011; Pancel and Köhl 2016). Although there is no generally accepted definition of SFM, the concept has been promoted by the international community. Criteria and indicators, as well as guidelines for strengthening SFM in tropical forests were launched by the FAO and ITTO (ITTO 2015, 2016; FAO 2017). As set out in the chapters of the thematic context, although the widespread use and strong promotion of SFM, there are still uncertainties about the actual contribution of current forest management practices to sustainability (Nasi and Frost 2009). Several studies examined cutting cycles and harvest intensities in tropical forests of South America (e.g., Piponiot et al. (2018), Piponiot et al. (2019), Macpherson et al. (2012), ter Steege et al. (2002)), with the joint consensus questioning the sustainability of current management.

Table 1. Experimental sites and forest tenure types (from Gräfe et al. (2020b))

Country	Site	Silvicultural System/Logging Type	Ownership	Tenure Type	Cutting Cycle	Code
Belize	Rio Bravo 305	Polycyclic / controlled selective logging based on minimum harvesting diameter (MHD) and maximum allowable cut (MAC) from yield model	Private forest	Private managed by owner	40 years	PR
	Rio Bravo 102					
	Quiche Ha	Polycyclic / conventional selective logging	State forest	Community managed with annual cutting permits	1 year	CM
Guyana	Greatfalls	Polycyclic / conventional selective logging based on MHD				
	Orealla					
	Ituni					
Suriname	Mapane	Polycyclic / controlled selective logging based on MHD and fixed MAC	State forest	Large scale concession	30 years	LSC
	Kabo	Polycyclic / semi-controlled selective logging based on MHD and fixed MAC				
Trinidad and Tobago	Rio Claro	Polycyclic / conventional selective logging based on MHD with individual tree sale	State forest	Periodic block system	30 years	PBS
	Cats Hill					

The study was carried out in four Caribbean countries: Belize, Guyana, Suriname, and Trinidad and Tobago. For each country, at least two research sites were selected. The data utilized for the study was assessed on experimental plots covering a total area 10 km^2 to compare current forest management practices of four forest tenure types (Table 1) that commonly exist in the study countries: large scale concessions (LSC), private forests (PR), periodic block system forests (PBS), and community managed forests (CM).

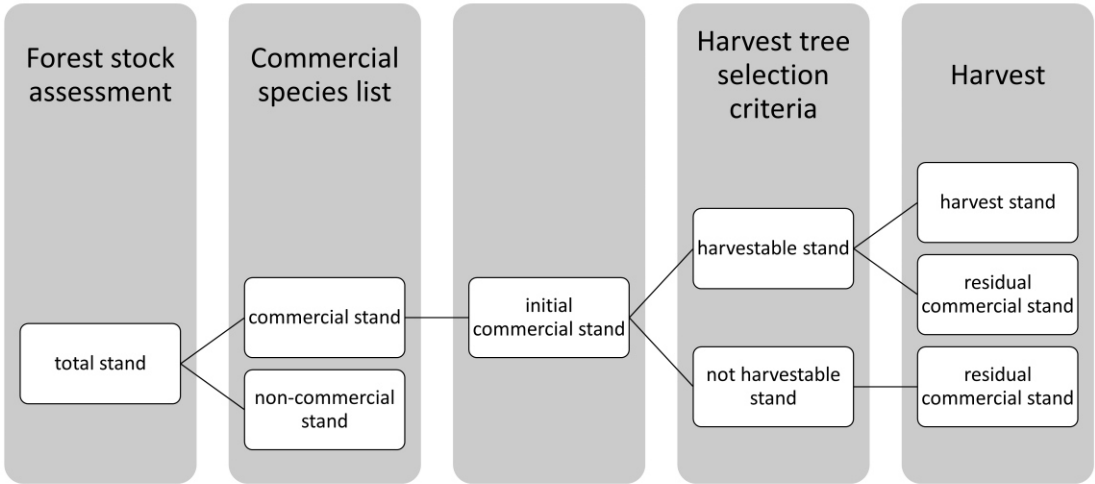

Figure 2. Systematics of stand terminology (from Gräfe et al. (2020b))

Only a proportion of the total volume is made of so called commercial species with a merchantable value on the timber market. Depending on the tree selection, the trees were divided into groups: (1) harvestable trees = trees that met the criteria for harvest and were potential harvest trees, (2) harvest trees = trees of the harvestable stand that were selected to be harvested during the actual or upcoming harvest, and (3) residual trees = trees of commercial species that formed the remaining commercial stand after logging. The harvested and the residual commercial stand together formed the initial commercial stand (Figure 2).

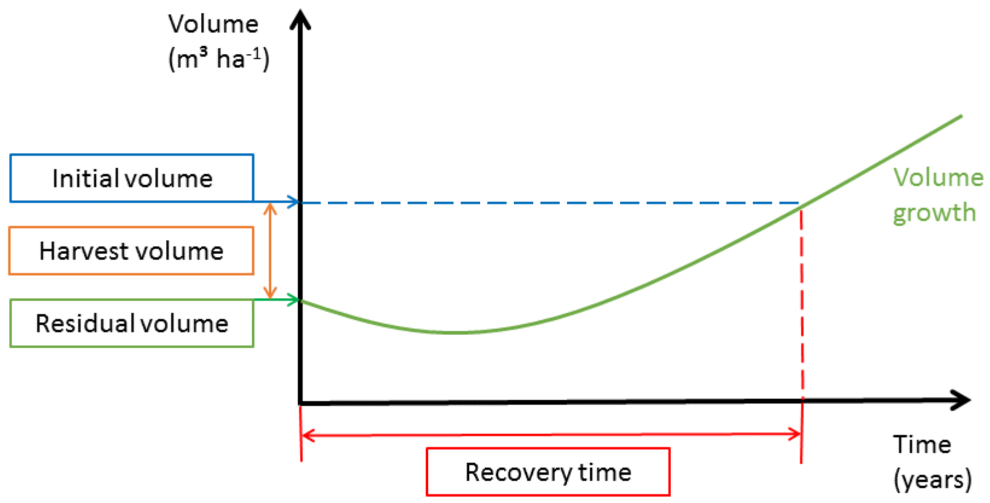

Figure 3. Growth simulation example (from Gräfe et al. (2020b))

As an indicator of sustainable timber production, the recovery times expected under the initial condition of the stands were calculated and compared with currently practiced cutting cycles. Three growth scenarios were simulated using diameter growth rates from empirical data from studies in the region of 1.6 mm year $^{-1}$ (G1.6), 2.7 mm year^{-1} (G2.7) and 4.5 mm year^{-1} (G4.5). In order to compensate for the recruitment of young trees, which was not included in the calculations, a mean annual mortality rate (MR) of 1% year^{-1} for the overall volume of the stand over the entire simulation period was applied (Sist and Ferreira 2007; Sist and Nguyen-Thé 2002; Sheil and May 1996). The initial volumes were determined for all commercial trees as well as for commercial trees with a minimum harvesting DBH-threshold ≥45 cm (MHD). The harvesting percent was calculated based on the ratio of initial commercial volume and harvested volume. The recovery time was calculated using the annual volume increment and the volume of the initial commercial stand. Recovery time here means (1) the time the forest needs to recover its initial commercial volume ignoring the commercial DBH classification and (2) the time the forest needs to recover its initial commercial volume of trees with DBH ≥ MHD. The results of the growth simulation are presented in graphical form showing the residual volume in relation to initial volume and harvest volume and the time needed for recovery (Figure 3).

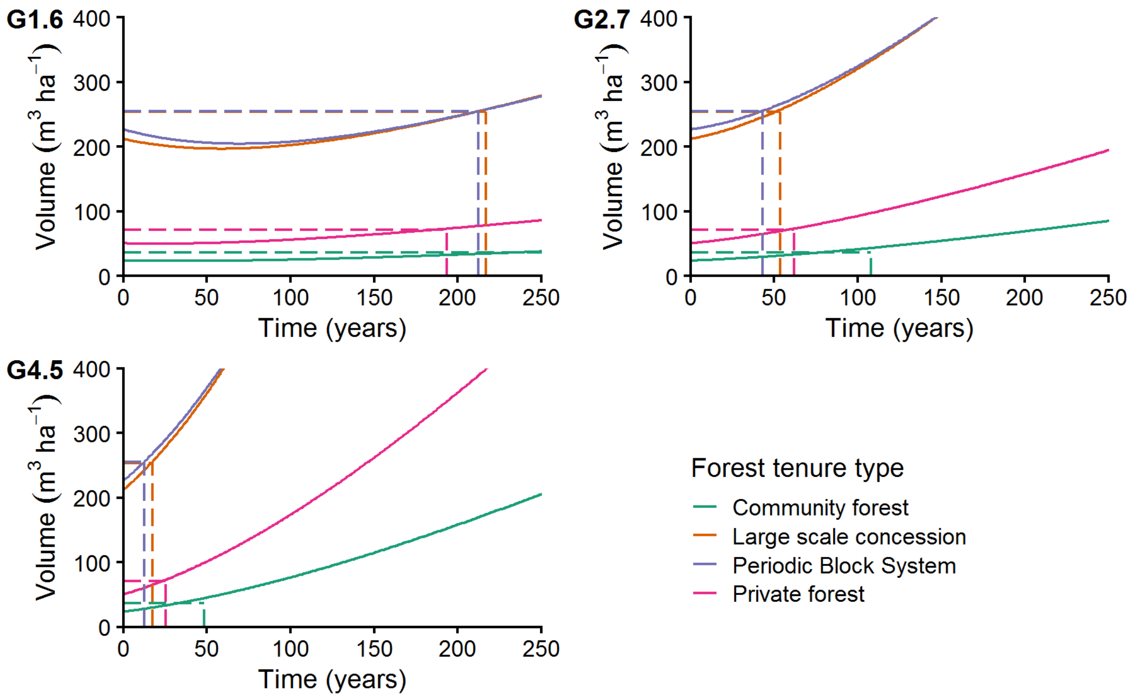

Figure 4. Increment of commercial species volume (from Gräfe et al. (2020b))

Highest initial volumes were found in LSC and PBS managed forests. Lowest volumes were found in CM and PR forests. Assuming the lowest growth rate for all commercial trees, none of the stands studied reached the initial pre-harvest volumes within the currently practiced cutting cycles. Assuming the highest growth rate for all trees, LSC, PBS, and PR forests reach the initial pre-harvest volume (Figure 4). Looking at the subset of commercial trees with a DBH ≥45 cm, all stands will reach the initial volume within 30 years only if the highest growth rate is assumed (Figure 5).

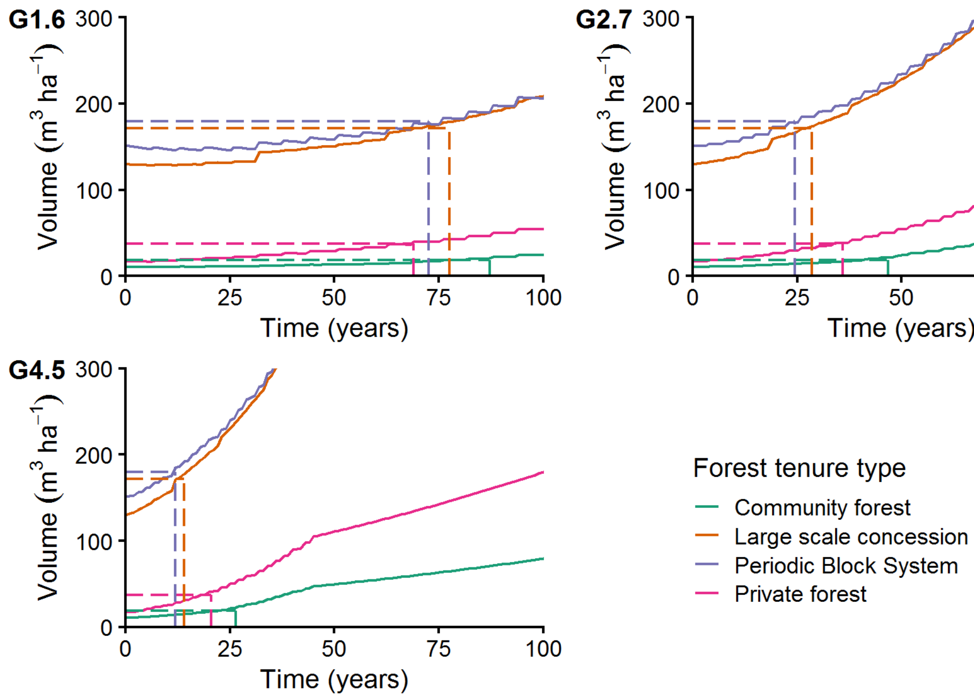

Figure 5. Increment of commercial species volume of trees with DBH ≥45 cm (from Gräfe et al. (2020b))

The results show that general harvest codes do not guarantee sustainable forest management in the tropics. Local stand conditions must always be one of the guiding principles of sustainable timber utilization. Applying the rigid rules, which do not take into account the current conditions of the stands, entails long-term risk of forest degradation.

1.2 Discussion in the thematic context

The first paper analyses and questions the sustainability of common forest management practices in four common forest tenure types in Central and South America. The results and findings of the paper help to better assess the sustainability of current tropical forest management and thus make an important contribution to answering the first key question of this thesis.

In defining sustainable forest management, economic, ecological and social aspects can be combined and weighted differently. Accordingly, the chosen definition plays a decisive role in the assessment of sustainability (Gräfe et al. 2020b). In the paper, monocyclic management systems, in which timber harvesting is carried out at long intervals without intermediate silvicultural measures, are considered. Sustainability is defined as the time it takes a forest stand to recover the volume of timber harvested. Based on the recovery time, sustainable cutting cycles can be determined. From this it can be deduced whether the cutting cycles currently practised are actually sustainable.

The paper shows that the sustainable use of tropical natural forests is not guaranteed by applying general logging rules. Rather, the current state of the stands must be assessed through pre-harvest inventories and taken into account when planning harvesting operations. Harvesting operations must be based on the current volume of trees, their number and diameter distribution. If these are not sufficient, harvesting operations must be postponed to a later date. In this way, stand growth and recovery time can be used as reference values for determining harvest intensities and harvest cycles. The resulting flexible consideration of the specific conditions of each stand is a prerequisite for sustainable forest management.

2 Gräfe et al. (2020)[10]: "Future crop tree release treatments in neotropical forests – an empirical study on the sensitivity of the economic profitability"

The second paper of the cumulative dissertation was written by Sebastian Gräfe, Claus-Martin Eckelmann, Maureen Playfair, Mike Oatham, Ramon Pacheco, Quacy Bremner and Michael Köhl, and was published in the peer-reviewed Elsevier journal "Forest economics and policy" on 13 October 2020.

2.1 Summary

The paper focuses on the economic aspects of future crop tree release treatments in four tropical countries of Central and South America (Belize, Guyana, Suriname, and Trinidad and Tobago). The treatments are considered to be investments that have to pay off for themselves by the additional growth of the released trees and the corresponding timber prices at the end of a 30 year cutting cycle.

Silvicultural treatments are a common tool used to increase the production of commercial timber in forest stands. The objective is to focus the volume growth of forest sites on individual commercially viable trees in order to increase their volume growth until the end of the cutting cycle. One form of silvicultural treatments is future crop tree release (FCTR) through liberation fellings. By removing the crown competition from neighbouring trees, FCTs are provided more growing space (Abetz 1975; Abetz and Klädtke 2002). FCTR supports the concentration of growth factors of a forest site on a small number of selected trees. In summary, FCTR can be described as high thinning in the upper crown layers, which removes competition from a given number of valuable trees. Thus, their diameter and volume growth rates are promoted and the time needed to reach final harvest diameters shortened. The increased growing space provides more light, water and

[10] Gräfe, S.; Eckelmann, C.-M.; Playfair, M.; Oatham, M. P.; Pacheco, R.; Bremner, Q.; Köhl, M. (2020a): Future crop tree release treatments in neotropical forests – an empirical study on the sensitivity of the economic profitability. In Forest Policy and Economics 121, p. 102329. DOI: 10.1016/j.forpol.2020.102329.

nutrients for the released tree. From an economic point of view, the treatments represent investments that pay for themselves through later, higher profits. A correspondingly strong stimulus to growth is therefore necessary to make the investment in treatments financially beneficial. Their impact on the growth or mortality of the remaining stand has been widely studied.

The paper considers the costs and the sensitivity of the profitability of liberation treatments in four Caribbean and South American countries. Liberation treatments are regarded as an investment that has to pay for itself through the additional growth of the remaining forest stand during the rotation period or through corresponding timber prices that must be achieved at the end of the commonly practiced cutting cycle of 30 years. The study is based on empirical data collected on experimental sites of 10 km² in Belize, Guyana, Suriname, and Trinidad and Tobago. In order to assess the costs of the liberation treatments, comprehensive time studies that include all working steps involved in the liberation of FCTs were carried out. The costs of the treatment were derived from the data of the time studies.

The aim of the silvicultural treatment is to increase the growth of the treated individuals. In order for the treatment to be profitable, the income generated by the additional growth at the end of the cutting cycle must at least cover the cost of the treatment. As future costs and returns are valued differently from present costs and returns, the analysis of the treatment was based on a variation of the net present value (NPV) method, which is a suitable method for evaluating the profitability of investments (Arnold 2014; Remer and Nieto 1995). If the NPV of an investment is larger than zero, the investment is considered to be profitable. For the calculations, an annual discount rate must be determined. Especially for long-term investments with high initial costs, the level of the discount rate has a considerable influence on the resulting NPV. For the calculations three discount rate scenarios were defined. To determine when the NPV becomes zero, either the required timber price per cubic meter or the required additional growth per FCT was chosen. The required timber price is a function of harvesting costs, treatment costs and the additional growth of the released FCT reduced by harvest losses. The required additional growth is a function of the treatment costs and the harvesting-cost free revenue as the difference of timber price and harvesting cost corrected for logging losses.

The profitability of treatments depends on several input parameters, such as treatment costs, achievable timber prices or the additional growth of treated trees. However, these parameters vary from region to region. To analyse the profitability by means of a sensitivity analysis, pre-defined ranges of input parameters were used. The sensitivity analysis was conducted in reference to the NPV by using ranges of treatment costs, tree growth rates and timber prices. Revenues are based on timber prices or increased growth at the end of the 30-year rotation period. The revenues after deducting harvesting costs are discounted to the present values using annual discount rates of 0.5%, 2.5% and 5%.

Two scenarios were selected as timber harvesting costs: (1) low harvesting costs of 14 US$ m^{-3} and (2) high harvesting costs of 28 US$ m^{-3}. For both scenarios, the growth necessary to cover the treatment costs or the timber prices to be achieved were calculated for timber prices between 50 and 500 US$ m^{-3} or for growth increases of 0.14 to 0.52 m^3 $tree^{-1}$ and treatment costs of 4.5 to 8.9 US$ per tree.

The relationships of the selected factors and their influence on the profitability of the treatments, were shown with a response surface in a three-dimensional space. The response surface represents all points of the selected combination of factors where the NPV is zero. The results of the sensitivity analysis form the basis for this calculation. Thus, the timber price needed to achieve a zero NPV[11] was analysed within the sensitivity analysis as a function of the treatment costs at different growth rates and presented as a line chart. The response surface represents the average discounted revenues per cubic meter needed to cover the investment as a function of average growth per FCT and treatment costs in a three-dimensional space. The same was done for the presentation of the calculation of the necessary additional growth, where NPV=0. The response surface represents the average growth per FCT needed to cover the investments for silvicultural treatments as a function of discounted revenues and treatment costs.

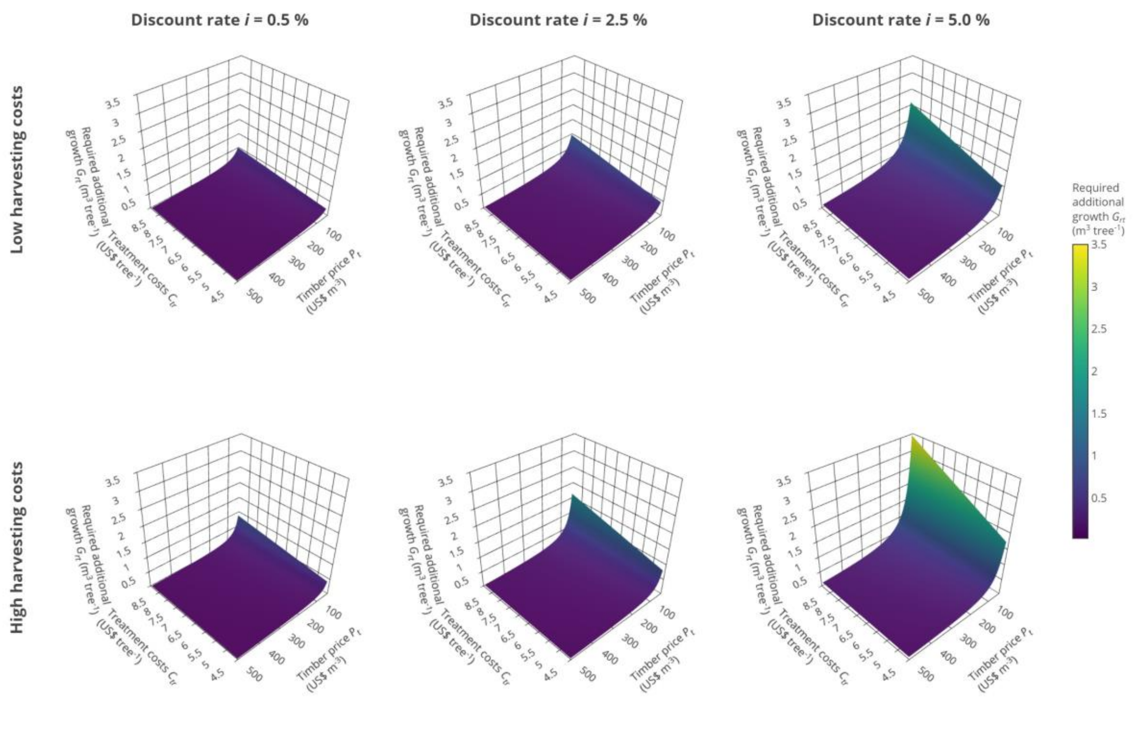

Figure 6. Required additional growth per tree (response surface) against treatment costs and timber price (from Gräfe et al. (2020a))

[11] NPV=0

The treatment costs range between US$ 4.5 and US$ 8.9 per released tree. The additional growth required per released tree to cover the expenses for silvicultural treatments depends on treatment costs and achievable timber prices and varies from 0.02 to 3.5 m^3 (Figure 6). Vice versa, if a potential increase in growth is assumed, timber prices must be between 34 and 578 US$ m^{-3} to at least cover the cost of treatments (Figure 7). The results show high sensitivity of profitability to the additional growth, the timber prices to be achieved and the discount rate chosen, which makes silvicultural treatments as investment exposed to high financial risk.

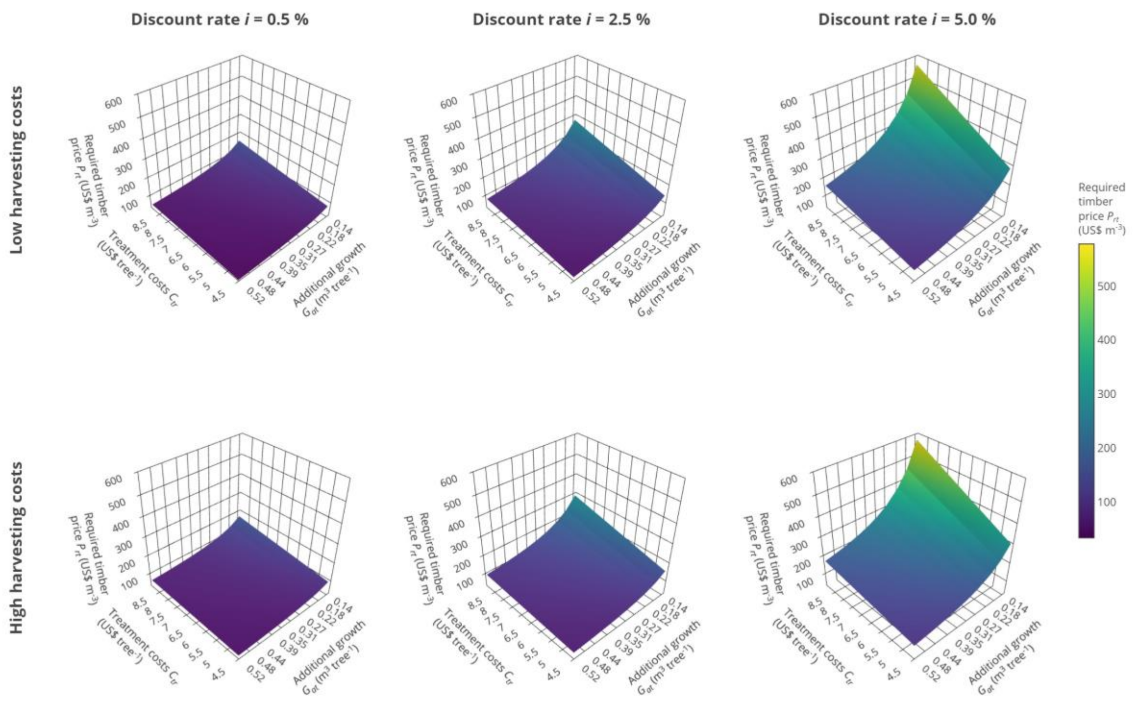

Figure 7. Required timber price (response surface) against treatment costs and additional growth (from Gräfe et al. (2020a))

The decision whether to use silvicultural treatments or not is often solely guided by the expected improvement of tree growth. The paper shows that growth alone is not sufficient as a decision criterion. While costs for the treatment are known at the time of the decision, future timber prices and harvesting costs as well as the additional growth actually achieved are subject to uncertainties. These uncertainties have a decisive influence on the economic risk assessment, which is reflected in the choice of the internal interest rate. The results of the paper demonstrate that investments in silvicultural treatments involve a considerable financial risk and that the decision to carry out silvicultural treatments should always be the subject of a thorough investment calculation.

2.2 Discussion in the thematic context

The second paper refers to the second core issue in the thematic context of this thesis and analyses the economic profitability of silvicultural treatments using the example of future crop tree release treatments.

Using an inverse approach, both the required timber price and the additional volume growth required to make the treatment profitable at the end of the 30-year rotation period were derived. With additional growth rates from 0.14 m^3 $tree^{-1}$ to 0.52 m^3 $tree^{-1}$, the timber prices that need to be achieved to break even between cost and benefit range from US$ 34 m^3 to US$ 578 m^3. Average FOB[12] timber prices for South America and the Caribbean are in some countries below the prices required to reach the break-even point. Treatment in these countries would therefore only be profitable if it focused on high quality trees in a stand that could achieve correspondingly high prices on the timber market. This shows that silvicultural treatments are associated with a high investment risk which, in addition to the general risks of organic production, depends in particular on the future development of timber prices and labour market costs. Both can be subject to very strong fluctuations. Economic growth and an increase in employment opportunities can make labour costs more expensive, and the increasing trade in currently less known tree species can have a significant impact on timber prices.

The calculated prices show a strong dependence on the assumed additional growth and the discount rates chosen. The strong influence of the discount rate on the profitability of silvicultural treatments is also reported in other studies (e.g. Brazee and Dwivedi (2015), Nakajima et al. (2017), Schwartz et al. (2016)).

Due to the relatively long planning periods in forestry and the relatively short investment periods of investors, the choice of interest rate is a well-known problem in forest asset management. Financial analyses usually favour projects where the expected return on investment does not exceed a period of 10 years (Karsenty 2000). This contrasts sharply with the 25 to 40 year rotation cycles common in tropical forests and with cash flows that are only realised at the end of the felling cycle. These revenues are subject to positive discount rates in the investment calculation and are therefore undervalued compared to short-term revenues. Furthermore, there is uncertainty about the conditions that will prevail in the future. The uncertainty increases with the length of the investment period. The costs of silvicultural treatment today are amortised at the earliest at the end of the felling cycle, in this case after 30 years. However, the success of the treatment is subject to various risks, such as harvest or storm damage to the released trees, growth rate decreases due to climatic changes or a decreasing demand for the released tree species on the timber market. Such risks play an important role in the choice of the discount rate. The greater the uncertainty in the future and the associated risks, the

[12] FOB stands for "free on board" and is an international trade term defined by the ICC (2019).

greater the preference for the present and the devaluation of future earnings due to risk factors in the discount rates. The duration of the concession contracts and the long-term rights of use of the forest stand represent a further uncertainty. In the study area, concessions are generally granted for a period of 30 years, which also defines the length of the felling cycle. If the concessionaire were to invest in silvicultural treatment, it is currently not certain that he would be able to benefit from its results. This of course means that a rationally acting concessionaire would not take the risk of making efforts to preserve forest capital in the long term without being able to benefit from the perspective.

According to the paper, a silvicultural treatment is profitable if it leads to additional growth rates of 0.2 m^3 $tree^{-1}$ to 3.5 m^3 $tree^{-1}$. Compared to the calculated growth rates of 0.14 to 0.52 m^3 $tree^{-1}$ after 30 years, this exceeds the biological growth potential of most individual trees. To make silvicultural treatments profitable at lower growth rates, more favourable conditions are needed, including low treatment and harvesting costs, assumed lower discount rates or higher achievable timber prices. Conditions may be less favourable at higher growth rates, including high treatment and harvesting costs, assumed high discount rates or lower timber prices. The potential additional growth of the released FCTs will only be sufficient to cover the investment costs under very favourable assumptions regarding costs and revenues. The approach presented makes it possible to determine the minimum growth required to cover the costs of silvicultural measures. If this required minimum growth is close to or exceeds the biologically possible growth, the silvicultural treatment should be rejected. The approach therefore offers the possibility for a rational economic decision that goes beyond the mere estimation of growth increase.

Whether silvicultural treatments are economically viable depends on a number of factors: (1) the FCTs released respond to the silvicultural treatment with increased growth and accumulate the necessary additional volume within the current felling cycle, (2) at harvest time they belong to the group of marketable and valuable tree species and can achieve the required high timber prices, (3) the treatment and harvesting costs are low, and (4) an appropriate discount rate has been chosen. The expected costs and revenues and the expected growth are subject to uncertainties which are reflected in the choice of interest rates. In addition, factors such as the origin and cost of capital required for treatment, the availability of alternative investment opportunities or the individual assessment of risks and current preferences may determine the choice of interest rates (e.g. Manley (2019), Sauter and Mußhoff (2018)). As long as there are no reliable and general statements on the increase in growth through silvicultural treatments, the uncertainties in the other factors relevant to the decision and the resulting expected interest rates will tend to speak against the implementation of silvicultural treatments.

The results of the paper confirm that growth alone is not sufficient for an economic assessment. Wood prices and harvesting costs at the end of the rotation period as well as the amount of costs for silvicultural treatments are indispensable for an economic evaluation. While the costs of silvicultural treatment are known at the time of the decision, future timber prices and harvesting costs as well as the additional growth actually achieved are subject to uncertainty. These uncertainties have a decisive influence on the economic risk assessment.

3 Gräfe and Köhl (2020)[13]: "Impacts of future crop tree release treatments on forest carbon as REDD+ mitigation benefits"

The third paper of the cumulative dissertation was written by Sebastian Gräfe and Michael Köhl, and was accepted for publication in the special issue "Impact of Sustainable Forest Management on Biomass Growth and Carbon Accumulation Capacity" of the peer-reviewed MDPI journal "Land" on 16 October 2020.

3.1 Summary

To reduce carbon emissions from forest degradation due to logging activities, the concept of reducing emissions from deforestation and forest degradation (REDD) was expanded to REDD+ by including sustainable forest management (SFM) practices. Silvicultural treatments are another SFM measure (Lamprecht 1989; Wadsworth 1997). While the effect of silvicultural treatments on the commercial timber volume of tropical forests has been investigated in various studies (e.g., Hu et al. (2020), Wadsworth and Zweede (2006), Peña-Claros et al. (2008), Verwer et al. (2008)), the effects of silvicultural practices on carbon dynamics in both commercial and non-commercial stands in the tropics is not well understood. The paper investigates silvicultural release treatments intended to achieve increased growth of selected trees by cutting competitor trees in their direct vicinity. The removal of competitors initially leads to a reduction in the carbon pool of the stand and represents a carbon loss. In this paper the time period needed to offset the carbon debt due to silvicultural treatments by the increased growth of FCTs in a set of tropical forest sites in Central and South America was investigated. Silvicultural treatments aim at a higher volume growth compared to untreated stands but are associated with costs. From an economic point of view, the discounted investments in silvicultural treatments must be compensated by the financial value increase. In the case of REDD+, this additional financial gain is achieved through the generation of additional carbon credits. The paper investigates whether the costs of the treatment can be compensated by the carbon benefits generated.

[13] Gräfe, S.; Köhl, M. (2020): Impacts of future crop tree release treatments on forest carbon as REDD+ mitigation benefits. In Land. 9. (Accepted for publication on 16 October 2020).

The carbon analysis carried out in the paper uses a recursive approach to determine the additional increases in biomass for which the treatment is financed assuming different carbon prices. By simulating the above ground biomass (AGB) growth of a released and a non-released FCT, the point in time when the released FCTs reaches both, the AGB gain of the non-released FCT and in addition the AGB loss caused by felling competitors was determined. The time needed for the FCT to compensate for the biomass loss through the treatment was determined running a growth simulation, where a growth increase of 30% through the treatment was assumed (Figure 8).

In the recursive approach presented in the paper, the required additional biomass growth per tree is a function of the carbon price and treatment costs. The carbon price is discounted to the current point in time and, together with the AGB of the removed competitors, gives the additional biomass increment required when the net present value (NPV) is zero[14].

[14] If the NPV of an investment is greater than zero, the investment is considered profitable.

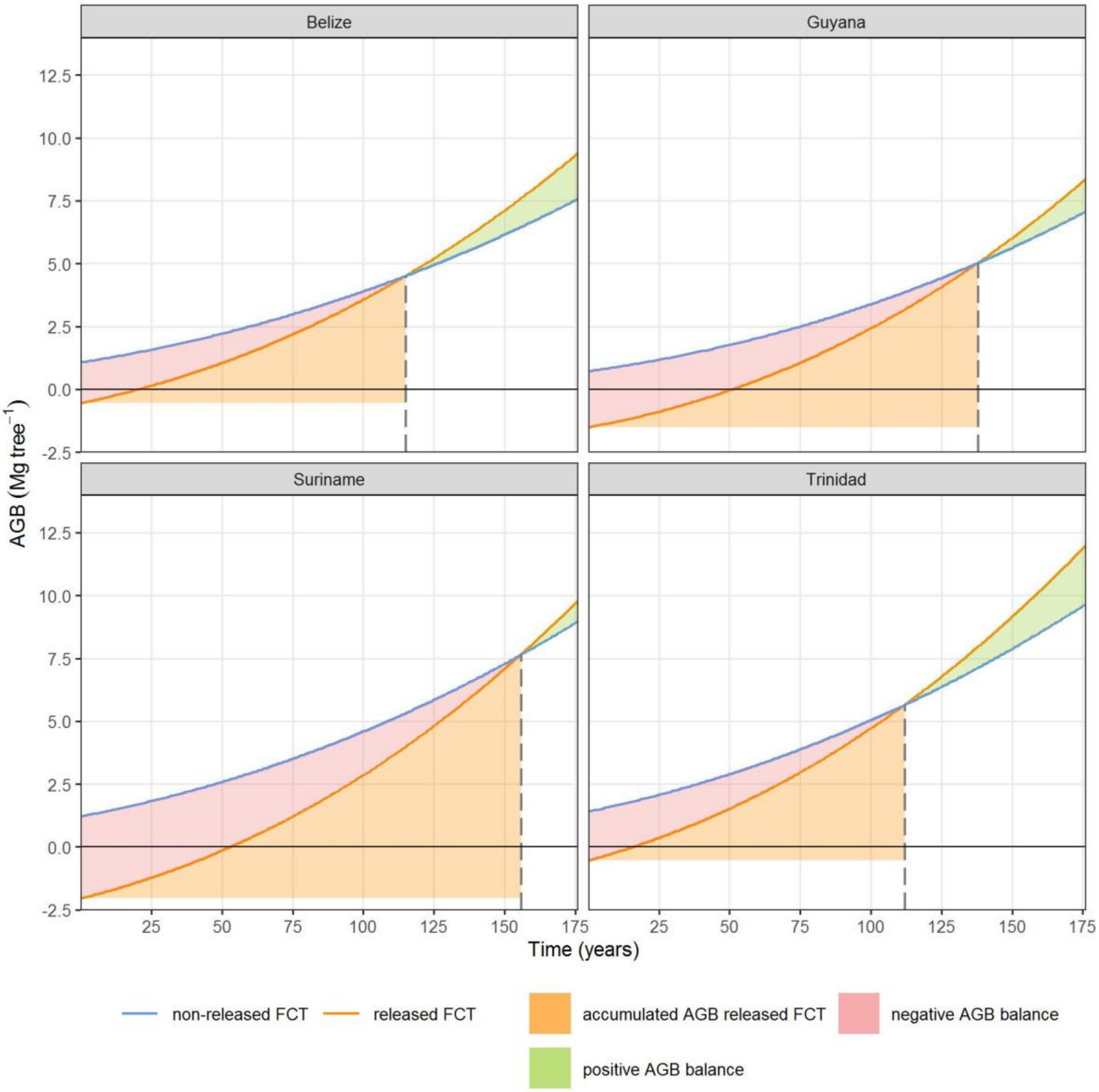

Figure 8. AGB growth simulation of released and non-released FCTs (from Gräfe and Köhl (2020))

The carbon analysis was performed in relation to the net present value using a discount rate of 2.5%. The revenues are based on the carbon prices at the end of the recovery time. The growth necessary to cover treatment costs was calculated for carbon prices between 5 and 100 US$ Mg CO_2^{-1} (Ramstein et al. 2019) and treatment costs of 4.2 to 8.4 US$ per tree which are based on the results of the time study. Then the response area (Figure 9) was calculated, which represents the average AGB growth per FCT needed to cover the investment in silvicultural treatments depending on the discounted revenues and treatment costs and to compensate for the carbon loss from the treatment.

An average of 2.3 FCTs per hectare were released through the removal of an average of 3.3 competitors per hectare. This corresponds to an average above ground biomass deficit of 2.3 Mg FCT^{-1}. Assuming a 30% increase in growth, the FCT would need on average 130 years to offset the carbon loss. For carbon prices from 5 to 100 US$ Mg CO_2e^{-1} an additional increment between 0.6 and 22.7 Mg $tree^{-1}$ would be required to cover the treatment costs of 4.2 to 8.4 US$ FCT^{-1}. Assuming a carbon price of 10 US$ Mg CO_2e^{-1}, the additional increment required would be between 5.8 and 11.4 Mg $tree^{-1}$, thus exceeding the biological growth potential of most individual trees (Köhl et al. 2017). The release of FCTs does not ensure an increase in forest carbon stocks and refinancing of treatment costs is problematic.

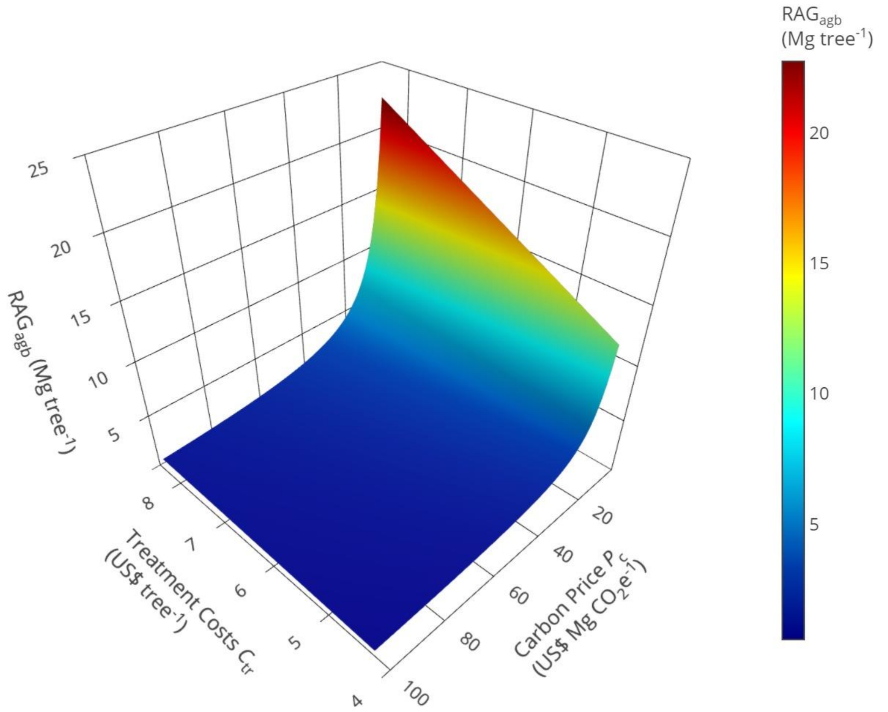

Figure 9. Response surface of the required additional AGB growth per tree (from Gräfe and Köhl (2020))

The paper shows that silvicultural release treatments do not ensure an increase in forest carbon stocks. Furthermore, it shows that refinancing treatment costs is problematic and that silvicultural release treatments as a sustainable forest management activity are not suitable as REDD+ activities.

3.2 Discussion in the thematic context

The third paper analyses the effect of silvicultural treatments on the carbon balance of the forest stand. Furthermore, it examines whether the treatment costs can be offset by possible financial carbon benefits. The results and findings of the paper make an important contribution to answering the third core question of this thesis.

Silvicultural liberation treatments aim at an increased volume growth of the liberated individuals. In the course of treatment, however, trees are felled, leading to a loss of carbon in the stand. The paper shows that a liberated FCT would need an average of 130 years to compensate for this carbon loss through increased growth. This is supported by Rutishauser et al. (2015), who found that the proportion of the initial above-ground carbon stock that was lost best predicted the time needed to recover the original carbon stocks. However, despite regional differences in forest management regulations in Central and South America, minimum logging cycles of 25 to 30 years with harvesting intensities of 10 to 30 $m^3 ha^{-1}$ are generally established (Keller et al. 2007), which is significantly shorter than the recovery times identified in the paper. As long as forests are managed according to strict harvesting regulations, with fixed harvesting cycles of 25 to 30 years, without taking into account site-specific stand conditions, exemption treatments can lead to carbon loss in the stand.

If a balanced carbon situation is achieved by extending harvest cycles, the question of financing can be resolved. Currently, most carbon emissions are traded at prices below US$ 10 Mg CO_2e^{-1} (Ramstein et al. 2019). At a carbon price of US$ 10 Mg CO_2e^{-1}, the required additional biomass growth after 130 years would be between 5.8 and 11.4 Mg per FCT, depending on treatment costs. Even after 130 years, such growth is not guaranteed as it exceeds the biological growth potential of most individual trees (Köhl et al. 2017). From a forest growth perspective, there is a significant risk that the FCTR treatments investigated in this study will not result in carbon gains. The release of FCTs in itself does not guarantee a significant increase in forest carbon stocks or sustainability in terms of above-ground biomass. Particularly critical is the fact that FCTR treatments within the regular intervention cycles of several decades of use lead to a loss of C compared to trees not released (Gräfe and Köhl 2020).

The approach to generating REDD+ payments must also be critically reviewed. One of the basic ideas of REDD+ is to reward activities that lead to the conservation or improvement of the forest C pool through incentive payments. The paper shows that refinancing the costs of treatments is a problem. The time periods required for refinancing clearly exceed a reasonable economic planning horizon. Even significantly higher CO_2 prices do not really improve the economic assessment. It should also be borne in mind that incentive payments are linked to transaction costs, which further complicates the economic impact at local level.

4 Conclusions of the cumulative dissertation

4.1 Sustainability of selective logging

Forest management through selective harvesting in the tropics aims at producing valuable timber over several harvesting cycles without promoting measures to stabilise or increase the population size of valuable timber species. When a species disappears, the next valuable species is used instead. It could be shown that the forest tenure types studied lead to different stand structures after earlier harvesting and recovery cycles and cause tensions between degradation and sustainable yield. The simulated growth scenarios clearly show that local conditions limit the ability of past harvesting regimes to achieve sustainable forest management in the future. This is also true if past harvesting processes have been carried out in accordance with existing harvesting codes. The application of general harvesting codes for the exploitation of tropical forests is, therefore, no guarantee of sustainable forest management. Previous experience with close to nature sustainable forest management practised in other regions of the world (e.g. Western Europe, North America and New Zealand) has shown that the law of the locality must be taken into account when assessing sustainability; this is no exception for tropical forests if their sustainable forest management is desired.

The thesis shows that the sustainability of forest use according to rigid rules must be critically evaluated. The application of rigid rules that do not take into account the current state of the stands carries the long-term risk of forest degradation. The felling rates and felling cycles often defined in the harvesting codes must, therefore, be reconsidered. Instead, local site conditions must always be used as the guiding principle for sustainable forest use. Two demands for the sustainable management of tropical forests can be derived from this. Firstly, inventories must be carried out before harvesting in order to create an objective information basis for planning harvesting operations. On the other hand, minimum standards, such as stand volume or balanced DBH distribution, should be defined for the stand conditions that must be met to justify harvesting operations. On the other hand, repeated surveys must be carried out for already harvested stands in order to determine growth patterns, natural mortality and recruitment under local conditions.

Further research on the regeneration ecology and growth dynamics of heterogeneous tropical forests is urgently needed to ensure sustainable timber harvesting. Studies on silvicultural treatments are also essential to improve diameter growth and reduce the recovery time until the next intervention. Silvicultural treatments mainly aim at (value) growth and tree species distribution, while cost and profitability are the guiding criteria for management measures. Studies on the economic aspects of silvicultural treatments are, therefore, required. In order to broaden the range of marketable species and reduce the pressure on the relatively few marketable species, studies on the market potential of lesser known species are urgently needed.

4.2 Profitability of silvicultural treatments

The decision whether to use silvicultural measures in the management of natural tropical forests is often based solely on the aspect of improving tree growth. The second paper of this thesis extends the perspective to an economic issue. The results presented are based on data and observations collected in four Caribbean countries, namely Belize, Guyana, Suriname, and Trinidad and Tobago. Nevertheless, the results allow statements that can also be applied to the management of natural tropical forests. Silvicultural treatment generates costs that can be considered as an investment. It is expected that this investment is less than the additional income generated by the growth stimulated by silvicultural treatments. The paper confirms that growth alone is not sufficient for an economic assessment. Timber prices and harvesting costs at the end of the rotation period, as well as the cost of silvicultural treatments, are essential for an economic evaluation. While the costs of silvicultural treatments are known at the time of the decision, future timber prices and harvesting costs and the additional growth actually achieved are subject to uncertainty. These uncertainties have a decisive influence on the economic risk assessment.

The results of the thesis have implications for practice, research and policy. Practitioners must have a good understanding of local growth conditions and long-term developments in the timber market. It is particularly important to know whether silvicultural treatments have a long-term or only short-term effect on their forest stands. If the latter is the case, silvicultural treatments need to be critically examined not only from an economic point of view. Other aspects such as sufficient liquidity, biodiversity or occupational safety should also be taken into account. The scientific community must focus even more on the local growth conditions of tropical forests. Findings from individual stands of the same age and rich in species cannot be transferred to tropical forests, as their growth dynamics are much more complex. Policy-makers are concerned with legal frameworks for the sustainable management of forests. The multifunctional sustainability of forest resources is as important as the balance of interests between the various stakeholders. Since silvicultural treatments always interfere with the residual stand and can lead to forest degradation if applied incorrectly, they are only legitimate if they safeguard the ecosystem functions of the residual stand and ensure economic benefits. The results of this thesis support the rational evaluation of such a profitability.

4.3 Impacts of silvicultural treatments on forest carbon as REDD+ mitigation benefits

The five activities of REDD+ that contribute to mitigation measures in the forest sector include the enhancement of forest carbon stocks and sustainable forest management (UNFCCC 2011). The release of FCTs does not in itself guarantee a significant increase in forest carbon stocks or sustainability in the sense of AGB. Particularly critical is the fact that FCTR treatments within the regular intervention cycles of several decades of exploitation lead to a loss of C compared to trees that are not released.

The approach to generating payments must also be critically reviewed. One of the basic ideas of REDD+ is to reward activities that lead to the conservation or improvement of the forest C pool through incentive payments. The paper shows that refinancing the costs of treatments is a problem. The time periods required for refinancing clearly exceed a reasonable economic planning horizon. Even significantly higher CO_2 prices do not really improve the economic assessment. It should also be noted that incentive payments are linked to transaction costs, which further complicates the economic impact at local level.

The recommendations that can be derived from the thesis are, therefore, that after harvesting operations in tropical forests, which already lead to significant C losses, no management measures are implemented that further reduce the forest's C pool. The FCTR treatments investigated in this thesis are not recommended as REDD+ activity, both from an economic point of view and with regard to the biological growth potential of the trees. Avoiding biomass losses during harvesting contributes much more to the conservation of the forest C stand.

The thesis gives a first indication of the effects of FCTR treatments in tropical forests on carbon stocks and result-based payments. The variability of tree species composition, stand structures and site factors in tropical forests indicates that further investigations are needed on the long-term interactions between silvicultural measures and tree growth, natural regrowth after harvesting and differences in carbon sequestration between different forest types and growth regions.

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ANNEX: SCIENTIFIC PAPERS AND PERSONAL CONTRIBUTION

Personal contribution

The presented scientific papers that, together with the comprehensive summary, constitute this cumulative dissertation reflect a substantial part of my scientific research. They were selected under the premise that they include a high level of personal involvement. This is reflected formally by the lead-authorship for all presented papers. This includes the development of methodologies and statistical backgrounds for the studies, the curation, validation, analysis and visualization of the data, the writing and submission as well as the responsibility for the review process of each paper and the physical execution of fieldwork. However, the contributions of the co-authors of the papers shall not be questioned.

None of the scientific papers presented here have been or are currently part of another cumulative dissertation.

forests

Article

Recovery Times and Sustainability in Logged-Over Natural Forests in the Caribbean

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Received: 17 January 2020; Accepted: 25 February 2020; Published: 26 February 2020

Abstract: Despite the widespread use and strong promotion of the sustainable forest management approach, there are still uncertainties about the actual contribution of current forest management practices to sustainability. We studied the problem of sustainable timber production in four tropical countries (Belize, Guyana, Suriname, and Trinidad and Tobago). Data assessed on experimental plots covering 10 km^2 were used to compare management practices of four forest tenure types that commonly exist in the study countries: large scale concessions (LSC), private forests (PR), periodic block system forests (PBS), and community managed forests (CM). As an indicator of sustainable timber production, we calculated the recovery times expected under the initial condition of the stands and compared them with currently practiced cutting cycles. Three growth scenarios were simulated using diameter growth rates (1.6/2.7/4.5 mm year^{-1}) from empirical data from studies in the region. Initial volumes were determined for all commercial trees as well as for commercial trees with a DBH-threshold ≥45 cm. Highest initial volumes were found in LSC and PBS managed forests. Lowest volumes were found in CM and PR forests. Assuming the lowest growth rate for all commercial trees, none of the stands studied reached the initial pre-harvest volumes within the currently practiced cutting cycles. Assuming the highest growth rate for all trees, LSC, PBS, and PR forests reach the initial pre-harvest volume. Looking at the subset of commercial trees with a DBH ≥45 cm, all stands will reach the initial volume within 30 years only if the highest growth rate is assumed. We show that general harvest codes do not guarantee sustainable forest management in the tropics. Local stand conditions must always be one of the guiding principles of sustainable timber utilization. Applying the rigid rules, which do not take into account the current conditions of the stands, entails long-term risk of forest degradation.

Keywords: sustainability; forest recovery; logged-over natural forests; sustainable forest management; reduced impact logging; conventional logging; cutting cycles

1. Introduction

The holistic approach of sustainable forest management (SFM) has become an integral part of modern tropical forest management and addresses the multiple ecological, economic, and social functions of forests [1–3]. Although there is no generally accepted definition of SFM, the concept has been strongly promoted by the international community and is an important foundation of the United Nations Convention on Biological Diversity (CBD), the United Nations Convention to Combat Desertification (CCD) and the United Nations Framework Convention on Climate Change (UNFCCC). The ITTO and FAO have launched criteria and indicators as well as guidelines for strengthening SFM of tropical forests [1,4,5].

Despite the widespread use and strong promotion of SFM, there are uncertainties as to whether current tropical forest management is sustainable [6]. Forest degradation by timber harvesting and wood fuel extraction is considered to have a significant impact on tropical forest ecosystems, though varying from region to region [7–9]. According to Blaser and ITTO [2], around 403 million hectares (ha) of tropical forests were managed under selective logging, and around 183 million ha were managed with a management plan until 2010. Several studies showed an increase in forest growth in logged compared to non-logged forests [10–16], which is caused by varying reasons. The level of disturbance caused by the intensity of trees removed from the current growing stock has a marked influence on the rate of recovery of the remaining stand; increasing intensity of disturbance generally reduced the growth of the remaining stand [10,17–21]. It is widely accepted that the implementation of reduce impact logging (RIL) and post-harvesting silvicultural treatments shows a positive impact on growing stock recovery [16,21–24]. Various studies examined and questioned cutting cycles and harvest intensities in tropical South America (e.g., Piponiot et al. [25], Piponiot et al. [26], Macpherson et al. [27], ter Steege et al. [28]), with the joint consensus questioning the sustainability of current management. Avila et al. [29] studied the effect of logging intensities on tree species composition on 41 permanent sample plots in the Brazilian Amazon over a period of 30 years and showed that high logging intensities with a basal area reduction of > 6.6 m^2 ha^{-1} had a substantial influence on tree species abundance with no signs of return to the pre-logging species composition. Schwartz et al. [30] compared areas where reduced impact logging (RIL) was applied with unlogged areas in the Tapajós National Forest, Eastern Amazon—Brazil and suggest additional silvicultural techniques such as liberation of future crop trees for maintaining the ecological outcome of RIL on the long run. Shima et al. [31] studied the diversity of unlogged and selectively logged Malaysian forests and found that a period of 40 years is not sufficient for selectively logged forests to regain their diversity. In the Guiana Shield, the sustainability of common forest exploitation was studied by Yguel et al. [32]. They studied 12 plots of 6.25 ha each in French Guiana, consisting of control plots, plots with selective logging, with selective logging and thinning, and with selective logging, thinning, and fuelwood harvesting. Harvesting has not affected species richness, but even the slightest form of disturbance has resulted in a decrease in total and commercial biomass. Based on these results, they conclude that the rotation periods commonly used in tropical forests are not sufficient for recovery. Lévesque et al. [33] studied the recovery rate and stem turnover in a primary tropical dry forest in Jamaica on a total sample area of 0.27 ha. Tree height, basal area, and tree diversity in partially cut plots had recovered by more than 80% 10 years after experimental cutting. Size classes with DBH ≥ 14 cm had fewer individuals compared with the pre-disturbance size-class distribution and the biomass lost by cutting could not be recovered.

The present paper utilizes data from study sites covering a total area of 10 km^2 and are located in four Caribbean countries to examine the sustainability of timber production by comparing four common forest tenure types. The production and regenerative capacity of forest stands is used as an indicator of sustainable timber production.

2. Materials and Methods

2.1. Countries, Study Sites, and Forest Tenure Types

The present study was carried out in four Caribbean countries: Belize, Guyana, Suriname, and Trinidad and Tobago. The climate in the selected countries is tropical with dry and rainy seasons. Suriname and Guyana show two rainy and two dry seasons, with the dry seasons extending from

February to April and from August to November. Belize and Trinidad and Tobago exhibit one dry season from January to May. In Trinidad and Tobago and Belize, forests are threatened by hurricanes. All four countries have experience in forest use and management dating back to the beginning of the 20th century [34–36].

For each country, at least two research sites were selected. Main decision criteria for the selection of sites were:

- logging was practiced at least once within the past 30 years;
- logging activities were carried out within the project period;
- the implemented forest management system was representative for the Caribbean;
- minimum size of 100 ha;
- participation of granted concessionaires, forest owners, or communities was secured

Four forest tenure types were covered by the site selection (Table 1): (1) large scale concession managed forest (LSC), (2) periodic block system (PBS), (3) private owned forest (PR), and (4) community managed forest (CM). The analyses shown refer to the respective tenure types and not to the countries involved. As the data and results are representative of the tenure types, they cannot be used to assess and compare individual countries.

Table 1. Sites and tenure types

Country	Site	Silvicultural System/Logging Type	Ownership	Tenure Type	Cutting Cycle	Code
Belize	Rio Bravo 305	Polycyclic / controlled selective logging based on MHD and MAC from yield model	Private forest	Private managed by owner	40 years	PR
	Rio Bravo 102					
	Quiche Ha	Polycyclic / conventional selective logging	State forest	Community managed with annual cutting permits	1 year	CM
Guyana	Greatfalls	Polycyclic / conventional selective logging based on MHD				
	Orealla					
	Ituni					
Suriname	Mapane	Polycyclic / controlled selective logging based on minimum harvesting diameter (MHD) and fixed maximum allowable cut (MAC)	State forest	Large scale concession	30 years	LSC
	Kabo	Polycyclic / semi-controlled selective logging based on MHD and fixed MAC				
Trinidad and Tobago	Rio Claro	Polycyclic / conventional selective logging based on MHD with individual tree sale	State forest	Periodic block system	30 years	PBS
	Cats Hill					

Large scale concession (LSC): Large scale concession managed in this case means a semi-/controlled management, which includes measurements e.g., establishment of annual cutting areas of 100 ha, pre-harvest inventory of harvestable species, planned skidding, directional felling, tree selection, and marking. The concessionaire has to prepare a management plan which has to be approved by the national forest authority prior to harvesting. The harvest has to follow guidelines published by the forest authority which include the maximum allowable cut per hectare (normally between 20 and 25 m^3 ha^{-1}) within 30 years; minimum distance of 10 m between harvest trees; protection of soil, water, and conservation values; block alignment; and the maximum area of roads to be constructed in a felling compartment [2,37].

Periodic Block System (PBS): The periodic block system is a polycyclic selective timber harvesting system. At least one block per year is opened and the trees within the open block are to be sold over a two-year period. After two years the block is closed and allowed to regenerate for a period of 30 years. The trees for sale are selected and marked by forest officers following guidelines for tree selection. So-called 'replacement trees' are required for each tree selected for harvest. These trees were to be of the same species and will form the residual stand after the logging. There is no pre-harvest inventory and skid trails are not pre-planned; they are created by loggers in an unplanned manner. Although a limited amount of timber is supposed to be removed from each block on a 30-year cycle, there are blocks that have been clearly over-harvested and trees that are not supposed to be taken are felled and sold to the loggers [38].

Private owned forest (PR): The private owned forest areas for this study are located within the Rio Bravo Conservation and Management Area (RBCMA) in north-western Belize. The RBCMA was part of a logging concession from the mid-19th century until 1982 [39]. Logging was done mainly for mahogany without any management prescriptions until a minimum girth limit was introduced in 1922. The first inventory was conducted in 1975 resulting in a commercial species volume of only 36 m^3 ha^{-1} [40]. The area is managed by the non-governmental organisation Programme for Belize (PFB) since 1988. PFB uses a yield model for the selection of the harvest stand which was developed based on the data of the national permanent sample plot network [41]. Before logging the owner has to apply for a cutting permission by presenting an annual plan of operations to the national forest authorities. A pre-harvest inventory has to be done, skid trails are pre-planned, and a post-harvest inventory has to be executed after logging. The cutting cycle is 40 years [40].

Community managed forest (CM): The communities participating in this study log their forest on an annual basis. The forest is state owned but managed by a community with conventional logging. Cutting permits, so called state forest permits (SFP), are granted on an annual basis. The SFP holder is not committed to present a management plan or to do pre-harvest activities like pre-harvest inventory or skid trail planning [2]. Measures of sustainable forest management (SFM) are written in a code of practice [42] which was adopted by the forests act of Guyana in 2009 [43].

2.2. Block Layout

In order to investigate the effect of silvicultural management systems in an objective manner, a randomized block design was chosen for the study. With exception of one site in Suriname, all sites had an area of 1 × 1 km. In each 1 × 1 km site, four blocks containing 32 plots of 50 × 100 m were installed (Figure 1). The individual blocks and the entire 1 × 1 km site were surrounded by a buffer-zone to avoid influences from neighboring stocks. The 32 plots were 0.5 ha in size. Due to the concessionaire's pre-set logging area alignment for one site in Suriname a modified block design had to be used: The site size was set to 0.8 × 1.25 km with two blocks inside. Within the two blocks, 140 sample plots with a size of 0.5 ha were installed. Both blocks were surrounded by buffer zones.

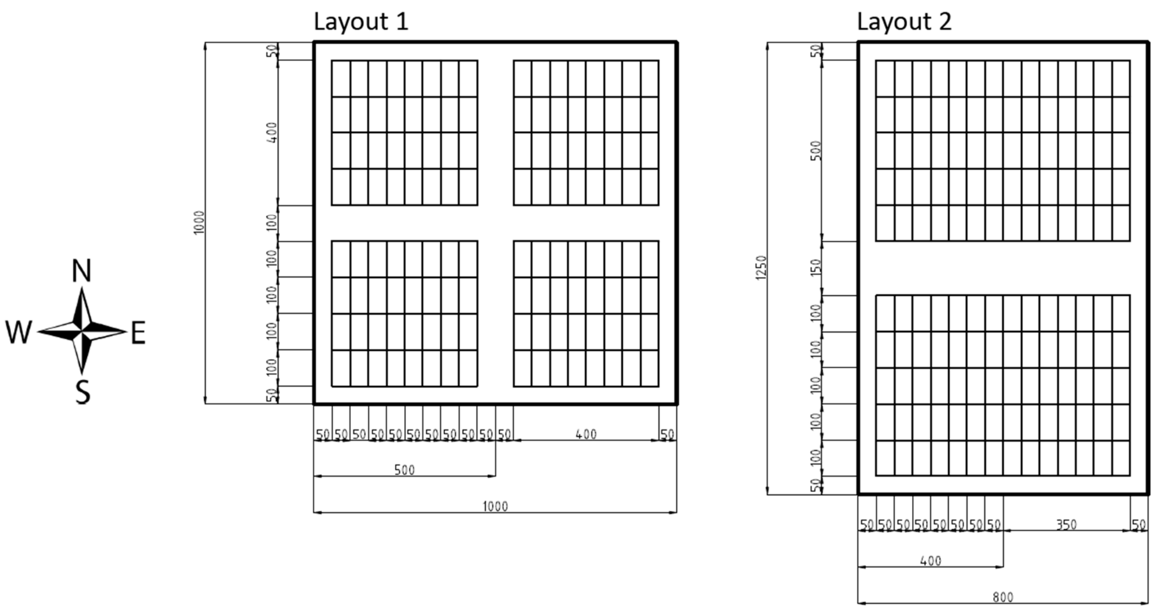

Figure 1. Block layout.

2.3. Forest Stock Assessment

A forest stock assessment (pre-harvest inventory) was implemented to obtain information about forest stand attributes: (1) diameter at 1.30 m height (DBH), (2) spatial distribution of trees, (3) log grade (LG), (4) species composition, (5) standing volume, and (6) harvestable timber volume. Log grade was determined using the categories presented in Table 2. Tree species was further categorized in commercial and non-commercial species. The classification was done using local species classification lists provided by the national forest authorities or forest management units. Within the sample plots, every tree with DBH ≥ 25 cm was recorded and mapped.

Table 2. Log grade categories

Options	Description	Category
High quality	Straight tree without visible damage due to fire, pests, diseases, animals, etc.	1
Medium quality	Tree with little defects or damage due to fire, pests, diseases, animals, etc.	2
Poor quality	Tree with several defects or damage due to fire, pests, diseases, animals, etc.	3
Dead or dying standing tree	A tree is dead when none of its parts are alive (leaves, buds, cambium) at 1.3 m or above. A tree is dying if it shows damage that will surely lead to death.	0

2.4. Commercial Species Classes

Only a proportion of the total volume is made of so called commercial species which have a merchantable value on the timber market. All commercial tree species were assigned to four classes (CSC): (1) class A includes species with the highest market value and demand on the timber market; (2) class B species are less valuable species, but with a high acceptance on the timber market; (3) class C species are marketable, but with low demand on the timber market; and (4) class D species are commercial species but with a weaker marketability. The species were categorised based on national species classifications which can be found in Alder [44], GFC [45], Ramnarine et al. [38], and SBB [46,47].

2.5. Tree Selection and Stand Terminology

The selection of trees to be harvested within the forest management units (FMU) is limited by several factors, e.g., the actual timber market demand, or the harvesting capacity of the FMU. In order to be able to compare the intensity of logging in a standardized way, two approaches for selecting harvestable trees were applied: (1) the FMU applied their local tree selection practices and selected the trees to be harvested on the basis of national criteria, and (2) the minimum harvesting diameter (MHD) and log quality were used as uniform, systematic criteria to determine trees to be harvested. Actual logging activities were performed based on the selection decisions of the FMUs.

Depending on the selection, the trees were divided into groups: (1) harvestable trees = trees that met the criteria for harvest (see Table 3) and that were potential harvest trees, (2) harvest trees = trees of the harvestable stand which were selected to be harvested during the actual or upcoming harvest, and (3) residual trees = trees of commercial species that formed the remaining commercial stand after logging. The harvested and the residual commercial stand together formed the initial commercial stand (Figure 2).

Table 3. Harvest tree selection criteria

	Large Scale Concession	Periodic Block System	Private Forest	Community Forest	Systematic Selection (Standardized Criteria)
Species class	A	A & B	A, B, C, D	A, B, C, D	A, B, C, D
MHD [1]	≥45 cm	≥50 cm	≥45 cm [2]	≥35 cm	≥45 cm
Log grade	1	1 & 2	1 & 2	1 & 2	1 & 2

[1] MHD = minimum harvesting diameter; [2] except mahogany.

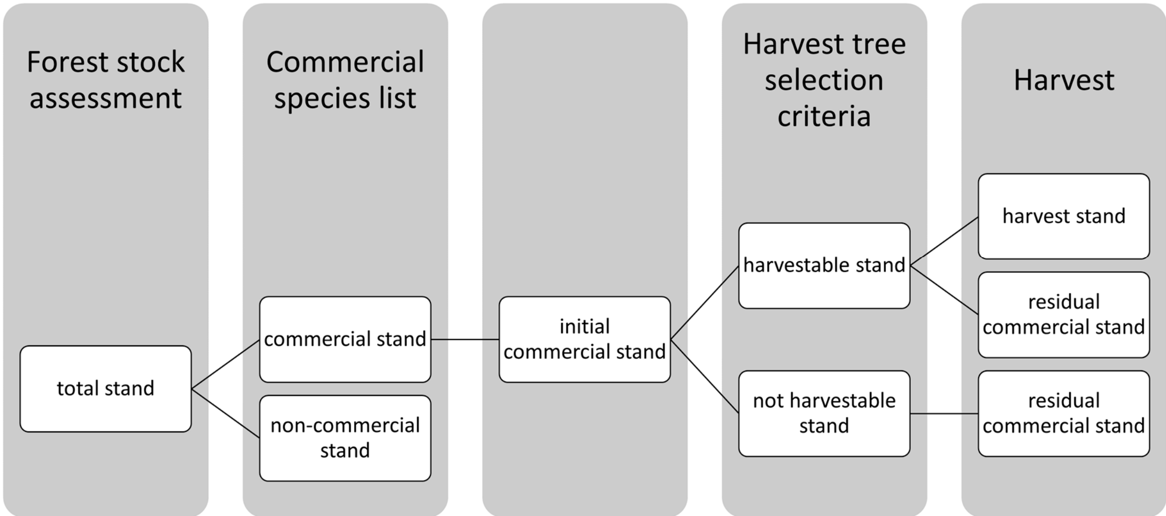

Figure 2. Systematics of stand terminology.

2.6. Volume Equation

The tree volume was estimated using a DBH-based allometric equation (Equation (1)) according to Alder and van Kuijk [48]. The equation was derived from 1849 felled sample trees covering 137 species.

$$V = 0.0005107 * DBH^{2.2055}, \tag{1}$$

where

V = volume in m^3

DBH = diameter at breast height in cm

2.7. Scenario Analysis

No post-harvest assessments were carried out after previous harvest operations, which did not allow for an empirical estimation of post-intervention tree growth. Therefore, growth rates were taken from former studies conducted in the region and implemented in a scenario analysis. The scenario analysis approach was chosen to include a wide range of potential site specific growth rates. We used a straightforward diameter-increment-approach to simulate the growth of the individual trees. The scenario analysis served to evaluate the quantity of harvestable volume, the resulting harvest intensity, and the tenure type specific cutting cycles (see Section 2.1). For the scenario analysis we used the selection of the harvest stand made by the forest management units.

2.7.1. Simulation Parameters

The parameters mean growth rate and mean annual tree mortality rate were varied for the simulation study. Mean growth rate here is expressed in annual diameter growth. In logged tropical forests diameter growth between 2.3 mm $year^{-1}$ and 4.6 mm $year^{-1}$ (Table 4) were reported by Werger [36] and Jonkers [49]. Smaller growth rates were usually observed in undisturbed forests whereas high growth rates result from silvicultural interventions or high intensity logging [36,50]. Vieira et al. [51] found growth rates from 1.7 mm year^{-1} (mean of minimum growth rates), 3.1 mm year^{-1} (mean of medium growth rates), to 3.9 mm year^{-1} (mean of maximum growth rates) for trees of DBH ≥ 10 cm. Lieberman et al. [52] reported growth rates from tropical wet forests in Costa Rica from 0.8 mm year^{-1} (mean of minimum growth rates), 2.7 mm year^{-1} (mean of medium growth rates), to 5.1 mm year^{-1} (mean of maximum growth rates) for trees DBH ≥ 10 cm. Mean growth rates of 2.3 mm year^{-1} for trees from logged tropical forests of French Guiana were published by Herault et al. [53]. For this study, we used fixed mean growth rates of 1.6 mm year^{-1}, 2.7 mm year^{-1}, and 4.5 mm year^{-1}.

Table 4. Mean growth rate references

References	Mean Growth Rates (mm year^{-1})		
	Minimum	Medium	Maximum
Werger [36], Jonkers et al. [49]	2.3		4.6
Vieira et al. [51]	1.7	3.1	3.9
Lieberman et al. [52]	0.8	2.7	5.1
Herault et al. [53]		2.3	

A mean annual mortality rate of 2.6% year^{-1} in logged forests was observed by Sist and Nguyen-Thé [54]. Vidal et al. [20] published mortality rates of 1.4% year^{-1} for RIL, 1.7% year^{-1} for CL within 15 years after logging and 5.9% year^{-1} for RIL and 6.3% year^{-1} for CL within 20 years after logging. Johnson et al. [55] observed mortality rates from the Guyana shield of 1.66% year^{-1}. In order to compensate for the recruitment of young trees, which was not included in our calculations, we applied a mean annual mortality rate of 1% year^{-1} for the overall volume of the stand over the entire simulation period [50,54,56].

2.7.2. Harvesting Percent and Recovery Time

We calculated the harvesting percent (Equation (2)) based on the ratio of initial commercial volume and harvested volume. Recovery time (Equation(30) here means (1) the time the forest needs to recover its initial commercial volume ignoring the commercial DBH classification and (2) the time the forest needs to recover its initial commercial volume of trees with DBH ≥ MHD. The recovery time was calculated using the annual volume increment and the volume of the initial commercial stand. The results of the growth simulation are presented in graphical form showing the residual volume in relation to initial volume and harvest volume and the time needed for recovery (see Figure 3 as an example).

$$\text{Harvesting percent} = \frac{\text{harvested volume}}{\text{initial volume}} * 100, \tag{2}$$

$$\text{Recovery time} = \frac{\text{initial volume} - \text{residual volume}}{\text{volume increment}}, \tag{3}$$

2.7.3. Simulation Scenarios

We calculated the time needed for the stand to reach its initial volume after harvesting (recovery time, see Section 2.7.2). On the one hand, a diameter-independent initial volume, which ignores the commercial DBH classification, was taken as a basis and on the other hand, an initial volume which only takes trees with a DBH ≥ 45 cm (MHD) into account (Table 5). To calculate the recovery time, we assumed three diameter growth levels (see Section 2.7.1): 1.6 mm year^{-1} (G1.6), 2.7 mm year^{-1} (G2.7) and 4.5 mm year^{-1} (G4.5). A mean mortality rate (MR) of 1% year^{-1} was applied.

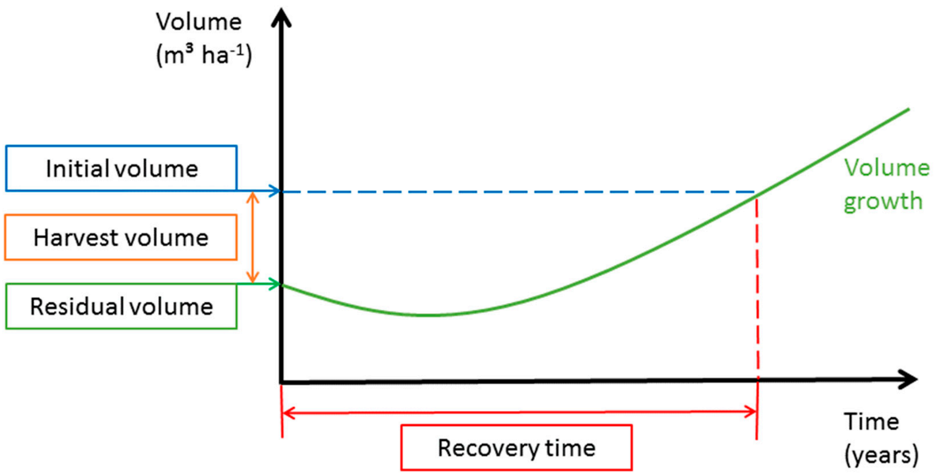

Figure 3. Growth simulation.

Table 5. Simulation subjects

No	Indicator	Mean Annual Mortality Rate	Mean Annual Diameter Growth
1	Time to recover from harvest to initial volume	1%	1.6 mm 2.7 mm 4.5 mm
2	Time to recover from harvest to reach initial volume of trees with DBH ≥ MHD	1%	1.6 mm 2.7 mm 4.5 mm

2.8. Descriptive Statistics

We used the statistical computing environment *R* in version 3.6.0 [57] and the *R*-package *lme4* [58] to perform a linear mixed effects analysis of the effect of the present forest tenure type on the harvested and commercial residual volume. With a mixed effects model we were able to incorporate both fixed- and random-effects terms in a linear predictor expression. As fixed effects, we entered tenure type into the model. As random effects, we added the study sites.

We used the *R*-package *emmeans* [59] to calculate the 95%-confidence intervals of the least-squares means from the fitted linear mixed effects model. To evaluate the differences in volume between the forest tenure types, we used pairwise comparisons of the least-square means and calculated the 95%-confidence intervals of the differences.

3. Results

3.1. Forest Stock Assessment

As described in Section 2.3, all trees with DBH ≥ 25 cm were recorded at the forest stock assessment. Total volumes (Figure 4) of 288 m^3 ha^{-1} (224–352 m^3 ha^{-1}) and 291 m^3 ha^{-1} (227–355 m^3 ha^{-1}) were found at large scale concession (LSC) and periodic block system (PBS), respectively. As indicated by the confidence intervals, significantly lower total volume was found at private forest (PR) with 146 m^3 ha^{-1} (82–210 m^3 ha^{-1}). As explained in Section 2.4, only a proportion of the total volume is made up of commercial species. Commercial volumes of LSC (258 ± 62 m^3 ha^{-1}) and PBS (276 ± 62 m^3 ha^{-1}) were significant higher than commercial volumes of CM (93 ± 62 m^3 ha^{-1}) and PR (104 ± 62 m^3 ha^{-1}).

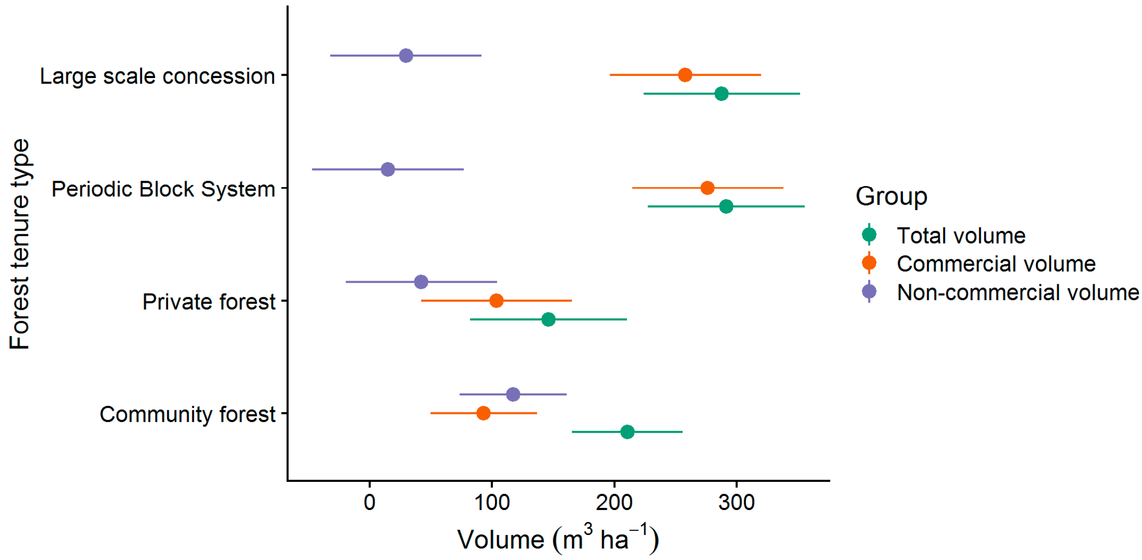

Figure 4. Commercial and non-commercial volumes and 95%-confidence intervals of the present forest tenure types.

Figure 5 shows the volume diameter distribution of commercial and non-commercial species. The percentage of commercial volume was 90% in LSC and 95% in PBS, while the proportion of commercial volume was 44% in CM. Commercial volume was present at all diameter classes in LSC as well as in PBS, and only in diameter classes up to 105 cm in CM.

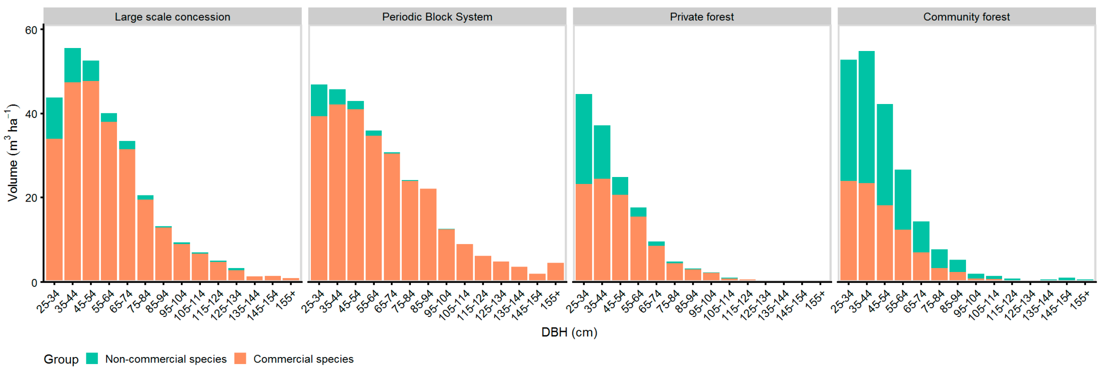

Figure 5. Volume-DBH distribution of commercial and non-commercial species.

However, only the commercial stand of marketable or potentially marketable trees (all CSC, LG 1 & 2) is relevant for the following considerations, which is why the non-commercial stand is not discussed further. The results for the mean volumes and the corresponding 95%-confidence intervals of the commercial stand (all CSC, LG 1 & 2) are presented in Figure 6. The two tenure types large scale concession (LSC) and periodic block system (PBS) had the highest initial volumes of 254 m^3 ha^{-1} (201–307 m^3 ha^{-1}) and 255 m^3 ha^{-1} (202–308 m^3 ha^{-1}) respectively. The lowest initial volumes were found in private forest (PR) with 71 m^3 ha^{-1} (18–124 m^3 ha^{-1}) and community forest (CM) with 37 m^3 ha^{-1} (−0.5–74 m^3 ha^{-1}). While the volumes of LSC and PBS as well as CM and PR did not differ significantly from each other, we could find strong differences between the volumes of the two tenure types LSC and PBS compared to CM and PR. The tenure types also differed in the distribution of the harvestable and residual volume. While the harvestable volume of 172 m^3 ha^{-1} (128–215 m^3 ha^{-1}) for LSC and 179 m^3 ha^{-1} (136–223 m^3 ha^{-1}) for PBS was significantly higher than the residual volume of 82 m^3 ha^{-1} (56–109 m^3 ha^{-1}) and 76 m^3 ha^{-1} (49–102 m^3 ha^{-1}), respectively, the harvestable volume at CM with 19 m^3 ha^{-1} (−12–50 m^3 ha^{-1}) and PR with 37 m^3 ha^{-1} (−6–81 m^3 ha^{-1}) did not differ significantly from the residual volume of 18 m^3 ha^{-1} (−0.8–37 m^3 ha^{-1}) for CM and 34 m^3 ha^{-1} (7–60 m^3 ha^{-1}) for PR.

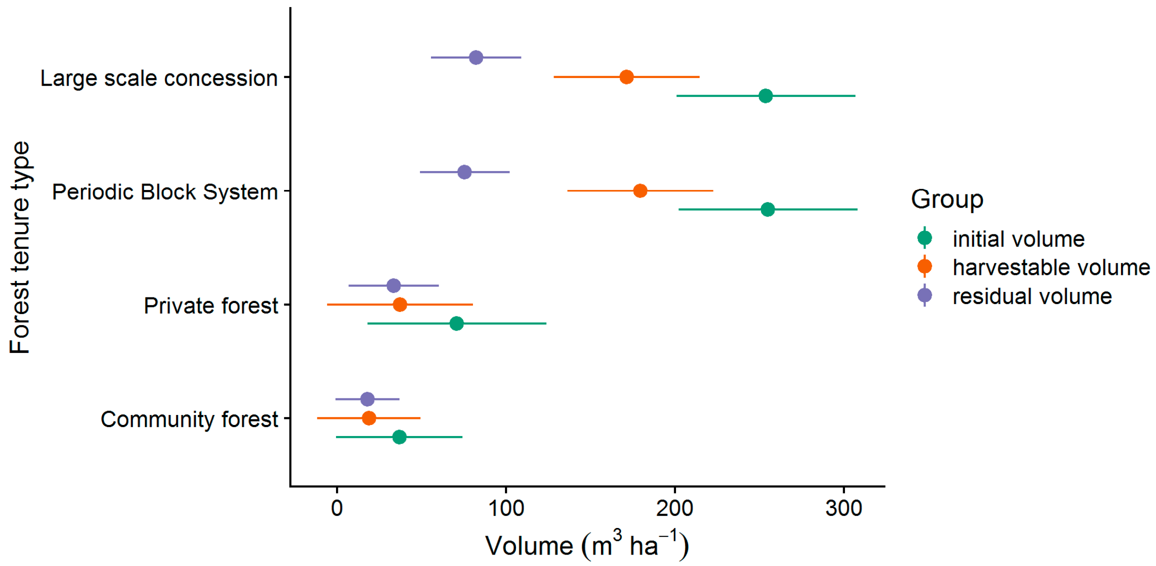

Figure 6. Mean commercial volumes (all CSC, LG 1 & 2) and 95%-confidence intervals.

In order to analyze the effect of the tenure types on the volume in more detail, a pairwise comparison was applied (see Section 2.8). The results of the pairwise comparison is presented in Figure 7. The effect of the tenure type differed significantly from zero except in the comparisons LSC with PBS and PR with CM. In all other comparisons, the tenure types LSC and PBS had a positive effect on volume compared to PR and CM. The largest differences were found in the comparisons between LSC or PBS and CM.

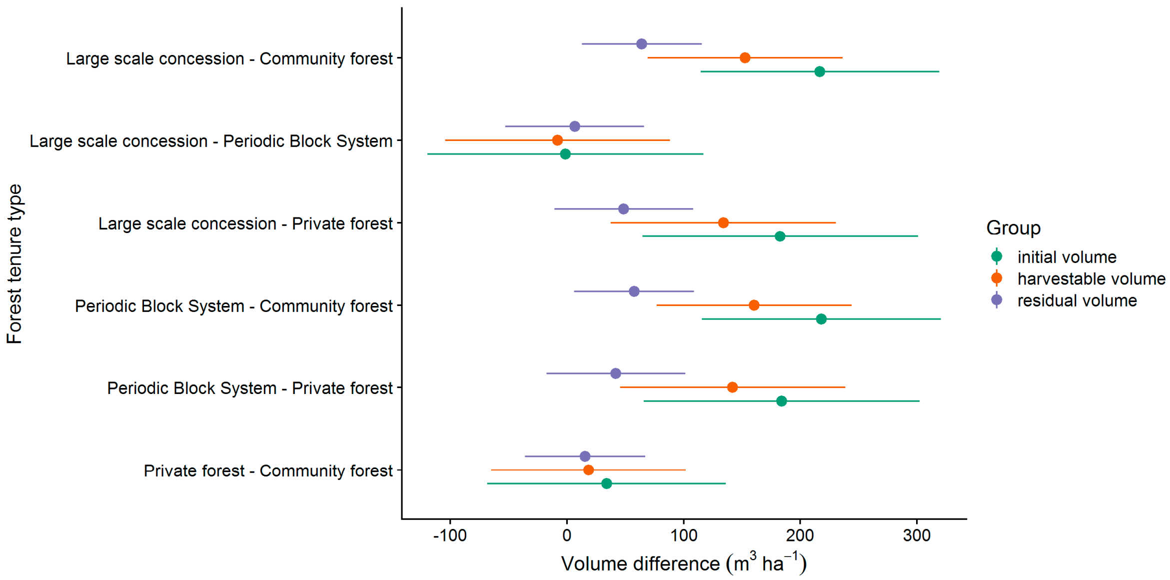

Figure 7. Pairwise comparison of the effect of the forest tenure types on the commercial volume (all CSC, LG 1 & 2).

3.2. Tree Selection and Species Class Composition

Highest harvest intensities in terms of removals from the growing stock could be found at CM forests showing a harvesting percent of 36%. Despite the high harvesting percent, the harvest volume was the lowest (13 m^3 ha^{-1}) of all tenure types. The low harvest volume with the simultaneously high harvesting percent resulted from the low initial commercial volume (37 m^3 ha^{-1}) of CM. In contrast, the relatively high initial commercial volume (254 m^3 ha^{-1}) at the LSC resulted in the highest harvest volumes (42 m^3 ha^{-1}) of all tenure types, while the harvesting percent was low (17%) compared to the CM and PR stands. The comparison of the national harvest tree selection with the standardized harvest tree selection (see Section 2.5) showed that CM used almost the entire potential of the harvestable volume when selecting the harvest stand. All three other tenure types used only part of the potentially harvestable stand.

Figure 8 shows the distribution of the harvest intensity (see Table 6) over the diameter classes. In LSC, PBS, and PR managed forests, the harvest trees were mostly selected from DBH ≥ 45 cm. Trees with DBH < 45 cm were selected for harvest only at the community managed forests and a small amount at the PBS managed forest. The highest commercial residual stand remained at the LSC and PBS sites, whereas the lowest commercial residual stand was found at the community forests. The highest distribution of the commercial residual stand over the DBH classes was found at the LSC and PBS managed sites.

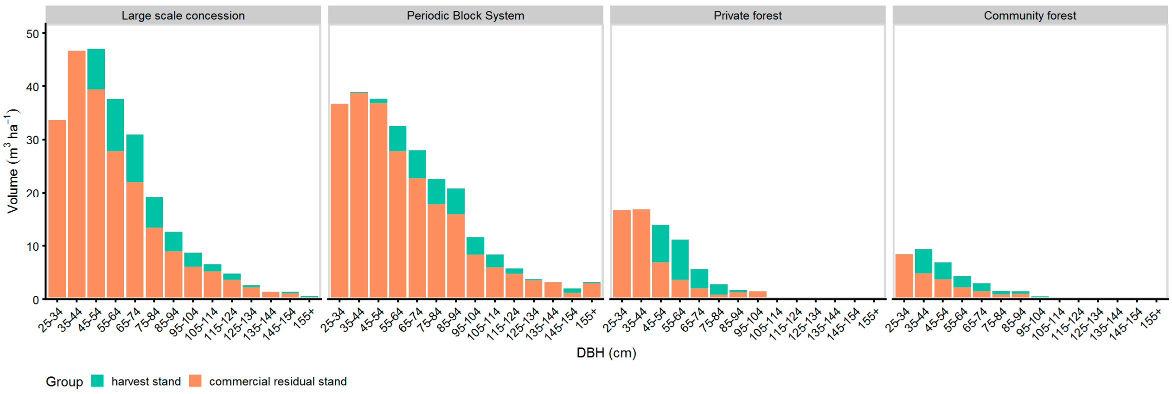

Figure 8. DBH-histogram of national harvest tree selection and commercial residual stand of trees with LG 1 & 2.

Table 6. Mean harvest intensities per forest tenure type

	National Harvest Tree Selection Criteria			Standardized Harvest Tree Selection Criteria		
Tenure Type	**Harvest Volume**	**Residual Commercial Volume**	**Harvesting Percent**	**Harvestable Volume**	**Residual Commercial Volume**	**Harvestable Percent**
	m^3 ha^{-1}	**m^3 ha^{-1}**	**%**	**m^3 ha^{-1}**	**m^3 ha^{-1}**	**%**
LSC	42	212	17	172	82	68
PBS	28	227	11	179	76	70
PR	20	51	29	37	34	52
CM	13	24	36	19	18	51

Figures 9 and 10 show the tree species class distribution of the harvest stand and the residual stand across the diameter classes. The amount of marketable timber species of class ‘A’ harvest trees was highest at the LSC managed sites and lowest at the PBS. At the commercial residual stand, the highest amount of class ‘A’ species was found again at the LSC managed sites, but lowest amounts were found at the CM sites.

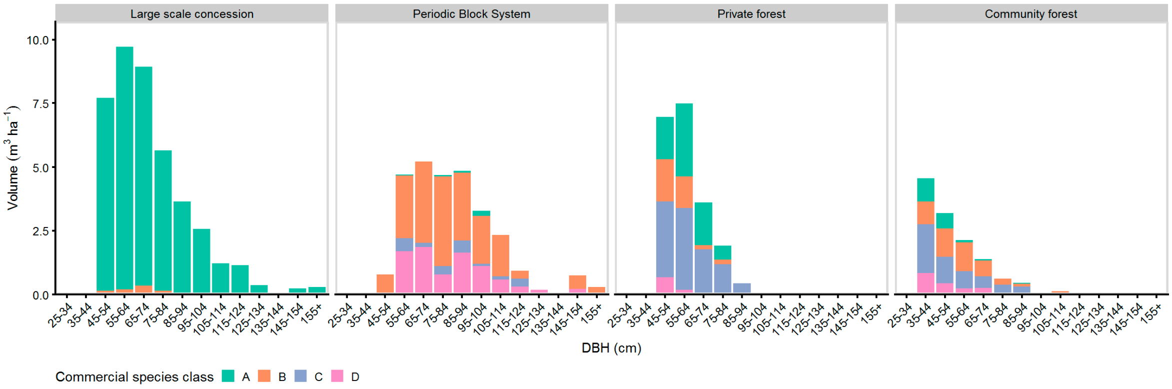

Figure 9. DBH-histogram of commercial species classes of trees with LG 1 & 2 selected for harvest.

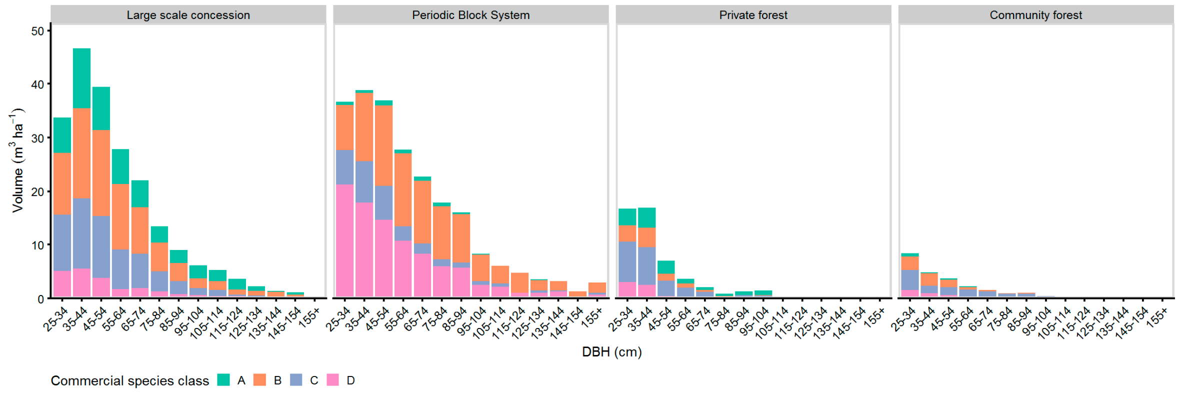

Figure 10. DBH-histogram of commercial species classes of commercial residual trees with LG 1 & 2.

3.3. Scenario Analysis

The analysis of the growth scenarios (Figure 11) resulted in a recovery time from 13 to 292 years to recover from harvest back to the initial volume, ignoring the commercial DBH classification of the trees (see Section 2.7.3). We found shortest recovery times at the PBS (13 years) and the LSC (18 years) managed stands at the highest diameter growth rate of 4.5 mm year^{-1}. Applying the highest growth rate at CM and PR managed stands resulted in a recovery time of 48 years (CM) and 26 years (PR). Applying a medium growth rate of 2.7 mm year^{-1} resulted in recovery times from 43 years in PBS managed forests to 108 years in CM forest. At the lowest growth rate of 1.6 mm year^{-1}, recovery times from 194 years in PR forests to 292 years in CM forests were calculated.

Considering only trees with DBH ≥ MHD for the growth simulation (Figure 12) resulted in recovery times from 12 years (PBS) to 87 years (CM). Applying the highest growth rate (G4.5) of 4.5 mm year^{-1} we found shortest recovery times at the PBS stands (12 years) and LSC managed stands (14 years). Longest recovery times at the highest growth rate were calculated for PR forests (21 years) and CM forests (27 years). At a low growth rate of 1.6 mm year^{-1} (G1.6) shortest recovery times were reached by PR stands (69 years) and the PBS managed sites (73 years). The CM stand recovered after 87 years, applying a low growth rate (G1.6).

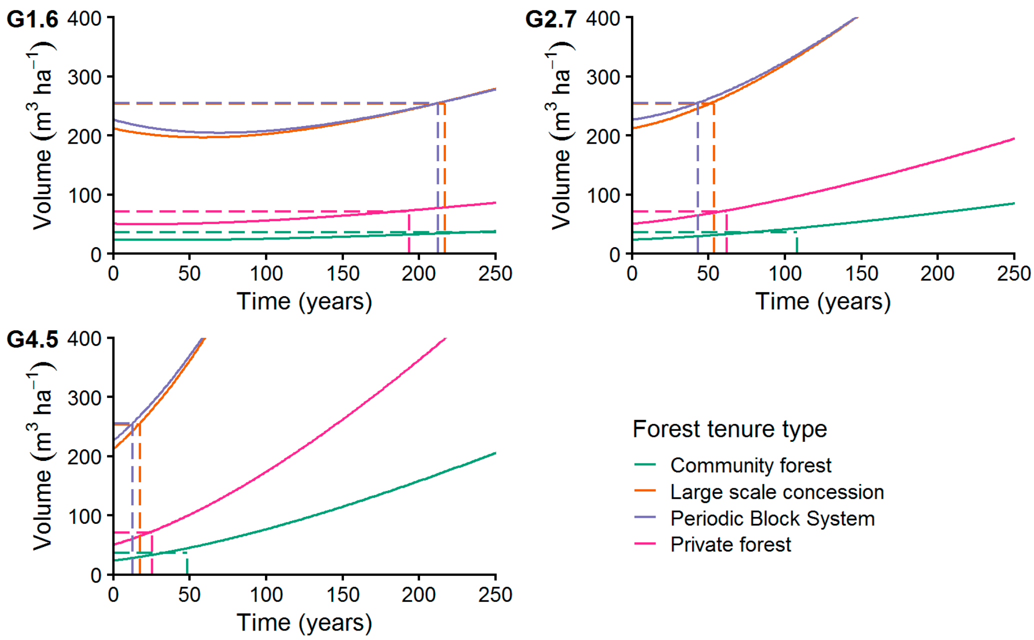

Figure 11. Increment of commercial species volume applying growth levels G1.6, G2.7, and G4.5 with MR = 1% p.a. The dashed lines connect the initial volume before harvesting with the years needed to achieve it after harvesting (recovery time, see Section 2.7.2).

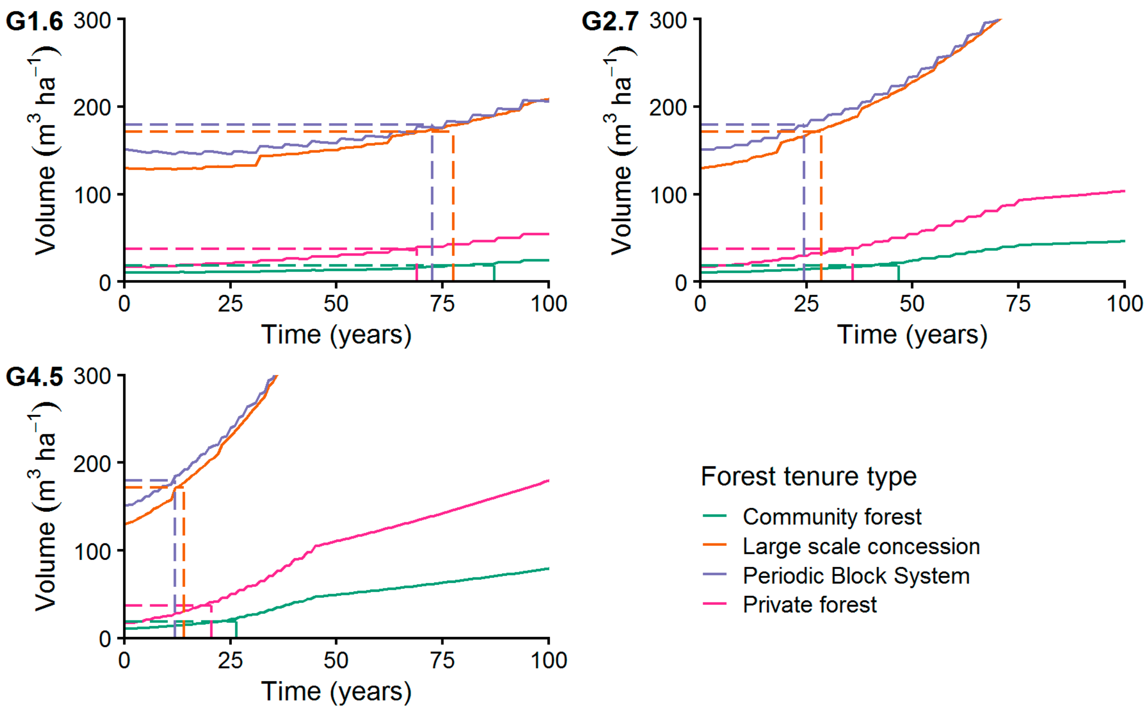

Figure 12. Increment of commercial species volume of trees with DBH ≥ 45 cm applying growth levels G1.6, G2.7, and G4.5 with MR = 1% p.a. The dashed lines connect the initial volume before harvesting with the years needed to achieve it after harvesting (recovery time, see Section 2.7.2).

4. Discussion

In defining sustainable forest management, economic, ecological, and social aspects can be combined and emphasized differently. Accordingly, the chosen definition plays a decisive role in the assessment of sustainability. For monocyclic management systems in which harvesting operations are carried out at long time intervals without interim maintenance operations, we define sustainability as the time a stand takes to recover the volume used. The recovery time is used to determine the sustainable cutting cycles. From this it can be deduced whether the cutting cycles of 30 to 40 years currently practised in the region under study are in fact sustainable. The initial volumes were determined for all commercial trees (total volume) as well as for commercial trees with a DBH over 45 cm.

Assuming an average annual growth rate of 1.6 mm for each tree, none of the stands studied reach the initial total volume within the currently practiced cutting cycles of 30 to 40 years. Assuming the highest annual growth rate of 4.5 mm for all trees, LSC, PBS, and PR reach the initial total volume. If the sub-set of trees with a diameter over 45 cm is considered, all stands reach the initial volume within 30 years only, if the highest annual growth rate (4.5 mm) is assumed. The time needed by a stand to recover the initial stand volume before harvesting serves as an indicator for sustainability. This renders the assessment of the initial stand before any logging operations necessary, because otherwise a stand volume that has already been degraded is used as a comparative measure. This does not permit an assessment of sustainability, as—on the contrary—this would in retrospect legitimize stand degradation.

The stands studied show clear differences in initial volumes and diameter distribution of commercial species classes. The initial volumes of commercial tree species of the systems PBS and LSC exceed the initial volumes of CM and PR by 200 m^3 ha^{-1}. No significant differences could be found between the initial volumes of PBS and LSC and between CM and PR. For forests of the Guyana Shield studies of Jonkers [60] as well as Alder and van Kuijk [48] indicate commercial volumes of 172 to 243 m^3 ha^{-1} and 195 to 237 m^3 ha^{-1}, respectively. Alder and van Kuijk [48] consider these volumes as relatively low for tropical forests. The volumes of CM and PR are well below the volumes reported by Alder and van Kuijk [48] and Jonkers [60] while the volumes of PBS and LSC are higher.

The reasons for the observed volumes are not only due to the different management activities, but also to differences in site conditions and geographical location. Three of the four CM stands, as well as the LSC stands, are located in regions with poor soils [61,62]. The two PR stands have been hit several times by hurricanes in the past [40]. LSC and CM are both in similar geographical locations and yet show large volume differences, so that the differences in stand volumes are likely caused by previous management practices. Compared to LSC, stands managed under CM are subject to a less restrictive set of rules and fewer controls. The connection between looser rules and controls for their compliance and the current CM stand structures is obvious.

Beside the market driven, selective extraction of timber species, the management of the LSC stands studied is subject to a code of practice and government controls [2,37], which define parameters such as maximum logging intensities, cutting cycles, or distance rules. The largely regulated use has led to stands with the highest proportion of merchantable volume within the stands studied. To ensure sustainability, it is not so much the permitted harvesting volumes as the cutting cycles that are decisive. This applies as well to individual timber species, which can be harvested in two or more successive cycles. Nevertheless, the Code of Practice [37] alone does not guarantee sustainable use, unless the currently defined cutting cycles of 30 years in LSC allow forests to regenerate. The currently practiced cutting cycles of 30 years have to be corrected in order to safeguard sustainable use. Currently practiced cutting cycles were also criticized by Piponiot et al. [25], Piponiot et al. [26], and Sist and Ferreira [50] who studied forest stands in Amazonia.

The upper limits set for harvest volumes refer only to the extracted stem volume. However, during harvesting operations, additional stand volume are caused by logging losses, e.g., due to skidding trails, or felling gaps [63,64]. Without taking these harvesting losses into account, the anticipated growth assumptions would require a cutting cycle for LSC to be extended to at least 40 years if average growth is assumed, so that the extracted volume can be compensated by growth. If logging losses are taken into account, the recovery periods are extended accordingly.

While distinct rules for the utilization of concessions are enforced, the use of CM is usually uncontrolled. This led to strong harvesting interventions in the past, which benefited from the exploitation of the access infrastructure created by large-scale concessions. As a result, CMs today contain significantly fewer numbers and volumes of commercial trees than LSCs and PBSs. Likewise, the volume of trees with larger diameters is smaller than in LSC and PBS, so that only small harvest volumes are available for future utilization. The uncontrolled and still on-going harvesting activities have put the CM stocks in a state from which they can no longer recover within the periods considered. The available data do not allow an indication of the period over which harvesting measures would need to be suspended to ensure recovery of stocks. However, it is evident that the current management of these stands is not sustainable. Our results therefore show, that community based forest management does not necessarily safeguard sustainability and therefore contradicts studies that see community forestry as a guarantee of the sustainability of forests [65–67].

The PR stands were subject to uncontrolled exploitation until 1988, which resulted in a low commercial volume of 36 m^3 ha^{-1} [40]. Despite the uncontrolled previous use and regular past disruptions by hurricanes, the volume under current management doubled during the last 30 years. This was made possible by management adapted to the individual stands. Before each intervention, a pre-harvest inventory is conducted and forms the basis for adjusting the harvesting levels to the respective stand conditions. The PR managed stands are thus an example for the improvement of stand conditions by introducing control measures and silvicultural measures adapted to the current status of stands. However, it remains to be proven through permanent observations that such an approach ensures sustainability in the long term.

Our work is based on case studies, which limits its validity. Specific management alternatives were examined for the countries considered. Therefore, no conclusions for the overall sustainability of forest management in the individual countries are possible. The simulations carried out have some limitations. Constant growth values were used, which do not take into account diameter distributions, neighborhood relations, or the social position of the individual trees. Recruitment and mortality were also not taken into account. Thus, the differences in individual tree growth, which show a high variability, especially in tropical natural forests, cannot be mapped [68,69]. Since there are no long-term observations in the investigated forest populations that allow a differentiated consideration of individual tree growth, mortality and recruitment, a simplifying approach based on stand volume and unified growth functions had to be chosen.

Despite the case study approach, our study allows some general statements. Our results clearly show that the sustainable use of tropical natural forests is not guaranteed by applying general harvesting rules. Rather, the current conditions of the stands must be assessed by pre-harvest inventories and taken into account when planning harvest interventions. Harvesting operations must be based on the current volume of commercial trees, their number, and diameter distribution. If these are not sufficient, harvesting operations must be postponed to a later point in time. This allows stand growth and recovery time to be used as benchmarks for determining harvesting intensities and harvesting cycles. The resulting flexible consideration of the specific conditions of any stand is a prerequisite for sustainable forest management.

5. Conclusions

Forest management through selective logging in the tropics aims at the production of valuable timber over several cutting cycles without fostering measures to stabilize or increase the population size of valuable timber species. When a species disappears, the next valuable species is used instead. We show that the investigated forest tenure types lead to different stand structures after earlier harvest and recovery cycles, and cause tensions between degradation and sustainable harvest volume. The simulated growth scenarios clearly show, that not under all local conditions will past harvest regimes enable sustainable forest management in the future. This also applies when past harvesting operations have been in accordance with existing harvest codes. The application of universal harvesting codes for the use of tropical forests is therefore no guarantee of sustainable forest management. Past experience of close-to-nature sustainable forest management practiced in other regions of the world (e.g., Western

Europe, North America, and New Zealand) indicated that the law of locality must be taken into account when assessing sustainability; this is no exception for tropical forests if their sustainable forest management is desired.

Our study shows that the sustainability of forest utilization according to rigid rules must be critically evaluated. The application of rigid rules, which do not take into account the current conditions of the stands, entails the long-term risk of forest degradation. The harvesting quantities and harvesting cycles often defined in harvesting codes must therefore be reconsidered. Rather, local stand conditions must always be the guiding principle of sustainable use. Two demands for the sustainable management of tropical forests can be derived from this. On the one hand, pre-harvest inventories must be carried out in order to provide an objective information basis for the planning of harvesting interventions. Minimum standards, such as standing volume or balanced DBH-distribution, should also be defined for the stand conditions that must be met in order to justify any harvesting intervention. On the other hand, for already logged-over stands, repeated inventories must be carried out to determine growth patterns, natural mortality, and recruitment under local conditions.

Further research on the regeneration ecology and growth dynamics of heterogeneous tropical forests is urgently needed to safeguard the sustainable utilization of timber. Studies on silvicultural treatments are also indispensable to improve diameter growth and to reduce the recovery time until the next intervention. Silvicultural treatments are mainly aiming at (value) growth and tree species distribution, while costs and profitability are the guiding criteria for management measures. Therefore, studies on the economic aspects of silvicultural treatments are necessary. In order to expand the range of marketable species and to reduce the pressure on the relatively few merchantable timber species, studies on the market potential of lesser-known species need to be urgently addressed.

Author Contributions: Conceptualization, M.K. and C.-M.E.; Methodology, S.G. and M.K.; Data curation, S.G.; Validation, S.G. and M.K.; Formal analysis, S.G.; Investigation, S.G., M.P., M.P.O., R.P., and Q.B.; Writing—original draft preparation, S.G. and M.K.; Writing—review and editing, M.P., M.P.O., R.P., and Q.B.; Visualization, S.G.; Supervision, M.K.; Project administration, C.-M.E. and M.K.; Funding acquisition, M.K. and C.-M.E. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the German Ministry for Food and Agriculture (BMEL) through the project "Ensuring long-term productivity of lowland tropical forests in the Caribbean" (GCP/SLC/205/GER). The main objective of this research project is to develop guidelines for the management of logged-over natural forests in the Caribbean. The project is being implemented as a regional government trust fund project conducted in partnership with the University of Hamburg and partner organizations in the participating countries.

Acknowledgments: We would like to express our gratitude to the Belize Forest Department, Belize, the Guyana Forestry Commission, Guyana, the Foundation for Forest Management and Production Control, Suriname, and the Forestry Division of Trinidad and Tobago, for contributing their valuable time and sharing their knowledge and insights to the realization of this research. We are thankful to Thomas Hausmann and Matthias Schwörer, BMEL, for their support and rewarding discussions. Philip Mundhenk deserves thanks for his patient assistance in the application of R. Two unknown reviewers carefully read the first draft of the manuscript and gave valuable hints for revision. We are deeply indebted to them for their contribution to improve the quality of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Forest Policy and Economics 121 (2020) 102329

Contents lists available at ScienceDirect

Forest Policy and Economics

journal homepage: www.elsevier.com/locate/forpol

Future crop tree release treatments in neotropical forests – an empirical study on the sensitivity of the economic profitability

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ARTICLE INFO

Keywords:
Silvicultural treatments
Future crop tree release
Economic analysis
Time study
Liberation fellings
Required additional growth

ABSTRACT

Silvicultural treatments are a common tool for increasing commercial timber production. Their impact on the growth or mortality of the remaining stand is well researched. This study focuses on the economic aspects of silvicultural treatments in neotropical forests. We have selected liberation treatments and consider them to be investments that are expected to pay for themselves through the additional growth of released trees and corresponding timber prices following a 30-year rotation period. The study is based on empirical data collected on experimental sites of 10 km^2 in Belize, Guyana, Suriname, Trinidad and Tobago. To determine the timber price or additional growth required to cover the treatment costs, we used a reverse approach based on net present values. The treatment costs range between US$4.5 and US$8.9 per released tree. The additional growth required per released tree to cover the expenses for silvicultural treatments depends on treatment costs and achievable timber prices and varies from 0.02 to 3.5 m^3. Conversely, if a potential increase in growth is assumed, timber prices must be between 34 and 578 US$ m^{-3} to at least cover the cost of treatments. We found a high sensitivity of profitability related to the additional growth, the timber prices to be achieved, and the discount rate chosen, which significantly increases the financial risk of silvicultural treatments as an investment tool. The decision whether to use silvicultural treatments or not is often solely guided by the expected improvement in tree growth. We, however, show that growth alone is insufficient as a decision criterion. While treatment costs are known when the decision to implement the measures is made, future timber prices and harvesting costs as well as the additional growth actually achieved are subject to uncertainties. These uncertainties have a decisive influence on the economic risk assessment, which is reflected in the choice of the internal interest rate. Our study demonstrates that investments in silvicultural treatments involve a considerable financial risk and that the decision to carry out silvicultural treatments should always be the subject of a thorough investment calculation.

1. Introduction

Silvicultural treatments are a common tool for increasing commercial timber production. The aim is to focus the volume growth of forest sites on individual commercially viable trees in order to increase their volume growth by the end of the cutting cycle. One form of silvicultural treatment is future crop tree release (FCTR) through liberation fellings. FCTR is applied in North America and Europe to positively influence the growth of so-called future crop trees (FCTs), which are identified in early stages of stand development (Abetz, 1990; Abetz and Klädtke, 2002; Burschel and Huss, 2003). By removing the crown competition from neighbouring trees, FCTs are given more growing space. FCTR supports the concentration of growth factors of a forest site on a small number of selected trees. In summary, FCTR can be described as high thinning in the upper crown layers resulting in the removal of competition from a given number of valuable trees. Thus the diameter and volume growth rates of FCTs is promoted and the time to reach final harvest diameters shortened. The increased growing space provides more light, water, and nutrients for the released tree. From an economic point of view, the treatments represent investments that pay for

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https://doi.org/10.1016/j.forpol.2020.102329
Received 20 April 2020; Received in revised form 6 October 2020; Accepted 8 October 2020

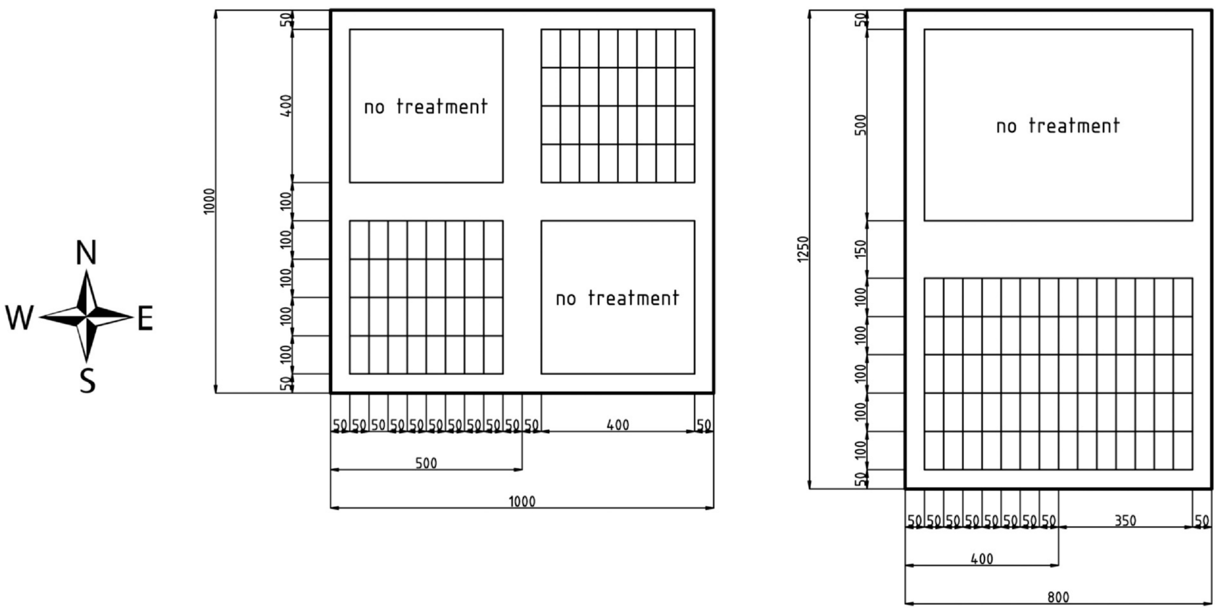

Fig. 1. Block layout. Left side: Belize, Guyana, Suriname 1, Trinidad; right side: Suriname 2 (Source: Gräfe et al. (2020), modified)

themselves through future higher profits. A correspondingly strong stimulus to growth is therefore necessary to make the investment in treatments financially beneficial.

The positive stimulation of tree growth by liberation treatments in temperate forests has been confirmed by numerous studies (Hein et al., 2007a, 2008; Hein et al., 2007b; Herbstritt et al., 2006; Mäkinen and Isomäki, 2004). Similar studies were conducted in tropical forests to analyse the effect of silvicultural treatments on the growth of FCTs. Wadsworth and Zweede (2006) examined liberation treatments on 20ha experimental plots and describe an additional increase of growth by 20% after 5.7 years compared to non-liberated trees. Villegas et al. (2009) showed that logging and the implementation of additional silvicultural treatments such as liana cutting and girdling of competing trees have a positive effect on the growth rates of FCTs. After four years, a growth rate increase of 22-27% was observed. Peña-Claros et al. (2008) analysed the effect of logging and application of additional silvicultural treatments (liana cutting and girdling of competing trees) on the growth rates of trees in general and on FCTs on twelve 27ha plots. Four years after the treatment, the growth rates of FCTs were 50-60% higher in plots that received silvicultural treatments than in untreated control plots. de Graaf et al. (1999) started conducting silvicultural treatments in Suriname in 1965. They reduced the basal area of non-marketable species from 20 m^2 ha^{-1} to 6 m^2 ha^{-1} and the total basal area to 10 m^2 ha^{-1}. The effects of these treatments lasted for less than 10 years. Even with short cutting cycles of 20-30 years, the treatments were only effective if they were repeated. The mortality rate increased with increasing intensity of the treatments. David et al. (2019) observed the effect of liberation on the diameter growth of five selected tree species over a period of 20 years. They found that liberation may accelerate diameter growth, but the strength of the effect depends strongly on the tree species. Kuusipalo et al. (1996) studied the effect of logging and crown liberation on the population dynamics of tree seedlings. They showed that crown liberation appeared to favour the recruitment of the seedlings from light-demanding pioneer species, instead of enhancing the regrowth of the desired timber stock. Looking at the effect of gap liberation on the growth of dipterocarp trees in a logged-over rainforest, Kuusipalo et al. (1997) showed that liberation improved the log quality and crown form of dipterocarp trees. Survival of dipterocarps was 33% higher and diameter increment twice as high in liberated gaps as in the untreated plots. The volume increment of Red Meranti (*Shorea* spp.) in the liberated gaps was twice as high compared to the volume in the untreated area. According to Kübler et al. (2020) the topographical position of a tree in tropical montane forests is more relevant for growth than the application of silvicultural treatments. The overall response to silvicultural treatments was only marginal.

While most studies on silvicultural treatments in tropical forests focus on growth or mortality of the remaining stand, we are not aware of any studies that investigate the economic profitability of silvicultural treatments in tropical forests. In this study we examine the costs and profitability sensitivity of liberation treatments in four Caribbean and South American countries (Belize, Guyana, Suriname, Trinidad and Tobago). We regard liberation treatments as an investment that should pay for itself through the additional growth of the remaining forest stand during the rotation period or through corresponding timber prices that must be achieved at the end of the commonly practiced cutting cycle of 30 years. In order to assess the costs of the liberation treatments, we carried out comprehensive time studies that include all working steps involved in the liberation of FCTs. The respective time studies were carried out on an area of 10 km^2. The costs of the treatment were derived from the data gathered from the time studies. In a reverse approach, we determined the necessary timber price at the end of the rotation period and derived the additional growth required by the released trees at time of harvest in order to amortize the treatment costs. Our analysis is based on the net present value approach and examines two harvest cost scenarios assuming three discount rates.

2. Methods

2.1. Study sites and experimental design

The present study was conducted in four Caribbean countries: Belize, Guyana, Suriname, and Trinidad and Tobago. The climate in the selected countries is tropical with dry and rainy seasons (Harris et al., 2020). In Suriname and Guyana there are two rainy and two dry seasons, with dry seasons lasting from February to April and from August to November (Nurmohamed et al., 2007). Belize and Trinidad and Tobago have one dry season lasting from January to May (Giannini et al., 2000). In Trinidad and Tobago and Belize the forests are threatened by hurricanes (Harris et al., 2020). In all four countries there is a wealth of experience in sustainable forest management and utilization dating back to the early 20th century (Record, 1926; Wadsworth, 1997; Werger, 2011). Three experimental sites each were selected in Belize

Table 1
Future crop tree selection criteria.

Criteria	Description
Species	The species of FCTs should achieve a high commercial value in the relevant timber markets. All project countries applied a species classification system (see above). FCTs should have been listed within either the highest or higher value species class A or B.
Social class	FCTs must be able to compete successfully after the release. So they were selected from trees whose canopies are already located in the dominant, co-dominant or strong intermediate social class.
Log grade	FCTs should have log grades requiring straight logs free of defects or visible diseases (log grade 1).
Vitality	FCTs should be of good health and vitality without low forks.
Age	Trees can qualify as FCTs at any age as long as they are expected to survive long enough to reach the next cutting cycle.
Distribution	FCTs should not all be concentrated in the "good quality" area of the forest stand. FCTs should be evenly distributed across the forest stand but their relative quality may differ, e.g. the "good quality" area of the stand may have FCTs with 10 m log length while the "poorer quality" area may have FCTs with 5 m log length.
Number/quantity	There was no defined number of trees to be identified as FCTs. A rule was established within the framework of this study that, one or two FCTs should be identified for each tree harvested. Finally, at least as many FCTs as trees harvested should be selected.

and Guyana, two each in Suriname and Trinidad.

A randomized block design was selected as experimental design (Gräfe et al., 2020). With the exception of one site in Suriname, all sites have an area of 1x1 km. In each of the 1x1 km sites, four blocks containing 32 plots of 50x100 m were installed (Fig. 1). The individual blocks and the entire 1x1 km site are surrounded by a buffer-zone to avoid influences from neighbouring stocks. The 32 plots are 0.5 ha in size. A modified block design had to be used for one site in Suriname due to the pre-set logging area alignment applied by the concessionaire. Here the size of the site was set to 0.8x1.25 km containing two blocks. Within the two blocks 140 sample plots with a size of 0.5 ha are installed. As with the other blocks, these two blocks were also surrounded by a buffer zone. In all blocks the silvicultural treatment was carried out on half the area, i.e. in one out of the two blocks at the site located in Suriname and in two out of the four blocks at the three sites located in the other countries.

2.2. Pre-harvest inventory

The silvicultural treatment (see 2.3) was planned on the basis of a pre-harvest inventory. The pre-harvest inventory was implemented to obtain information about forest stand attributes. The following attributes were relevant for the implementation of the silvicultural treatment: (1) distribution of diameters at 1.30 m height (DBH), (2) spatial distribution of trees, (3) log grade, (4) social class, (5) species composition, (6) standing volume, (7) harvestable timber volume. Log grade was determined using the categories from FAO (2008). The social classes were defined using the classification system cited by Nyland (2016). Tree species were further classified into commercial and non-commercial species. All commercial tree species were assigned to four commercial species classes: class A includes species with the highest market value and demand on the timber market, class B species are less valuable species, but with a high acceptance on the timber market, class C species are marketable, but with low demand on the timber market, and class D species are commercial species, but with a weaker marketability. The species were categorized according to local species classifications presented by Alder (1993), GFC (2016), Ramnarine et al. (2002) and SBB (2013, 2014). Within the sample plots all trees with dbh ≥ 25 cm were recorded and mapped.

2.3. Future crop tree release treatment

Future crop tree release (FCTR) is a widely used silvicultural operation in European (Abetz, 1975; Wilhelm et al., 1999) and North American forests (Miller et al., 2007) and is also practiced in tropical forests (Lamprecht, 1989; Werger, 2011). FCTR selects trees in stands for which strong growth and high timber quality by harvest time is expected. To promote the growth of future crop trees (FCTs), they are released from neighbours that restrict their crown space and thereby compete for light. Enlarging the growing space of FCTs by felling neighbouring trees leads to an opening of the canopy. The resulting free space is subsequently filled by the expansion of the FCTs' crowns. However, if the canopy is opened too much it can over expose the FCT stems and stimulate the formation of epicormic branches, increase the risk of wind damage, and support the emergence of light demanding pioneer vegetation. To avoid these negative effects, only competitor trees that severely restrict the crown space of FCTs are removed. This represents a compromise between negative consequences of canopy opening and the desired increase in growth of the FCTs by expanding their growing space (Miller et al., 2007)

Prior to identifying the FCTs, the trees to be harvested in the current harvesting operation were selected. Using the data from a pre-harvest inventory, which included the exact locations, tree species and diameters of all commercial and non-commercial trees with a minimum DBH of 25 cm, a pre-selection of potential FCTs was made. Defined criteria for FCT selection were applied to screen the inventory data for FCTs (Table 1). Some criteria, such as "species", "log grade", "dbh" and "log length", were applied differently in the four countries in our study to take local demands and national regulations into account. The final selection of the FCTs was made together with the selection of the harvest trees in the field. At the same time, the competitor trees to be felled were marked. The felling of the competitor trees took place simultaneously with the timber harvest. As felled competitor trees were not intended for sale, they did not have to be considered for the economic analysis.

2.4. Analysis of economic profitability

2.4.1. Treatment costs

Silvicultural treatments aim at higher volume growth compared to untreated harvested stands and are subject to costs. From an economic point of view, the question therefore arises as to whether the investment made in silvicultural treatments are compensated by the increased growth. Therefore, time studies were carried out in the project to quantify the cost of silvicultural treatments and to create the basis for an economic evaluation.

In all plots the felling crew consisted of the chainsaw operator and an assistant. The assistant included was responsible for the preparation of the felling process, which includes tasks such as cleaning the escape route from vegetation, cutting off lianas, or cutting off the bark of the tree to be felled. The chainsaw operator carried out the actual felling of the trees. Directional felling of trees harvested and competitor trees was applied to reduce the risk of damaging the FCTs. To avoid biases caused by different work performance of individual groups, different groups were used for each plot.

An essential prerequisite of a time study is the division of the entire workflow into its operational elements, hereinafter referred to as work elements (Table 2). The time for the execution of each work element was recorded. However, only the work elements "searching", "preparation", "felling" and "maintenance" were used for the cost

Table 2
Work elements.

No.	Work element	Definition	Category
1	Searching	searching and identification of the target tree, including walking to the next tree	Production
2	Preparation	felling preparation, e.g. liana cutting, clean up, determination of felling direction and rescue ways	
3	Felling	tree felling starts from chainsaw engine start until the tree lies on the ground	
4	Maintenance	maintenance of the chainsaw, e.g. sharpen the chain, refuel	
5	Break	resting break	No production
6	Other	other activities which do not fit into the work elements 1 - 6	

Table 3
Machinery costs data.

Model	Stihl MS 880 + 90cm Bar	Reference
Purchase cost (C_p)	1900 US$	Saw and Lawnmower (2020)
Fuel consumption (K_{gas})	4 L hr^{-1} (3.7-4.3 L hr^{-1})	KWF et al. (2009)
Oil/grease consumption (K_{oil})	0.99 L hr^{-1} (0.36-1.62 L hr^{-1})	KWF et al. (2009)
Effective machine hours per year (T_{emh})	241	Whiteman (1999a, 1999b)
Expected life time (T_{el})	5 years	Whiteman (1999a, 1999b)

calculation, as they are directly linked to the felling process of individual trees.

The time-study data was collected during the silvicultural operations at nine experimental plots with a total area of 291 hectares from January to December 2018. The data included searching for trees, felling preparation, felling, and maintenance operations. During logging operations, the chainsaw operator and assistant were responsible for their own safety. The presence of a third person taking time measurements on the logging site could bias working times, as during felling operations additional time is needed to ensure the safety of the additional person present on the logging site. Thus, instead of exposing a third person to safety risks and to avoid biased time recordings, helmet cameras were chosen as the preferred method for work documentation and time recording. The operation was recorded on video using a “Garmin Virb X” action camera (by Garmin Ltd., Olathe, United States). The camera was mounted on the chainsaw operator´s helmet and switched on at the beginning of work. Once the camera was switched on, it recorded all the work elements until it was switched off. Thus, the chainsaw operator and his assistant could concentrate on their work and own personal safety. At the end of a working day, the recorded data was transferred to a computer. The computer-aided evaluation of the time required for all work elements was carried out later based on the video recordings.

The analysis of the recorded video material was performed with the open-source event logging software “BORIS” (Friard and Gamba, 2016). The video recordings made it possible to record all steps in the felling of trees. By some crews the cameras were occasionally switched off between felling operations, so that rest periods or maintenance times were partly insufficiently recorded. For the felling work in the strict sense, however, sufficient recordings are available so that representative statements about the time required for different felling operations can be derived.

In order to determine the time required for the release of an individual FCT, the effective working time (T_{ewh}) per FCT was calculated. The following work elements (see Table 2) were included in the EWT calculation: (1) searching, (2) preparation, (3) felling and (4) maintenance. For the calculation of the effective machine time (T_{emh}) per FCT, the times measured under the work element "felling" were used.

The data for labour costs was taken from Alaimo et al. (2017). The monthly minimum wages (W_{mm}) in Latin American and Caribbean countries reach from 253 to 883 US$ corrected for purchasing power parity (PPP). We used PPP instead of market exchange rates as PPP is generally regarded as a better measure of overall well-being (Callen, 2007). The monthly minimum wage is the basis for the assistant´s salary. It is assumed, that the chainsaw operator´s wage is 50% higher, than the assistant´s wage and that non-wage labour costs (C_{nw}) amount to 49.5% of wage costs (Alaimo et al., 2017). The hourly costs of labour (C_{lh}) are calculated by Eq. (1) assuming 20 working days per month (N_{wdm}) and 8 working hours per day (T_{whd}):

$$C_{lh} = \frac{W_{mm}}{N_{wdm} \times T_{whd}} \times (1 + C_{nw}) \tag{1}$$

Where:

C_{lh} = hourly costs of labour (US$ hour^{-1})
C_{nw} = average non-wage labour costs amount (%)
N_{wdm} = working days per month
T_{whd} = working hours per day
W_{mm} = monthly minimum wage (US$ month^{-1})

The chainsaw model "Stihl MS 880" with a 90 cm bar is often used in logging operations in the Caribbean. The operating hour costs of the chainsaw was is calculated using data (Table 3) from Whiteman (1999b), Whiteman (1999a), KWF et al. (2009), and Saw and Lawnmower (2020).

The prices for gasoline (P_{gas}) and oil (P_{oil}) are assumed to be 0.776 US$ per litre of gasoline and 20 US$ per litre of chainsaw chain and bar oil. The machine cost per hour (C_{mh}) is calculated using Eq. (2) and includes the depreciation cost per hour (C_{dh}) given by Eq. (3):

Machine cost per hour:

$$C_{mh} = C_{dh} + (K_{gas} \times P_{gas}) + (K_{oil} \times P_{oil}) \tag{2}$$

where

$$C_{dh} = \frac{C_p}{T_{emh} \times T_{el}} \tag{3}$$

C_{dh} = depreciation cost per hour (in US$)
C_{mh} = machine cost per hour (in US$)
C_p = purchase cost (in US$)
K_{gas} = fuel consumption (in litre hour^{-1})
K_{oil} = oil consumption (in litre hour^{-1})
P_{gas} = gasoline price (in US$ litre^{-1})
P_{oil} = oil price (in US$ litre^{-1})
T_{el} = expected life time (in years)
T_{emh} = effective machine hours per year (in hours)

2.4.2. Treatment revenues

The prices for timber were taken from the FAO forestry production and trade database (FAOSTAT, 2020). The prices were country average free-on-board (FOB) for non-coniferous round wood and logs from 2018 (Table 4). Timber prices in Central and South America range from 45 to 619 US$ m^{-3}. Timber prices from French Guiana are excluded because

Table 4
Average timber prices (FOB) for non-coniferous round wood from 2018. Source: FAOSTAT, 2020.

	Export Value	Export Quantity	Unit Value
	US$	m^{-3}	US$ m^{-3}
Central America			
Belize	112,000	181	619
Costa Rica	22,563,000	131,752	171
El Salvador	2,623,000	10,492	250
Guatemala	5,469,000	12,306	444
Honduras	2,415,000	5,146	469
Mexico	20,908,000	57,460	364
Nicaragua	2,086,000	6,934	301
Panama	45,395,000	363,000	125
South America			
Argentina	598,000	3060	195
Bolivia (Plurinational State of)	526,000	11,774	45
Brazil	61,450,000	400,693	153
Chile	3,055,000	28,000	109
Colombia	25,425,000	61,819	411
Ecuador	87,728,000	280,768	312
Guyana	17,231,000	120,416	143
Paraguay	1,842,000	8,557	215
Peru	4,305,000	11,391	378
Suriname	64,410,000	533,931	121
Uruguay	29,644,000	230,774	128
Venezuela (Bolivarian Republic of)	2,173,000	5,349	406

our analysis is based on the minimum wages of countries not belonging to the European Union. For our analysis we use timber prices (P_t) for logs pre-delivered at landings, ranging from 50 to 500 US$ m^{-3}. The prices include hauling the logs to a log landing where they can be loaded onto a truck. The prices are average prices, which are not differentiated by log grade or tree species.

Timber harvesting can be realized with two approaches: Reduced impact logging (RIL) and conventional logging (CL). CL is a commonly applied form of logging to cut down trees. It leads to a desirable high yield for logging companies, but has a high impact on the remaining forest stand and soils. RIL is the intensively planned and carefully controlled implementation of timber harvesting operations to minimize environmental impacts on forest stands and soils

Costs of harvesting by CL and RIL were reported by Medjibe and Putz (2012) based on several studies including those from South America which are listed in Table 5. Harvesting costs (C_h) of RIL range from 13.84 to 28.23 US$ m^{-3}. We use 14 US$ m^{-3} to simulate a low harvesting cost scenario and 28 US$ m^{-3} to simulate a high harvesting cost scenario.

Harvest losses (L_h) are both, residues of harvested trees lying on the ground, and trees that have been severely damaged by the harvesting operation. Logging residues range from parts of the trees, such as high stumps or left-over trunk sections, to entire trees that have been knocked down during the felling process. According to Pearson et al. (2014) the wood volume of harvest residues examined in Belize, Bolivia, Brazil, Guyana, Indonesia, and the Republic of Congo is two to five times higher than the volume of timber removed. In tropical countries, the yield in terms of above-ground biomass per felled tree is estimated at 54% in Africa, 46% in Asia-Pacific, 56% in Latin America and the Caribbean and an average of 50% in all tropical countries (Dykstra, 1991). Enters (2001) comes to the conclusion, that “for every cubic meter of wood extracted from the forest another is left behind”. We assume an average yield of 50% of the harvested commercial trees.

Table 5
Costs of logging and operation.

Reference	Location	Logging method	Harvest volume	Costs per m^3	Costs per ha
			m^3 ha^{-1}	US$ m^{-3}	US$ ha^{-1}
Holmes et al. (2002)	Fazenda Cauaxi, Brazil	CL	26.1	15.66	408.73
		RIL	24.9	13.84	344.62
Boltz et al. (2001)	Para, Brazil	CL	25.8	13.50	348.30
		RIL	19.7	16.34	321.90
van der Hout (1999)	Pibiri, Guyana	CL	28.5	28.28	805.98
		RIL	31	28.23	875.13
Barreto et al. (1998)	Fazenda Agrosete, Brazil	CL	29.7	24.95	741.02
		RIL	38.6	26.48	1022.13

2.4.3. Statistical analysis

The working elements necessary for silvicultural treatments depend on specific local conditions, the number of FCTs selected and the amount of working days per site, which results in an unbalanced experimental design of the time study. We used the statistical computing environment *R* (R Core Team, 2019) and the *R*-package *lme4* (Bates et al., 2015) to perform a linear mixed effects analysis. With a mixed effects model we were able to incorporate nested random-effects terms in a linear predictor expression. As random effects, we added the working days nested within the experimental sites nested within the project countries. One of the advantages of the mixed model approach is it´s robustness to unbalanced data (Nelder and Wedderburn, 1972).

2.4.4. Growth simulation

The tree volume (V) was estimated using a *dbh*-based allometric equation according to Alder and van Kuijk (2009). The equation was derived from 1849 felled sample trees covering 137 species (Eq. 4).

$$V = 0.0005107 * dbh^{2.2055} \tag{4}$$

where
dbh = diameter at breast height in cm
V = volume in m^3

On the experimental sites no growth measurements were carried out after previous interventions, which does not allow for an empirical estimation of post-intervention tree growth. Therefore, growth rates are taken from former studies conducted in the region and implemented in a straightforward diameter-increment-approach to simulate the growth of the individual FCTs. The growth simulation serves to estimate the difference of volume growth between released and non-released FCTs at the end of the cutting cycle (T_{cc}) of 30 years.

In logged tropical forests, mean diameter growth between 0.8 to 5.1 mm $year^{-1}$ were reported by several studies (Table 6). After a release treatment, liberated trees showed growth increases of 20-60% in various studies (Table 7). For this study, we use a fixed mean diameter growth rate of 2.7 mm $year^{-1}$ for non-released FCTs and 30% increased growth rate of 3.51 mm $year^{-1}$ for released FCTs. We simulated tree growth over a period of 30 years, which corresponds to the usual cutting cycles in the region, and determined an additional growth of the released FCTs of 0.14 m^3 $tree^{-1}$ to 0.52 m^3 $tree^{-1}$.

Table 6
DBH mean growth rate references (Gräfe et al., 2020).

Mean growth rates (mm $year^{-1}$)			References
Minimum	Medium	Maximum	
2.3		4.6	Werger (2011), Jonkers et al. (2003)
1.7	3.1	3.9	Vieira et al. (2004)
0.8	2.7	5.1	Lieberman et al. (1985)
	2.3		Herault et al. (2010)

Table 7
Published growth increases after release treatment.

Growth increase after release treatment	References
20%	Wadsworth and Zweede (2006)
22–27%	Villegas et al. (2009)
50–60%	Peña-Claros et al. (2008)
33%	Kuusipalo et al. (1997)

2.4.5. Net present value, discount rate and required additional growth

The goal of the silvicultural treatment is to increase the growth of the treated individuals. In this study, the silvicultural treatment is seen as an economic investment. In order for the treatment to be profitable, the income generated by the additional growth at the end of the cutting cycle must at least cover the costs of the treatment. As future costs and returns are valued differently from present costs and returns, the analysis of the treatment was based on a variation of the net present value (NPV) method, which is a suitable method for evaluating the profitability of investments. Costs and returns can be calculated by discounting to the so-called (net) present value. If the NPV of an investment is larger than zero, the investment is considered to be profitable. For the calculations an annual discount rate must be determined. Especially for long-term investments with high initial costs, the level of the discount rate has a considerable influence on the resulting NPV. For our calculations we defined three discount rate scenarios with discount rates (i) of 0.5%, 2.5% and 5% per year. To determine when the NPV becomes zero, we chose either the required timber price per cubic meter (P_{rt}) or the required additional growth per FCT (G_{rt}). The required timber price (Eq. 5) is a function of harvesting costs (C_h), treatment costs (C_{tr}) and the additional growth (G_{at}) of the released FCT reduced by harvest losses. The required additional growth (Eq. 6) is a function of the treatment costs and the harvesting-cost free revenue as the difference of timber price (P_t) and harvesting cost corrected for logging losses.

$$P_{rt} = \frac{C_{tr} \times (1+i)^{T_{cc}}}{(1-L_h) \times G_{at}} + C_h \tag{5}$$

$$G_{rt} = \frac{C_{tr} \times (1+i)^{T_{cc}}}{(P_t - C_h) \times (1-L_h)} \tag{6}$$

where

$$C_{tr} = C_{fc} \times N_c \tag{7}$$

with

$$C_{fc} = (C_{lh} \times T_{ewh}) + (C_{mh} \times T_{emh}) \tag{8}$$

C_{fc} = felling cost per competitor (in US$ m^{-3})
C_h = harvesting costs (in US$ m^{-3})
C_{lh} = hourly cost of labour (in US$)
C_{mh} = machinery cost per hour (in US$)
C_{tr} = treatment costs per FCT (in US$)
G_{at} = additional growth per tree until the end of the cutting cycle (in m^3)
G_{rt} = required additional growth per released FCT when NPV = 0
i = annual discount rate (in %)
L_h = harvesting losses (in %)
N_c = number of removed competitors per released FCT
P_{rt} = required timber price to achieve when NPV = 0
P_t = timber price (in US$ m^{-3})
T_{cc} = cutting cycle (in years)
T_{emh} = effective machine time per tree (in hours)
T_{ewh} = effective working time per tree

2.4.6. Sensitivity analysis and response surface

The profitability of treatments depends on several input parameters, such as treatment costs, achievable timber prices, or the additional growth of treated trees. However, these parameters vary from region to region. Using pre-defined ranges of input parameters we were able to analyse the profitability by means of a sensitivity analysis (Table 8). The sensitivity analysis is conducted in reference to the NPV by using ranges of treatment costs, tree growth rates, and timber prices.

Table 8
Sensitivity analysis input parameters.

Factor	Unit	Values or range
Additional growth (G_{at})	m^3 tree^{-1}	0.14-0.52
Discount rate (i)	%	0.5; 2.5; 5
Harvesting costs (C_h)	US$ m^{-3}	14; 28
Treatment costs (C_{tr})	US$ tree^{-1}	4.5-8.9
Timber price (P_t)	US$ m^{-3}	50-500

Revenues are based on timber prices or increased growth at the end of the 30-year rotation period. The revenues after deducting harvesting costs are discounted to the present values using annual discount rates of 0.5%, 2.5% and 5%. Two scenarios are selected as timber harvesting costs: (1) low harvesting costs of 14 US$ m^{-3} and (2) high harvesting costs of 28 US$ m^{-3}. For both scenarios, the growth necessary to cover the treatment costs or the timber prices to be achieved are calculated for timber prices between 50 and 500 US$ m$^{-3,}$ or for growth increases of 0.14 to 0.52 m^3 tree^{-1} and treatment costs of 4.5 to 8.9 US$ per tree.

The sensitivity analysis refers to individual trees. The calculations were based on information from 501 FCTs recorded on the plots. From this information, mean values for the number of competitors felled are derived

To show the relationships of the selected factors and their influence on the profitability of the treatments, we calculated a response surface in a three-dimensional space. The response surface represents all points of the selected combination of factors where the NPV = 0. The results of the sensitivity analysis form the basis for this calculation. Thus, the timber price needed to achieve a zero NPV (NPV = 0) was analysed within the sensitivity analysis as a function of the treatment costs at different growth rates and presented as a line chart. The response surface represents the average discounted revenues per cubic meter needed to cover the investment as a function of average growth per FCT and treatment costs in a three-dimensional space. We did the same for the presentation of the calculation of the necessary additional growth, where NPV = 0. The response surface represents the average growth per FCT needed to cover the investments for silvicultural treatments as a function of discounted revenues and treatment costs.

3. Results

3.1. Summary of the future crop tree release treatment

The silvicultural treatment (chapter 2.3) was carried out during commercial harvest operations. An average of 5.4 trees per hectare

Table 9
Commercial harvest and silvicultural treatment observations.

Parameter	Harvested trees	Total FCTs	Released FCTs	Removed competitors
	n ha^{-1}	n ha^{-1}	n ha^{-1}	n ha^{-1}
Fixed effects				
Intercept	5.4	5.6	2	3
SE	1.1	1.3	0.9	1.3
CI	0.7 – 10.2	-0.7 – 11.9	-1.8 – 5.7	-2.9 – 8.9
Random effects				
SD site	1.2	3.7	1.5	2.3
SD country	1.7	0.0008	1.2	1.8
SD residuals	4.5	5.2	2.5	4.1

SE = standard error; CI = confidence interval; SD = standard deviation.

Table 10
Time study.

Parameter	Searching	Felling prep.	Felling	Main-tenance	Break	Other
Observations	862	961	968	158	72	226
	min/tree	min/tree	min/tree	min/event	min/event	min/event
Fixed effects						
Intercept	3	3	5.5	3.4	1.9	6.8
SE	0.7	0.7	1	1.2	0.3	3.8
CI	0.6 – 5.3	-0.06 – 6.1	1.4 – 9.7	-0.9 – 7.7	-4.1 – 7.9	-6.3 – 19.9
Random effects						
SD day	0.3	0.7	1.3	2.6	1	4.7
SD site	1.5	2	2.6	0.5	0.4	7.2
SD country	0.7	0.1	0.002	2	0.0003	5
SD residuals	2.2	2.2	3.4	2.7	1.6	1.8

SE = standard error; CI = confidence interval; SD = standard deviation.

(Table 9) were harvested and 5.6 trees per hectare were selected as FCTs on the treatment plots. Out of the selected FCTs, an average of two FCTs per hectare received the treatment. The remaining FCTs were already so far released from competition by the removal of the harvested trees that no further treatment was indicated. To release FCTs, an average of three competitors per hectare were removed. Combined with the release by harvested trees, an additional 1.5 trees had to be felled on average per FCT. The standard deviations presented for the attributes total FCTs, released FCTs and removed competitors indicate that the random effects of the sites are stronger than the effects of the countries.

3.2. Economic analysis

3.2.1. Time expenditure per tree and treatment costs

The data collected during the time study (Table 10) included searching for 862 trees, felling preparation of 961 trees, felling of 985 trees, post-processing of 684 trees, and 158 maintenance observations. In addition, 72 breaks and 226 other activities, which did not fit in one of the pre-defined categories, were recorded. The difference in the number of observations per parameter is due to the fact, that not every work element was recorded with the same frequency. Tree searching and felling preparation took on average 3 minutes each, felling and post-processing on average 5.5 minutes per tree, and maintenance of machinery on average 3.4 minutes per event. For the time needed per work element random effects of the countries are smaller than the effects of the sites or the respective working day. For the work elements searching, felling preparation and felling the effect of the site is stronger than the effect of the respective working day. Maintenance is more effected by the working day than the site.

The results of the time study together with the results of the silvicultural treatment form the basis for determining the treatment costs. The treatment costs were calculated using Eqs. 7 and 8 based on the measured time taken to release the FCTs together with the parameters presented above, such as costs of labour, machinery costs and number of competitors removed per FCT. The treatment costs were calculated at 4.5 to 8.9 US$ per released FCT.

3.2.2. Sensitivity analysis and response surface

In order for the treatment to be profitable at the end of the cutting cycle, the increase in growth achieved by the treatment and the resulting revenue from timber sales must result in a NPV = 0. We investigated both the required growth increases at different timber prices and the required timber prices at different growths that must be achieved for NPV = 0. We assumed different treatment costs, harvest costs and discount rates.

Fig. 2 shows the required timber price (P_{rt}) above the treatment costs (C_{tr}) assuming rates of additional growth of the released FCTs (G_{at}) ranging from 0.14 m^3 tree^{-1} to 0.52 m^3 tree^{-1}. The required timber price is shown for a low harvesting costs scenario (LHC) and a high harvesting costs scenario (HHC) with discount rates (i) of 0.5%, 2.5% and 5%. The timber prices that must be achieved for the treatment to be profitable at the end of the 30-year cutting cycle range from 34 US$ m^{-3} to 578 US$ m^{-3}. These are not FOB timber prices, but prices for logs pre-delivered at the log landings. Unlike FOB prices, these prices do not include transport costs from the logging site to the nearest port. The calculated prices show a strong dependence on the assumed additional growth and the discount rate chosen. Since a treatment is an investment with a relatively long duration of 30 years, periodic or accumulating factors over time, such as annual discounting or annual growth, have a large impact. Assuming a discount rate of 0.5%, the required timber prices range from 34 US$ m^{-3} (LHC, $G_{at}=0.52$ m^3 tree^{-1}, $C_{tr}=4.5$ US$ tree^{-1}) to 176 US$ m^{-3} (HHC, $G_{at}=0.14$ m^3 tree^{-1}, $C_{tr}=9$ US$ tree^{-1}) depending on the harvest cost scenario, growth rate and treatment costs. Assuming a discount rate of 2.5 %, the prices range from 50 US$ m^{-3} (LHC, $G_{at}=0.52$ m^3 tree^{-1}, $C_{tr}=4.5$ US$ tree^{-1}) to 295 US$ m^{-3} (HHC, $G_{at}=0.14$ m^3 tree^{-1}, $C_{tr}=9$ US$ tree^{-1}). Assuming a discount rate of 5 %, the prices range from 89 US$ m^{-3} (LHC, $G_{at}=0.52$ m^3 tree^{-1}, $C_{tr}=4.5$ US$ tree^{-1}) to 578 US$ m^{-3} (HHC, $G_{at}=0.14$ m^3 tree^{-1}, $C_{tr}=9$ US$ tree^{-1}). The assumption of smaller growth rates leads to a larger sensitivity of the chosen discount rate or the level of treatment costs compared to larger growth rates. The influence of the discount rate and the treatment costs increases with decreasing growth rates. Compared to the growth rates and the choice of discount rate, the harvest costs have relatively little effect on the required timber price.

Fig. 3 shows the required timber price as a three-dimensional response surface, which is a function of treatment costs and additional growth of the released FCTs. All points of the response surface represent the timber price that must be achieved at the end of the cutting cycle for the NPV to be zero. The illustration shows the strong influence of the assumed discount rates for an investment with a 30-year term. The influence of the harvesting costs, on the other hand, is considerably smaller.

Fig. 4 shows the required additional growth (G_{rt}) of the released FCTs for the two harvest cost scenarios (LHC and HHC) and three discount rates ($i=\{0.5\%;\ 2.5\%;\ 5\%\}$) over the treatment costs (C_{tr}) assuming timber prices (P_t) from 50 US$ m^{-3} to 500 US$ m^{-3}. Assuming timber prices between 50 US$ m^{-3} and 500 US$ m^{-3} at the end of the cutting cycle, the required additional growth per FCT must be between 0.02 m^3 tree^{-1} and 3.5 m^3 tree^{-1} to make the treatment profitable. With an assumed discount rate of 0.5%, the required additional growth ranges from 0.02 m^3 tree^{-1} (LHC, $P_t=500$ US$ m^{-3}, $C_{tr}=4.5$ US$ tree^{-1}) to 0.94 m^3 tree^{-1} (HHC, $P_t=50$ US$ m^{-3}, $C_{tr}=9$ US$ tree^{-1}). Assuming an interest rate of 2.5%, the required additional growth ranges from 0.04 m^3 tree^{-1} (LHC, $P_t=500$ US$ m^{-3}, $C_{tr}=4.5$ US$ tree^{-1}) to 1.7 m^3 tree^{-1} (HHC, $P_t=50$ US$ m^{-3}, $C_{tr}=9$ US$ tree^{-1}). Assuming an interest rate of 5%, the required additional growth ranges from 0.08 m^3 tree^{-1} (LHC, $P_t=500$ US$ m^{-3}, $C_{tr}=4.5$ US$ tree^{-1}) to 3.5 m^3 tree^{-1} (HHC, $P_t=50$ US$ m^{-3}, $C_{tr}=9$ US$ tree^{-1}). If high timber prices are assumed, the treatment costs or the choice of the discount rate have relatively little effect on the required additional growth. However, the sensitivity of the required additional growth in relation to treatment costs or discount rates increases with decreasing timber prices.

Fig. 5 shows the response surfaces, which represent the break-even point of the required additional growth as a function of the treatment costs and revenues. The response surfaces are shown separately for low and high harvesting costs and discount rates of $i=\{0.5\%;\ 2.5\%;\ 5\ \%\}$. With low treatment costs and high timber prices, the growth rates of both harvesting cost scenarios differ only slightly. The influence of harvesting costs increases with lower wood prices and higher treatment costs.

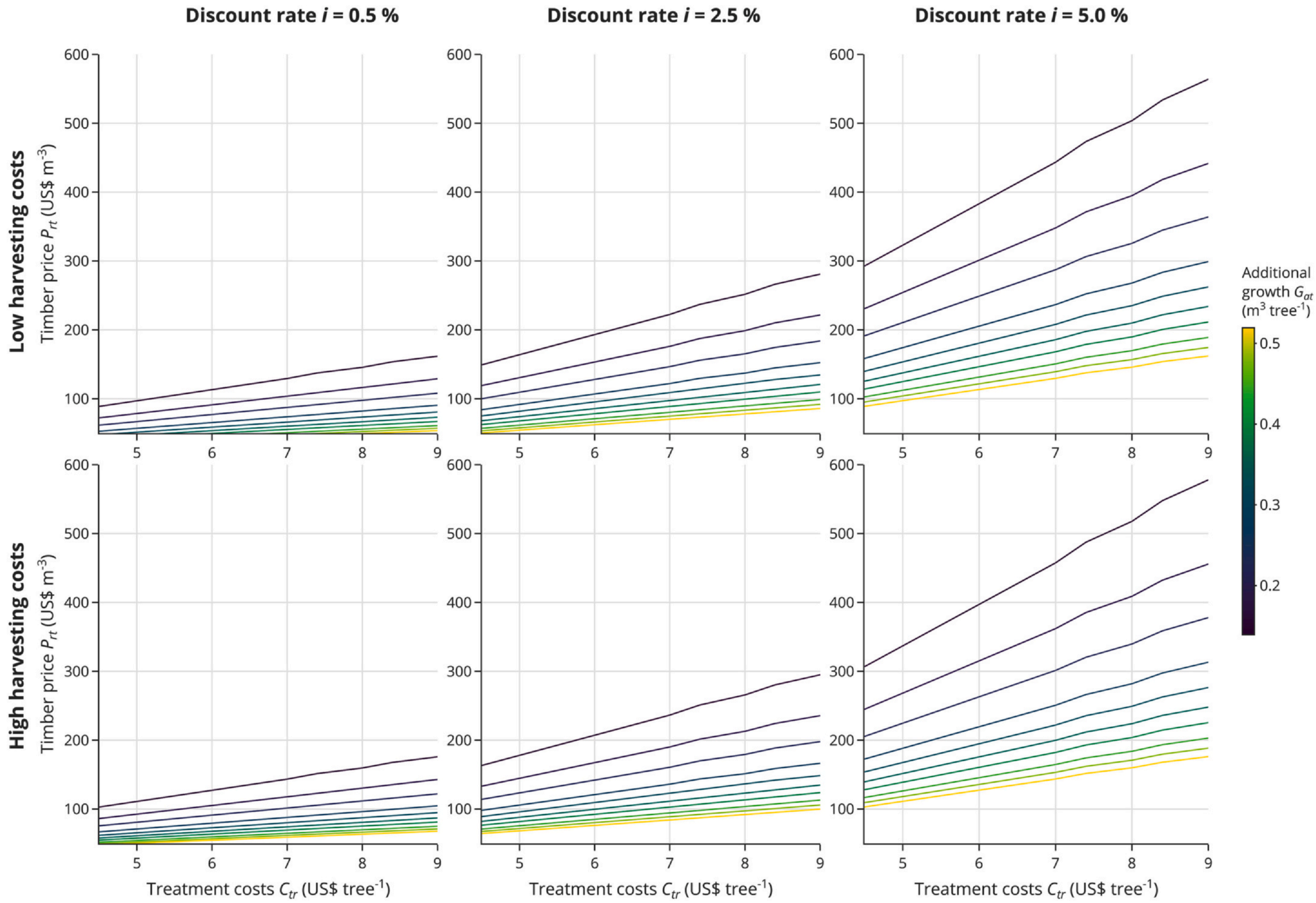

Fig. 2. Required timber price P_{rt} against treatment costs C_{tr} assuming a range of additional growth G_{at} increase.

4. Discussion

Silvicultural treatments, such as the FCT release treatment, can enhance the growth of the treated trees, but their implementation comes with costs. A silvicultural treatment can be regarded as an investment that will pay for itself through future payments. For an evaluation either future timber prices must be discounted or the current investment must be prolonged. At the end of the rotation period, the sales value of the additionally grown timber volume, which is achieved by the silvicultural treatment, must at least cover the costs of the silvicultural treatment. If the added value achieved is greater than the cost of the silvicultural treatment, the investment has paid off economically, resulting in a higher profit. If the added value is lower, the costs of the silvicultural treatment have not been amortised and an economic loss is generated.

Our study is based on empirical surveys from four Caribbean countries. Extensive time studies were conducted during the implementation of the treatments to determine the cost of the treatment. Timber prices, labour costs, and growth rates of the region were taken from literature or public databases.

In this study, the silvicultural treatment was carried out in parallel with regular timber harvesting. On average, about the same number of FCTs (5.6 trees ha^{-1}) as harvest trees (5.4 trees ha^{-1}) was identified. Removal of competitor trees was necessary for less than half of the selected FCTs to achieve a release. On average, 1.5 competitors were felled per FCT. The standard deviation of the number of FCTs is higher between the sites than between the countries studied. As our methodology was consistent in all countries, this indicates that the results are meaningful across countries. As the treatment was carried out together with regular timber harvesting, some FCTs could already be released by the harvesting activity and the removal of neighbouring harvest trees. Thus potential competitors were removed without additional costs through regular timber harvesting. An increase in the number of competitors needed to be removed for the release of a FCT would have led to higher treatment costs. Wadsworth and Zweede (2006), for example, identified and removed an average of 2.9 competitors per FCT in order to achieve a sufficient release. An assumption of three competitors to be removed per FCT would lead to a doubling of treatment costs and the additional growth required. The costs of a treatment should be kept as low as possible. Costs can be reduced by combining the treatment with regular timber harvesting or by carrying out the treatment immediately after harvesting as a post-harvesting activity.

We conducted extensive time studies to determine the treatment costs. Also here the standard deviation of the mean of the observed times between sites was larger than between countries. For the work elements searching, preparation, felling, and post-processing the standard deviation between sites was also larger than between the different working days. This suggests that the number of days worked has no effect on the time required per work element. Only the time needed for maintenance and breaks were influenced by the number of days worked. The effect of the sites is partly due to the effect of the felling crews and the level of organization of the managing company, such as properly implemented pre-harvest planning.

Using a reverse approach, we derived both the required timber price and the additional volume growth needed to make the treatment profitable at the end of the 30-year rotation period. We assumed a range of costs, growth increments, and timber prices that are common for the study region. For the calculation of the harvest cost-free returns, we

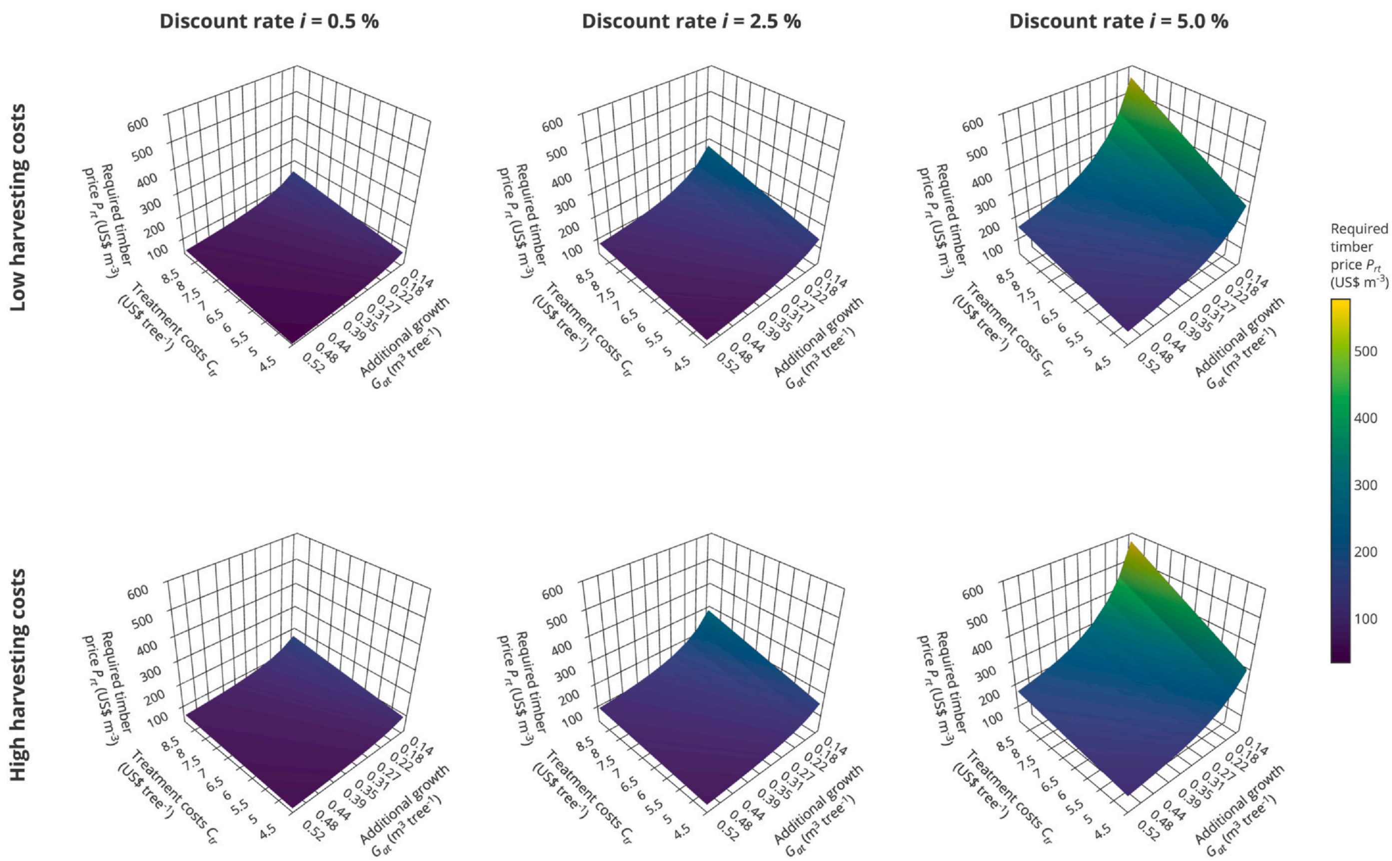

Fig. 3. Required timber price P_{rt} (response surface) against treatment costs C_{tr} and additional growth G_{at}.

assumed a low harvest cost and a high harvest cost scenario. With additional growth rates ranging from 0.14 m^3 tree^{-1} to 0.52 m^3 tree^{-1}, the timber prices that must be achieved to reach the break-even points between cost and benefits range from 34 US$ m^3 to 578 US$ m^3. The average FOB timber prices for South America and the Caribbean are in some countries below the prices, which would be necessary to reach the break-even point. Thus, a treatment in these countries would only be profitable if it focuses on high-value trees of a stand, which are able to achieve correspondingly high prices on the timber market. This shows that a silvicultural treatment involves a high investment risk, which, in addition to the general risks of biological production, is particularly dependent on the future development of timber prices and costs on the labour market. Both can be subject to very strong fluctuations. Economic growth and an increase in employment opportunities can make labour costs more expensive, and the increasing trade in currently lesser-known tree species can influence timber prices substantially.

However, the calculated prices show a strong dependence on the assumed additional growth and the selected discount rates. The strong influence of the discount rate on the profitability of silvicultural treatments is also reported in other studies (e.g. Brazee and Dwivedi (2015), Nakajima et al. (2017), Schwartz et al. (2016)). Looking at forestry as a competitive industry, Nakajima et al. (2017) a discount rate of 4% is considered to be appropriate. Schwartz et al. (2016) used the National Development Bank of Brazil's long-term interest rate of 6% as discount rate for a profitability analysis of regeneration treatments in the Brazilian Amazon. Sauter and Mußhoff (2018) examined the preferences of German foresters in their choice of discount rates and arrived at a discount rate of 4.1%. Since the discount rate is determined, among other things, by the economic situation of a country (Brazee and Dwivedi, 2015), they cannot simply be transferred from one country to another. We, therefore, used interest rates of 0.5%, 2.5% and 5% to cover a wide range of possible future interest rate developments. Due to the relatively long planning periods in forestry and the relatively short investment periods of investors, the choice of the interest rate is a well-known problem in forest asset management. Financial analyses would hardly favour projects in which the expected return on investment exceeds a period of 10 years (Karsenty, 2000). This is in strong contrast to the usual cutting cycles of 25 to 40 years in tropical forests, and cash returns that are realized only at the end of the cutting cycle. These revenues are subject to positive discount rates in the investment calculation and thus undervalued compared to short-term revenues. Discounting and the choice of discount rate express the preference of the individual for the present, and higher discount rates stand for a greater depreciation in the future. The selected interest rate therefore also depends on the expected time horizon at which profits can be realized (Karsenty, 2000). In addition, there is uncertainty about the conditions that will prevail in the future. The uncertainty increases with the length of the investment period. The costs generated by a silvicultural treatment today, are amortized at the earliest at the end of the cutting cycle, in our case after 30 years. However, the success of the treatment is exposed to various risks. For example, the felling of competitor trees opens the canopy to a certain degree, which increases the disposition of the released trees to storm damage. In addition to storm damage, climatic changes, such as dry periods, can also lead to a decline in the expected growth. Furthermore, there is the risk that the tree species selected for treatment today will no longer be interesting for the timber market in 30 years and that the required timber prices will no longer be achievable. Such risks play an important role in the selection of the discount rate. The greater the uncertainty in the future and the risks involved, the greater the preference for the present and the devaluation of future returns via risk factors on the discount rates. The duration of the concession contracts and the long-term exploitation rights of the forest stand represent a further uncertainty. In the study area, concessions are usually granted for a period of 30 years, which also defines the

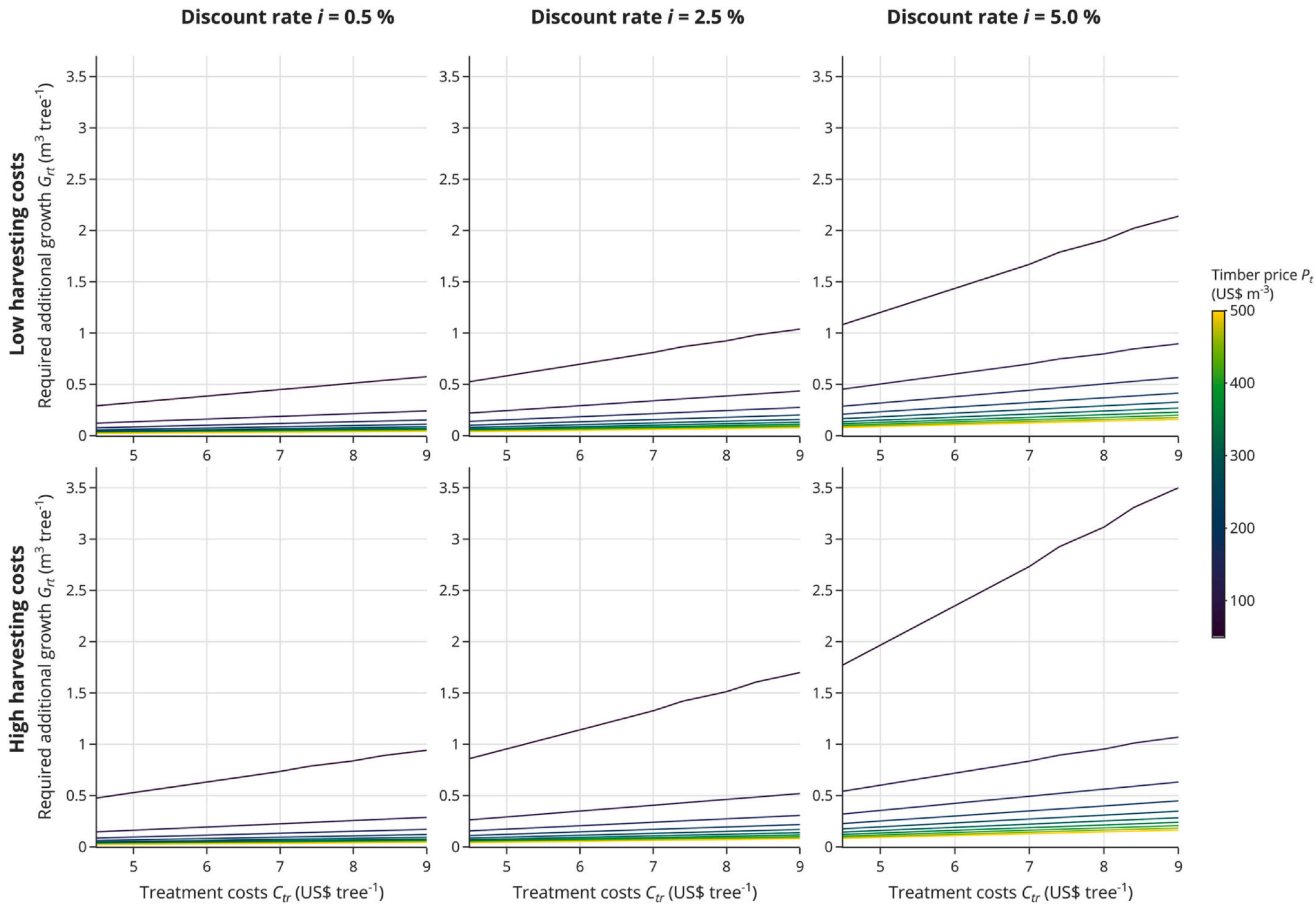

Fig. 4. Required additional growth G_{rt} against treatment costs C_{tr} assuming a range of timber prices P_t.

length of the cutting cycle. If a concessionaire invests in a silvicultural treatment, there is no guarantee that it will be profitable. This of course means that a rationally acting concessionaire would not take the risk of making efforts to preserve the forest capital in the long term without being able to benefit from the prospect. Political or organizational changes are required in order to ensure that concessionaires or forest managers invest in silvicultural treatments, but whose effects may only become visible after the expiry of the concession contract. Either the state can carry out the silvicultural treatments or assume their costs (e.g. Karsenty et al. (2008)). Or the concessionaire can be assured of an extension of the exploitation right or a second period of exploitation. In this context, consideration must also be given to the general extension of the duration of concessions and the cutting cycles defined by them (e.g. Zimmerman and Kormos (2012)). With concession periods that allow for the regeneration of a stand after harvesting and thus for repeated use by one and the same concessionaire, the concessionaire would be interested in the highest possible volume growth of commercially valuable tree species. With the prospect of profits through measures that accelerate the growth of certain trees, the willingness of the concessionaire to implement silvicultural treatments could also be increased.

In addition to the long planning periods, the risks of organic production also play a decisive role in investment planning. Possible biotic and abiotic risks, which lead to a loss in value of the FCTs, burden the investments with uncertainties, and are usually reflected in higher interest rates in the investment calculation. Our explanations show that these interest rates are difficult to offset by additional growth or rising timber prices. The situation is further aggravated by the fact that, due to their age, the people who initiate an investment today are rarely the profiteers of the investment, which does not necessarily increase the will to invest. If the terms of concessions end before the next harvest cycle, investments in silvicultural treatments become obsolete. These considerations suggest that silvicultural treatments can only be justified to a limited extent by the prospect of economic value creation. Alternative financing options were, therefore, considered elsewhere. One possibility is the subsidization of silvicultural treatments by government agencies (Karsenty et al., 2008). By the extension of the duration of a concession as suggested by Zimmerman and Kormos (2012) investments in silvicultural treatments could also be promoted, as the prospect of profits from increased growth increases the willingness to invest.

Our investment calculations assume that the forest owner has sufficient liquidity in the planning period. Since silvicultural treatments significantly increase the time horizon required to amortize the capital invested, an additional economic risk may arise, which should not be underestimated, especially in the study area.

The potential for increased growth through silvicultural treatments is a fundamental assumption for appropriate investments. However, some studies have shown that caution is indicated here. de Graaf et al. (1999) showed that the mortality rate in the residual stand increased with the intensity of treatments. Kuusipalo et al. (1996) reported that liberation treatments lead to an increase in the occurrence of pioneer vegetation instead of increasing the growth of desired species. Mills et al. (2019) showed that the removal of lianas from FCTs can lead to growth increases of 38-63%. Since the removal of lianas is significantly cheaper than felling competitor trees, the possible return of investment is also to be assessed more positively.

According to our study, a silvicultural treatment is profitable when

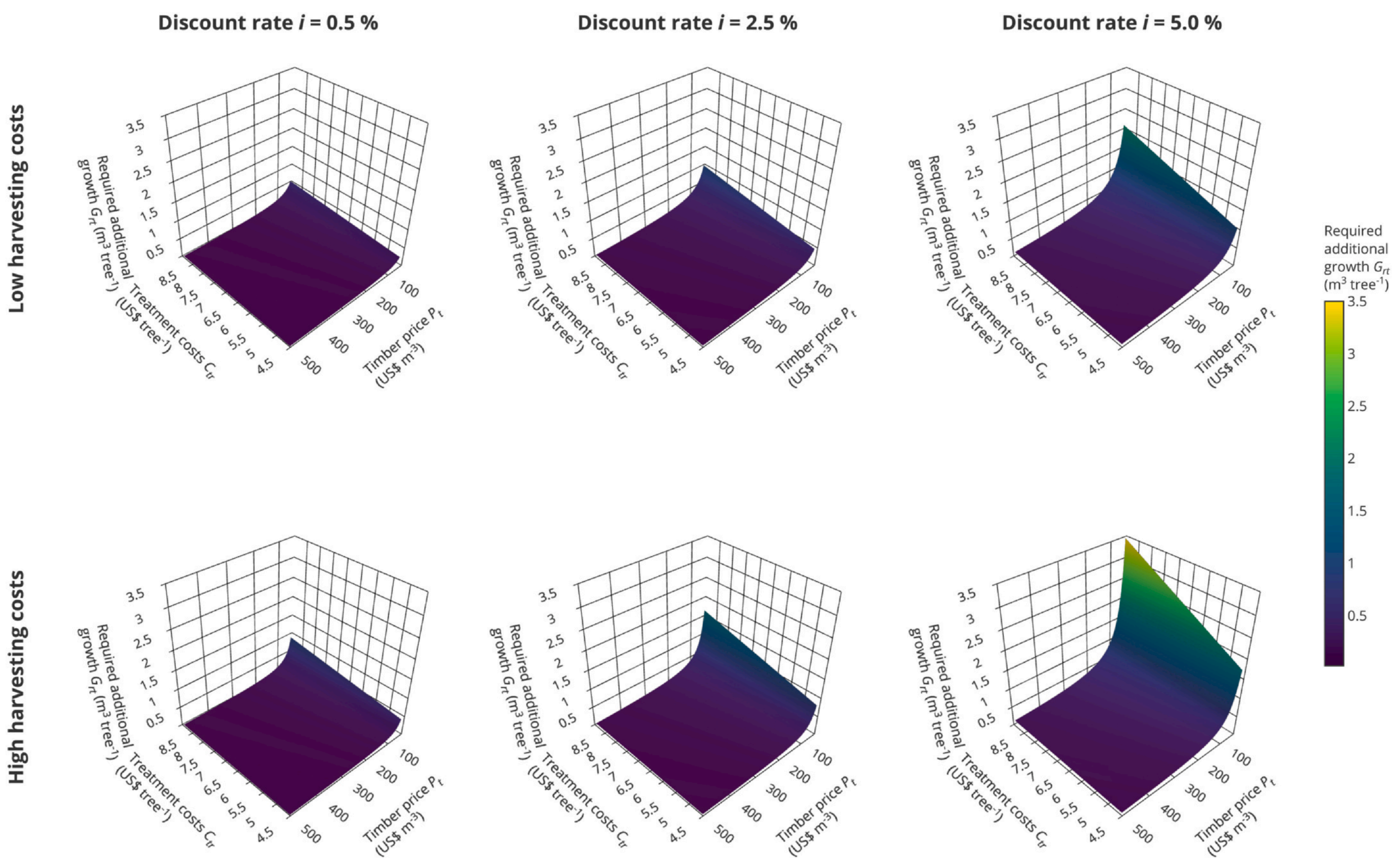

Fig. 5. Required additional growth (G_{rt}) per tree (response surface) against treatment costs (C_{tr}) and timber price (P_t).

it results in additional growth rates of 0.2 m^3 tree^{-1} to 3.5 m^3 tree^{-1}. To make silvicultural treatments profitable under lower growth rates requires more favourable conditions including low treatment and harvesting costs, assumed lower discount rates, or higher achievable timber prices. For higher growth rates conditions can be less favourable including high treatment and harvesting costs, high discount rates, or lower timber prices. In logged tropical forests mean diameter growth between 0.8 to 5.1 mm year^{-1} were reported by Herault et al. (2010), Jonkers et al. (2003), Lieberman et al. (1985), Vieira et al. (2004), and Werger (2011). In several studies growth increases of liberated trees by 20-60% after release treatments were observed (e.g. Kuusipalo et al. (1997), Peña-Claros et al. (2008), Villegas et al. (2009), Wadsworth and Zweede (2006)). We applied published growth values to simulate the additional volume growth of the released FCTs and obtained over a period of 30 years an average additional total growth of 0.14 to 0.52 m^3 tree^{-1}. These growth figures show that the growth of up to 3.5 m^3 tree^{-1} required to amortize an investment in silvicultural treatments significantly exceeds the biological growth potential of trees. Only under very favourable assumptions regarding costs and revenues will the potential additional growth of exempted FCTs be sufficient to cover the investment costs. The approach presented allows to determine the minimum required growth to cover the costs of silvicultural measures. If this minimum required growth is close to or exceeds the biologically possible growth, the silvicultural treatment should be rejected. Our approach, therefore, offers the possibility for a rational economic decision, which goes beyond the mere appraisal of an increase in growth.

Whether silvicultural treatments are economically viable depends on a number of factors: (1) the released FCTs respond to the silvicultural treatment with increased growth and accumulate the required additional volume within the current cutting cycle, (2) and belong to the group of the marketable and valuable tree species at the time of harvesting and can achieve the required high timber prices, (3) treatment and harvesting costs are low, and (4) an appropriate discount rate has been selected. Expected costs and revenues as well as expected growth are subject to uncertainties, which are reflected in the choice of interest rates. In addition, factors such as the origin and cost of the capital required for the treatment, the existence of alternative investment opportunities or the individual assessment of risks and present preferences can determine the choice of interest rates (e.g. Manley (2019), Sauter and Mußhoff (2018)). As long as no reliable and general statements on the increase in growth through silvicultural treatments are available, the uncertainties in the other factors relevant to decision-making and the resulting anticipated interest rates will tend to speak against the implementation of silvicultural treatments.

The factors that determine the profitability of silvicultural treatments vary from region to region and from stand to tree species. As profitability is determined by the interaction of all factors, a general evaluation is not possible. In addition to a proper accounting and controlling system, detailed and individual information on tree species, timber prices, costs and growth is needed. The cost structure must be known so that treatment costs and harvesting costs can be calculated exactly for the specific case. The duration of the concession contract determines the length of the cutting cycle. The longer the cutting cycle, the greater the influence of the discount rate. The discount rate can only be determined appropriately if the preferences and individual circumstances of the investor and the capital to be invested are known. In order to determine the required timber price, which must be achieved at the end of the cutting cycle, the species-specific growth rates as well as the species-specific reaction to the treatment for the respective location must be known. Data from growth studies and silvicultural experiments at similar locations should be available. In order to be able to evaluate the calculated required timber price, information about the development of timber prices at the end of the cutting cycle would have to be available. Data on the development of timber prices and growth rates would also be necessary if the required additional growth is to be determined and interpreted. At the latest with the assumption of the additional growth or the future timber prices large uncertainties arise, which can be met only with a risk addition on the discount rate. If the risk of losses is taken into account in the selection of the interest rate, a conservative approach is highly unlikely to result in profits when investing in silvicultural treatments and investments with a shorter cash return are preferred.

Our analysis focused exclusively on the economic aspects of commercial forestry. For a holistic evaluation of silvicultural treatments, however, their effects on climate, environment, and biodiversity in forest ecosystems must also be considered. Forests play an important role in the global carbon cycle as they act both as carbon sinks and carbon sources (Butarbutar et al., 2019). Ekholm (2020) determined the optimal rotation period taking into account carbon prices and damage risks. He shows that the carbon price has a greater impact on determining the optimal rotation period than forest damage risks. With appropriate carbon prices, increasing forest carbon stocks through longer rotations would be an economically attractive option despite the higher forest damage risk. An increase in forest carbon stocks implies a reduction in harvest volume (Ekholm, 2020). Silvicultural treatments can help to concentrate the harvest volume specifically on the value drivers of the stand. However, we are not aware of any recent studies on the effects of silvicultural release treatments on the carbon pool of the stand. There is a lack of knowledge as to what time span is required for the released FCTs to compensate for the C-loss caused by the felling of competitors, or whether the growth potential of a tree is even large enough to compensate for the respective C-loss. Besides the effects of silvicultural treatments on the carbon pool of the forest, further effects on the forest ecosystem and its biodiversity have to be considered. Forest management measures have a variety of impacts at ecosystem level, which vary according to the intensity of logging and silvicultural treatments and the care with which these treatments are applied. Since different forest ecosystems react differently to the same intervention, there is a wide variety of possible responses. Silvicultural measures, which are carried out after harvesting and are designed to promote the growth of certain commercial tree species, can lead to changes in the species composition and successional stages of the stand. In particular, future crop tree release treatments could lead to the local extinction of rare or endangered tree species of low commercial value (Putz, 2011). According to Yguel et al. (2019) logging and silvicultural treatments have a negative impact on seed size and biomass, but not on species richness.

5. Conclusions

The decision whether to use silvicultural treatments in the management of natural tropical forests is often guided solely by the aspect of improving tree growth. With our study we extend the horizon of consideration to an economic issue. The results shown are based on data and observations obtained in four Caribbean countries, namely Belize, Guyana, Suriname, and Trinidad and Tobago. Nevertheless, the results allow statements that can also be applied to the management of natural tropical forests. Silvicultural treatment generates costs that can be seen as an investment. The expectation is that this investment will be less than the additional income provided by increased growth stimulated by silvicultural treatments. Our study confirms that growth alone is not sufficient for an economic assessment. Wood prices and harvesting costs at the end of the rotation period as well as the amount of costs for silvicultural treatments are indispensable for an economic evaluation. While the costs of silvicultural treatment are known at the time of the decision, future timber prices and harvest costs as well as the additional growth actually achieved are subject to uncertainty. These uncertainties have a decisive influence on the economic risk assessment.

Our study has implications for practice, research, and policy. Practitioners must have a good understanding of local growth conditions and long-term developments in the timber market. Especially important is the knowledge of whether silvicultural treatments have a long-term or only a short-term effect on their forest stands. If the latter is true, the silvicultural treatment will need to be critically examined not only from an economic point of view. Other aspects, such as sufficient liquidity, biodiversity, or occupational safety should also be considered. The scientific community must focus even more on the local growth conditions of tropical forests. Findings from even-aged, single species stands cannot be transferred to tropical forests, since their growth dynamics are much more complex. Policy is concerned with regulatory frameworks for the sustainable management of forests. The multi-functional sustainability of forest resources is just as important as the reconciliation of the diverse stakeholders' interests. Since silvicultural treatments always interfere with the remaining stand and can lead to forest degradation if applied incorrectly, they are only legitimate if they safeguard the ecosystem functions of the remaining stand and ensure the economic benefit. The findings of this study support the rational assessment of such profitability.

Funding

This work was funded by the German Federal Ministry of Food and Agriculture (BMEL) through the project "Ensuring long-term productivity of lowland tropical forests in the Caribbean" (GCP/SLC/205/GER). The main objective of this research project is to develop guidelines for the management of logged-over natural forests in the Caribbean. The project is being implemented as a regional government trust fund project conducted in partnership with the University of Hamburg and partner organizations in the participating countries.

Declaration of Competing Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Acknowledgments

This work was funded by the German Federal Ministry of Food and Agriculture (BMEL) through the project "Ensuring long-term productivity of lowland tropical forests in the Caribbean". We would like to express our gratitude to the Belize Forest Department, Belize, the Guyana Forestry Commission, Guyana, the Foundation for Forest Management and Production Control, Suriname, and the Forestry Division of Trinidad and Tobago, for contributing their valuable time and sharing their knowledge and insights to the realization of this research. We are thankful to Thomas Hausmann and Matthias Schwörer, BMEL, for their support and rewarding discussions. Philip Mundhenk deserves thanks for his patient assistance in the application of R.

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Impacts of Future Crop Tree Release Treatments on Forest Carbon as REDD+ Mitigation Benefits

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Received: 3 September 2020; Accepted: 15 October 2020; Published: date

Abstract: Sustainable forest management activities, such as future crop tree (FCT) release treatments, became part of the REDD+ strategy to avoid carbon emissions from forests. FCT release treatments are intended to achieve increased growth of FCTs by removing competitor trees. This initially leads to a reduction of the forest carbon pool and represents a carbon debt. We estimated that the time it takes for FCTs to offset the carbon debt through increased growth on experimental sites of 10 km^2 in Belize, Guyana, Suriname, and Trinidad and Tobago. We further investigated whether the costs of treatment can be compensated by the generated financial carbon benefits. An average of 2.3 FCT per hectare were released through the removal of an average of 3.3 competitors per hectare. This corresponds to an average above ground biomass (AGB) deficit of 2.3 Mg FCT^{-1}. Assuming a 30% increase in growth, the FCT would need on average 130 years to offset the carbon loss. For carbon prices from US$ 5 to 100 Mg CO_2e^{-1} an additional increment between 0.6 and 22.7 Mg $tree^{-1}$ would be required to cover the treatment costs of US$ 4.2 to 8.4 FCT^{-1}. Assuming a carbon price of US$ 10 Mg CO_2e^{-1}, the additional increment required would be between 5.8 and 11.4 Mg $tree^{-1}$, thus exceeding the biological growth potential of most individual trees. The release of FCTs does not ensure an increase in forest carbon stocks, and refinancing of treatment costs is problematic.

Keywords: forest biomass, forest carbon, mitigation, REDD+, sustainable forest management, silvicultural treatments

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1. Introduction

Forests are an important contributor to the global carbon cycle. They act both as a carbon storage and a carbon source. Worldwide, an estimated 662 Pg C are sequestered in forests [1], of which 306 to 324 Pg C are stored in tropical forests. Between 0.47 and 1.3 Pg C are annually sequestered by tropical forests [2].

In addition to their role as carbon storage [3–5], forests are also considered as a source of carbon [6–8]. Estimates presented by the FAO Forest Resources Assessment 2020 indicate that the total global forest carbon stock decreased from 668 Pg C in 1990 to 662 Pg C in 2020 [1]. Besides deforestation, a major cause of carbon emissions from forests is forest degradation due to poor management practices [7–9]. For example, Pearson et al. [7] reported 0.99 to 2.33 Mg C emissions per extracted cubic meter of harvested wood in tropical forests, with the main emissions coming from harvest damage to the remaining stand and from infrastructure development. In addition, according to Putz et al. [10] emissions of 100 Mg C per hectare are caused by conventional logging of tropical forests.

To reduce carbon emissions from forest degradation due to logging activities, the concept of reducing emissions from deforestation and forest degradation (REDD) was expanded to REDD+ to include sustainable forest management (SFM) practices. The positive effects of the implementation of SFM practices, such as reduced impact logging (RIL) or forest certification, on the carbon emissions of tropical forests has been confirmed by several studies [11–15]. For instance, Galante et al. [16]

reported that applying RIL can potentially reduce carbon emissions by approximately 1 to 7 Mg CO_2 ha^{-1} per year if conventional logging is taken as a baseline. West et al. [12] showed that the post-logging annual increment of above ground biomass was six times higher in RIL than in conventional logging (CL).

Silvicultural treatments are another SFM measure [17]. While the effect of silvicultural treatments on the commercial timber volume of tropical forests has been investigated in various studies [18–22], the effects of silvicultural practices on carbon dynamics in both commercial and non-commercial stands is not well understood.

One form of silvicultural treatment is future crop tree release (FCTR), which is an intermediate treatment that usually happens between cutting cycles. By removing neighboring trees from those individuals with future crop tree (FCT) features, the goal is to reduce crown area competition by increasing growing space for FCTs. By concentrating the available resources, the volume growth of the remaining trees is expected to increase over time [23–25]. FCTR can increase the average diameter increment of the remaining trees and the proportion of commercial timber by 37% in temperate forests [26–30]. Effects on the growth of released FCTs in tropical forests have been investigated, among others, by Wadsworth and Zweede [19], Villegas et al. [20], Peña-Claros et al. [21], Graaf et al. [31], David et al. [32], and Kuusipalo et al. [33,34]. Overall, FCTR can increase volume growth by 20 to 60% in tropical forests [19–21,34]. However, the main focus of these studies is on commercial volume, while carbon has not been investigated. The removal of competitors initially leads to a reduction of the carbon pool of the stand and represents a carbon loss. In this study we explore the time period needed to offset this carbon debt due to silvicultural treatments by the increased growth of FCTs in a set of tropical forest sites in Central and South America. Silvicultural treatments aim at a higher volume growth compared to untreated stands, but are associated with costs. From an economic point of view, the discounted investments in silvicultural treatments must be compensated by the financial value increase [35]. In the case of REDD, this additional financial gain is achieved through the generation of additional carbon credits. We investigate whether the costs of the treatment can be compensated by the carbon benefits that are generated.

2. Materials and Methods

2.1 Study Sites

The data for this study were collected at 10 experimental sites in four Central and South American countries: Belize, Guyana, Suriname, and Trinidad and Tobago (Figure 1). Four forest tenure types were covered by the sites: (1) a privately owned forest and community managed forest in Belize, (2) a community managed forest in Guyana, (3) a large scale concession managed forest in Suriname, and (4) a periodic block system managed forest in Trinidad. The sites have been studied in previous research that includes a detailed description of the four forest tenure types, the management practices and the forest inventory [36]. The selected countries have a tropical climate with dry and rainy seasons. In Suriname and Guyana there are two rainy and two dry seasons, with dry seasons lasting from February to April and from August to November [37]. Belize and Trinidad and Tobago have one dry season lasting from January to May [38]. The mean annual precipitation is 2041 mm (Belize), 2375 mm (Guyana), 2390 mm (Suriname) and 1605 mm (Trinidad) [39]. Three experimental sites each were selected in Belize and Guyana, and two sites were selected in Suriname and Trinidad. Except for one site in Suriname, all sites cover an area of 100 ha (1 x 1 km). A randomized block design was chosen as the experimental design. At each site, four blocks composed of 32 plots of 0.5 ha (50 x 100 m) were installed. To avoid influences from neighboring stands, the individual blocks and the entire 1 x 1 km area were surrounded by a buffer zone. Due to the orientation of the impact areas specified by the concessionaire, a modified block design was required for one site in Suriname. In this site the size of the area was set at 0.8 x 1.25 km with two blocks, each consisting of 70 sample plots with a size of 0.5 ha each. Similar to the other blocks, these two blocks were also surrounded by a buffer zone. Silvicultural treatments were applied on half of the area in all sites, i.e. in one of the two blocks at the Surinam site and in two of the four blocks at the three sites in the other countries. The remaining area was used as control for future analysis of treatment effects and not included in the current study.

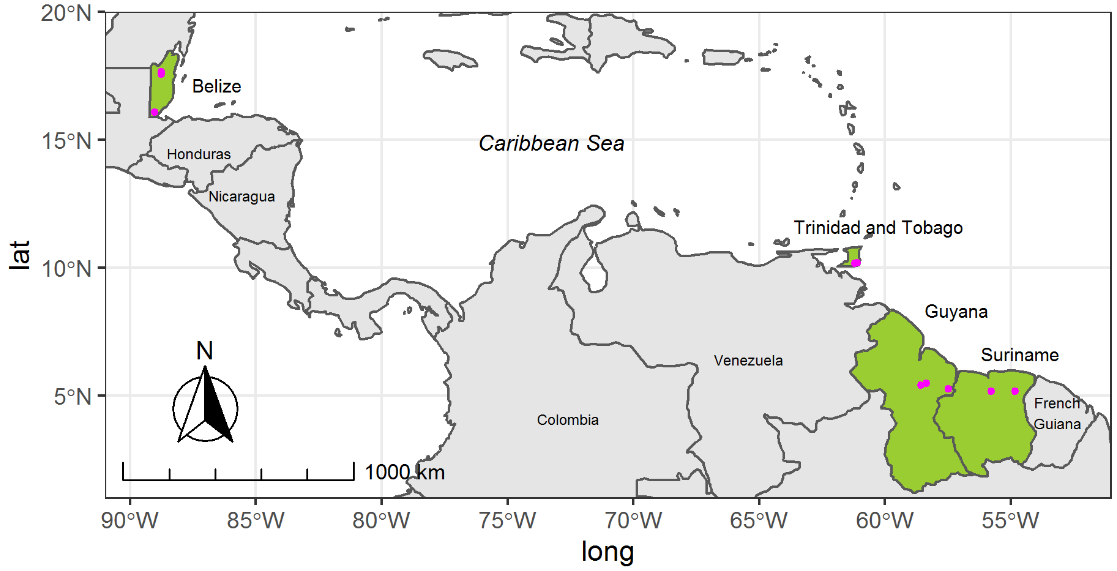

Figure 1. Project countries (green) and study sites (magenta).

2.2. Pre-harvest Iinventory

The planning of the silvicultural treatment was based on the information collected from a pre-harvest inventory [36] to characterize the overall structure of the forest stands. Log quality was assessed according to categories defined by the Food and Agriculture Organization of the United Nations [40]. The definition of social classes was based on the classification system cited by Nyland [41]. Furthermore, the tree species were recorded and classified into commercial and non-commercial species. All commercial tree species were assigned to four commercial species classes (CSC): (1) Class A comprises the species with the highest market value and the highest demand on the timber market, (2) Class B are the species with high acceptance on the timber market but with a lower market value, (3) Class C are marketable species but with low demand on the timber market, and (4) Class D are commercially exploited species but with a weaker marketability [36]. The classification of the species was based on local species classifications [42–46]. At each plot all trees with DBH ≥ 25 cm were measured and mapped. The threshold diameter was established in order to select an economically viable number of trees and to avoid including a high number of small trees that subsequently disappear from the stand due to natural mortality.

2.3. Silvicultural Treatment

The silvicultural treatment applied for this study is a future crop tree release (FCTR) treatment. FCTR is an intermediate silvicultural treatment designed to reduce competition for those individuals that are selected for future harvesting [47]. To be selected as a FCT, the trees were evaluated according to tree species, crown class, log grade, vitality, age, distribution and quantity (Table 1).

Table 1. Characteristics of future crop trees (FCTs) ([35], modified).

Criteria	Description
Species	The species of FCTs should achieve a high commercial value in the relevant timber markets. All project countries applied a species classification system (see above). FCTs should have been listed within either the highest or higher value species class since they are the future value drivers of the stand.

Crown class	Future crop trees must be able to compete successfully after the release. So they were selected from trees whose canopies are already located in the dominant, co-dominant or strong intermediate crown class.
Log grade	FCTs should have log grades requiring straight logs free of defects or visible diseases (log grade 1).
Vitality	FCTs should be of good health and vitality without low forks.
Age	Trees could qualify as FCTs at any age as long as they are expected to survive long enough to reach the next cutting cycle.
Distribution	FCTs should not all be concentrated in the "good quality" area of the forest stand. FCTs should have been evenly distributed across the forest stand but their relative quality may differ, e.g. the "good quality" area of the stand may have FCTs with 10 m log length while the "poorer quality" area may have FCTs with 5 m log length.
Quantity	There was no defined number of trees to be identified as FCTs.

Some criteria such as species, log grade and DBH varied between countries according to local requirements and national regulations. The liberation of the FCTs was done by the selective felling of their competing trees. For this purpose, the individual growing space of a tree is to be expanded by reducing the direct competition in the crown region. To achieve this, trees whose crowns exceed or touch those of the FCTs are identified and felled as so-called competing trees. Trees whose crowns did not touch the crowns of the FCTs or whose crowns were below the crowns of the FCTs were not selected as competitors in order to avoid large canopy openings.

On all plots, the felling crew consisted of the chainsaw operator and an assistant. Among other duties, the assistant had the task of preparing the felling process, e.g. cleaning the escape route from vegetation or cutting off lianas and the bark of trees to be felled. After the assistant had finished the work, the chainsaw operator started the felling process. One team worked per experimental area. Each experimental area was assigned a different crew. The working skills of the chainsaw operators were comparable, as all had many years of logging experience in the respective forest types.

2.4. Time Study

We used time study data to quantify the cost of silvicultural treatments as a basis for an economic evaluation. The division of the entire work process into its operational elements, referred to below as work elements (Table 2), is an essential prerequisite for a time study. The time required for the execution of each work element was recorded. However, only the work elements "searching", "preparation", "felling" and "maintenance" were used for the cost calculation. The time study data used for this study were also subject of a previous research, that includes a detailed analysis [35].

Table 2. Work elements for a time study during the FCT release ([35], modified).

No.	Work element	Definition	Category
1	Searching	searching and identification of the target tree, including walking to the next tree	Production
2	Preparation	felling preparation, e.g. liana cutting, clean up, determination of felling direction and rescue ways	
3	Felling	tree felling starts from the chainsaw engine start until the tree lies on the ground	
4	Maintenance	maintenance of the chainsaw, e.g. sharpen the chain, refuel	
5	Break	resting break	No production
6	Other	other activities which do not fit into the work elements 1–6	

The time study was conducted during the silvicultural work on the experimental sites from January to December 2018. To record the individual work elements, a camera was mounted on the helmet of the chainsaw operator. The video recordings were later used for the computer-aided evaluation of the time required for all work elements, using the open source software for event logging "BORIS" [48].

2.5. Descriptive statistics

The necessary working elements of silvicultural treatments depend on specific local conditions, the number of FCTs selected and the amount of working days per site. Therefore, the magnitude of each work element recorded differs between the sites, which results in an unbalanced experimental design of the time study. We used the statistical computing environment *R* [49] and the *R*-package lme4 [50] to perform a linear mixed effects analysis. With a mixed effects model we were able to incorporate nested random-effects terms in a linear predictor expression. We fitted the model with AGB per hectare and trees per hectare as the response variables and the countries as the fixed effects. As random effects, we added the working days nested within the experimental sites. One of the advantages of the mixed model approach is its robustness to unbalanced data [51]. The residuals of the model are normally distributed.

2.6. Treatment Costs

2.6.1. Costs of Labor

The minimum monthly wages (W_{mm}) of Latin America and the Caribbean were used as the basis for calculating the labor costs [35]. The monthly minimum wage, corrected by purchasing power parity, ranged from US$ 253 to 883 [52]. The monthly minimum wage was used as the basis for the assistant's salary. The salary of the chainsaw operator was taken from the assistant's salary multiplied by a factor of 1.5. The level of the non-wage labor costs (C_{nw}) was assumed to be 49.5% of the wage costs [52]. The labor costs per hour (C_{lh}) were calculated assuming 8 working hours per day (T_{whd}) and 20 working days per month (N_{wdm}) (Equation (1)).

$$C_{\text{lh}} = \frac{W_{\text{mm}}}{N_{\text{wdm}} \times T_{\text{whd}}} \times (1 + C_{\text{nw}}), \quad (1)$$

where
C_{lh} = hourly costs of labor (US$ hour^{-1})
C_{nw} = average non-wage labor costs amount (%)
N_{wdm} = working days per month
T_{whd} = working hours per day
W_{mm} = monthly minimum wage (US$ month^{-1})

2.6.2. Machinery Costs

The machine costs were calculated using the chain saw model "Stihl MS 880" equipped with a 90 cm long saw blade. This model and sword length is often used in logging operations in the Caribbean. The data from Whiteman [53,54], KWF et al. [55], and Richardson Saw and Lawnmower [56] served as the basis for the calculation of the operating hour costs (Table 3).

Table 3. Machinery data ([35], modified).

Chainsaw type	Stihl MS 880 + 90cm Bar
Purchase cost (C_p)	US$ 1900
Fuel consumption (K_{gas})	4 L hr^{-1} (3.7–4.3 L hr^{-1})
Oil/grease consumption (K_{oil})	0.99 L hr^{-1} (0.36–1.62 L hr^{-1})
Effective machine hours per year (T_{emh})	241
Expected life time (T_{el})	5 y

Prices for gasoline (P_{gas}) and oil (P_{oil}) were estimated at US$ 0.776 per litre of gasoline and US$ 20 per litre of chainsaw chain and bar oil. Machine cost per hour (C_{mh}) was calculated using Equation (2) and includes depreciation cost per hour (C_{dh}) which is derived from Equation (3). The effective machine time (T_{emh}) per FCT was derived from the work element "felling".

Machine cost per hour:

$$C_{\mathrm{mh}} = C_{\mathrm{dh}} + (K_{\mathrm{gas}} \times P_{\mathrm{gas}}) + (K_{\mathrm{oil}} \times P_{\mathrm{oil}}), \quad (2)$$

where

$$C_{dh} = \frac{C_{\mathrm{p}}}{T_{\mathrm{emh}} \times T_{\mathrm{el}}}, \quad (3)$$

C_{dh} = depreciation cost per hour (in US$)
C_{mh} = machine cost per hour (in US$)
C_{p} = purchase cost (in US$)
K_{gas} = fuel consumption (in litre hour^{-1})
K_{oil} = oil consumption (in litre hour^{-1})
P_{gas} = gasoline price (in US$ litre^{-1})
P_{oil} = oil price (in US$ litre^{-1})
T_{el} = expected life time (in years)
T_{emh} = effective machine hours per year (in hours)

2.7. Carbon Analysis

2.7.1. Above Ground Biomass Growth Simulation

The above ground biomass (AGB) was estimated using a biomass–diameter regression model for moist forests according to Chave et al. [57].

$$\mathrm{AGB} = \exp[-1.803 - 0.976E + 0.976\ln(\rho) + 2.673\ln(DBH) - 0.0299[\ln(DBH)]^2], \quad (4)$$

where
AGB = above ground biomass in kg,
DBH = diameter at breast height in cm,
E = environmental stress factor, and
ρ = wood specific density.

The wood specific density (ρ) was determined using the getWoodDensity function from the *R*-package BIOMASS [58]. The function assigns to each taxon a species- or genus-level average if at least one wood density value in the same genus as the focal taxon is available in the global wood density database [59]. For unidentified or unknown trees the stand-level mean wood density is assigned to the tree [58]. The environmental stress factor (*E*) was determined from a global gridded layer of *E* at 2.5 arc sec resolution [57] using the tree location coordinates.

Due to the lack of growth measurements at the experimental sites after previous interventions, we implemented growth rates from previous studies conducted in the region into a simple diameter growth approach to simulate the growth of the individual FCTs. Using the growth simulation, the time to reach initial AGB and the difference in biomass growth between released and non-released FCTs after this time can be estimated. The difference in biomass growth is a benchmark for the assessment of the required additional biomass growth (RAG_{agb}).

In logged tropical forests, several studies have determined an average diameter growth per tree between 0.8 and 5.1 mm year^{-1} [60–64]. After release treatment, growth increases of 20 to 60% of the released trees were observed in several studies [19–21,34]. For this study we use a fixed mean diameter growth rate of 2.7 mm year^{-1} for unreleased FCTs and a 30% increased growth rate of 3.51 mm year^{-1} for released FCTs.

2.7.2. Carbon Prices

In 2019, carbon prices ranged from US$ 1 to 127 Mg CO_2e^{-1} [65]. For our calculations we assumed prices (P_c) from US$ 5 to 100 Mg CO_2^{-1}.

2.7.3. Discount Rate

The costs and revenues of the treatment are incurred at different times. Future costs and returns are subjectively assessed differently than current costs and returns. Our analysis of the treatment was based on a variation of the net present value (NPV) method, which is a suitable method for assessing the profitability of an investment [66,67]. By using an annual discount rate, when applying the NPV method, costs and revenues can be calculated by discounting to the so-called (net) present value. The choice of the discount rate has a significant impact on the valuation of investments, especially for investments whose profitability is considered over a long time horizon. Revenues from investments in silvicultural treatments are usually only generated after relatively long periods of time, which is why the assumption of a high discount rate can lead to supposedly negative results in the profitability analysis [68,69]. We therefore chose a low discount rate (i) of 2.5% per annum for our calculations.

2.7.4. Required Additional Growth

For a FCT treatment to work properly in both economic and carbon balance terms, two conditions must be met: (1) the carbon losses caused by the treatment must at least be compensated for by the increased growth until harvest time; (2) the income generated by the additional growth until the time of harvest must at least cover the costs of the treatment.

The carbon analysis carried out here uses a recursive approach to determine the additional increases in biomass for which the treatment is financed assuming different carbon prices. By simulating the AGB growth of a released and a non-released FCT, we determined the point in time when the released FCTs reaches both, the AGB gain of the non-released FCT and in addition the AGB loss caused by felling competitors. The time (T_r) needed for the FCT to compensate for the biomass loss through the treatment was determined using the growth simulation presented above. A growth increase of 30% through the treatment was assumed. For the sake of simplicity, we assume that the entire C content of the felled competitors is released by decomposition processes.

If the net present value of an investment is greater than zero, the investment is considered profitable. In the recursive approach used here, the required additional biomass growth per tree (RAG_{agb}) is a function of the carbon price (P_c) and treatment costs (C_{tr}). The carbon price is discounted to the current point in time and, together with the AGB of the removed competitors, gives the additional biomass increment required when the NPV is zero (Equations (5) and (6)).

$$\mathrm{RAG_{agb}} = \frac{C_{\mathrm{tr}} \times (1+i)^{T_{\mathrm{r}}}}{P_{\mathrm{c}}} \times \frac{1}{F_{\mathrm{agb}} \times F_{\mathrm{c}}}, \quad (5)$$

where

$$C_{tr} = [(C_{lh} \times T_{ewh}) + (C_{mh} \times T_{emh})] \times N_c, \quad (6)$$

C_{lh} = hourly cost of labour (in US$)
C_{mh} = machinery cost per hour (in US$)
C_{tr} = treatment costs per FCT (in US$)
F_{agb} = AGB to C conversation factor = 0.5 [70–72]
F_c = C to CO_2e conversion factor = 44/12 = 3.67 [73]
i = annual discount rate (in %)
N_c = number of removed competitors per released FCT
P_c = carbon price (US$ Mg CO_2^{-1})

RAG_{agb} = additional AGB growth per tree within the recovery time (in Mg tree^{-1})
T_{emh} = effective machine time per tree (in hours)
T_{ewh} = effective working time per tree
T_r = recovery time (in years)

The revenues are based on the carbon prices at the end of the recovery time. The growth necessary to cover treatment costs was calculated for carbon prices between US$ 5 and 100 Mg CO_2^{-1} [65] and treatment costs of US$ 4.2 to 8.4 per tree, which are based on the results of the time study. The response area was next calculated; it represents the average AGB growth per FCT needed to cover the investment in silvicultural treatments depending on the discounted revenues and treatment costs, and to compensate for the carbon loss from the treatment.

3. Results

3.1. Effects of Selective Logging and FCTR Treatment

The mean of the total above ground biomass of all sites before the intervention was 186 Mg ha^{-1} (95 % confidence interval (CI): 96.2, 276), with the highest AGB estimated for Trinidad (Mean: 237 Mg ha^{-1}, CI: 141.7, 332) and the lowest for Belize (Mean: 124 Mg ha^{-1}, CI: 46.7, 202). The most frequently occurring commercial tree species at the experimental sites are *Bucida buceras* L., *Vitex gaumeri* Greenm., *Brosimum alicastrum* Sw. and *Swietenia macrophylla* King in Belize, *Catostemma commune* Sandwith, *Eperua falcata* Aubl., *Eperua grandiflora* (Aubl.) Benth. and *Humiria balsamifera* Aubl. in Guyana, *Mora excelsa* Benth., *Pentaclethra macroloba* (Willd.) Kuntze, *Clathrotropis brachypetala* (Tul.) Kleinh. and *Spondias mombin* L. in Trinidad, and *Dicorynia guianensis* Amshoff, *Qualea rosea* Aubl., *Tetragastris* sp. Gaertn. and *Casearia javitensis* Kunth in Suriname. During commercial harvesting, an average of 20.9 Mg ha^{-1} (CI: 1.34, 40.5) were removed by harvesting an average of 5.2 (CI: 2.5, 7.8) trees per hectare (N). The harvest intensity (Table 4) was highest in Suriname (AGB: 35.4 Mg ha^{-1}, N: 7.6 trees ha^{-1}) and lowest in Guyana (AGB: 7.5 Mg ha^{-1}, N: 3.7 trees ha^{-1}). For the treatment, an average of 2.3 (CI: 0.03, 4.6) FCTs per hectare with a mean total AGB of 2.8 Mg ha^{-1} (CI: 0, 6) or 1.2 Mg per individual FCT were released. The highest number of FCTs per hectare were released in Trinidad (N: 3.4 trees ha^{-1}) and the lowest number in Guyana (N: 0.4 trees ha^{-1}). An average of 3.3 (CI: 0, 6.6) competitors were removed per hectare, with maximum numbers in Suriname (N: 4.8 trees ha^{-1}) and minimum numbers in Guyana (N: 0.54 trees ha^{-1}). This corresponds to an average for all countries of 1.4 competitors per FCT. Per hectare, the average AGB of the removed competitors was 5.4 Mg ha^{-1} (CI: 0, 11.7), with highest AGB removed in Suriname (AGB: 10.3 Mg ha^{-1}) and lowest in Guyana (AGB: 0.9 Mg ha^{-1}). The AGB of the residual trees, i.e. all trees not identified as harvest trees, FCTs or competitors was on average 149 Mg ha^{-1} (CI: 85.9, 213).

Table 4. Estimates of the above ground biomass (AGB) and number of trees (N) during the application of selective logging and release of future crop trees (FCTs), in four study cases.

	AGB (Mg ha^{-1})				N (Trees ha^{-1})			
	Mean	SE	95% CI		Mean	SE	95% CI	
			lower	upper			lower	upper
Selective logging								
Belize	15.1	3.41	6.8	23.5	5.2	0.7	3.5	6.9
Guyana	7.5	3.41	0	15.8	3.7	0.7	2	5.4
Suriname	35.4	4.15	25.2	45.6	7.6	0.8	5.5	9.6
Trinidad	26.3	4.15	16.1	36.5	4.3	0.8	2.2	6.3
FCTs								
Belize	2.8	0.8	0.7	4.9	2.6	0.8	0.6	4.6
Guyana	0.3	0.8	0	2.4	0.4	0.8	0	2.4
Suriname	3.9	1	1.3	6.4	3.2	1	0.7	5.6

Trinidad	4.8	1	2.2	7.3	3.4	1	1	5.8
Competitors								
Belize	4.2	1.6	0.3	8.1	4.1	1.3	1	7.2
Guyana	0.9	1.6	0	4.8	0.5	1.3	0	3.6
Suriname	10.3	2	5.5	15.2	4.8	1.6	0.9	8.6
Trinidad	6.6	2	1.8	11.4	4.3	1.6	0.4	8.1
Residual trees								
Belize	97.8	23.6	40	156	82.2	12.3	52.2	112
Guyana	151.5	23.6	93.7	209	106.8	12.3	76.7	137
Suriname	181	28.9	110.2	252	105.5	15	68.8	142
Trinidad	176.3	28.9	105.5	247	87	15	50.3	124
Total stand								
Belize	124	31.8	46.7	202	97.5	14.6	61.9	133
Guyana	163	31.8	85.1	241	115.2	14.6	79.5	151
Suriname	235	38.9	140.2	331	124.8	17.8	81.1	169
Trinidad	237	38.9	141.7	332	117.9	17.9	74.2	162

SE = standard error; CI = confidence interval

3.2. Carbon Analysis

For each FCT released, the mean initial AGB, which was calculated as the sum of the AGBs of the FCT and the removed competitors, was between 2.7 and 4.5 Mg, with the lowest initial AGB in Belize and highest in Suriname. The removal of the competitors reduced the mean initial AGB between 1.6 Mg in Belize and 3.3 Mg in Suriname, and only the FCT's mean AGB which ranged from 0.7 Mg tree^{-1} in Guyana to 1.4 Mg tree^{-1} in Trinidad remained. Trees which were not released from competitors produce biomass, which can immediately be considered as C-pool gain. The released FCTs produce more biomass than non-released trees, but first have to compensate for the AGB of the removed competitors before a C-pool gain can be achieved.

The growth simulation showed that with an anticipated 30% increase in growth achieved by the release, the average recovery time (T_r) that an FCT would need to reach the AGB gain of a non-released FCT and additionally compensate for the biomass loss due to the removal of competitors would range from 112 years in Trinidad to 156 years in Suriname. Compared to a non-released tree, the AGB-loss resulting from the removal of competitors is decreasing over time due to the increased growth of the released FCT (red areas in Figure 2). At the end of the recovery time (T_r), a break-even point is reached where the AGB growth of a FCT compensates for the AGB losses of the removed competitors and the growth of a non-released tree. Only after this break-even point does the release of FCTs actually lead to a gain in AGB (green areas in Figure 2). At the break-even points, AGBs were estimated between 5.1 Mg tree^{-1} after 115 years in Belize and 9.7 Mg tree^{-1} after 156 years in Suriname for released and between 4.5 Mg tree^{-1} in Belize and 7.7 Mg tree^{-1} in Suriname for non-released trees.

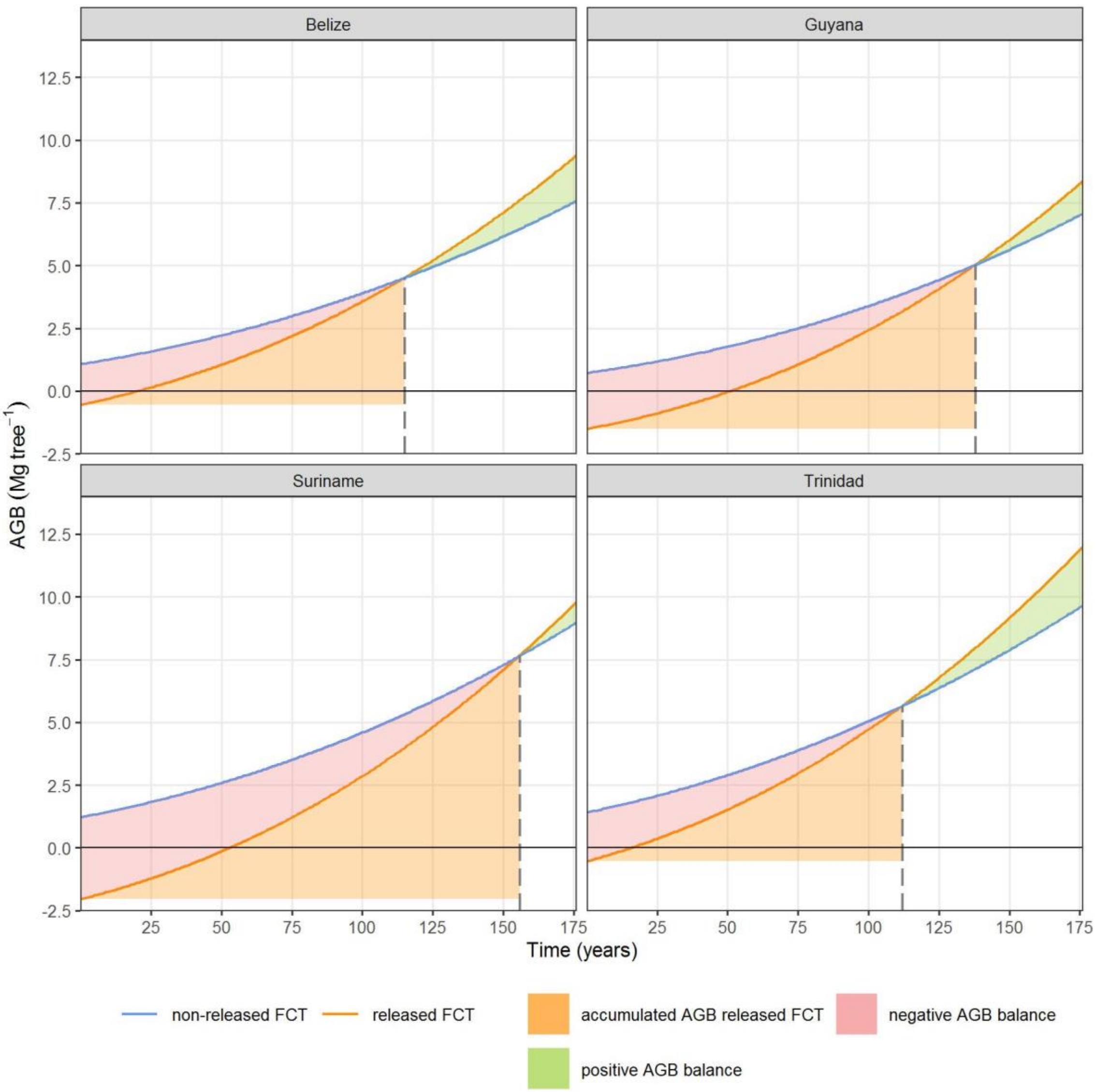

Figure 2. Above ground biomass (AGB) growth simulation by country of released and non-released FCTs.

Figure 3 shows the response area, which represents the financial break-even point of the required additional AGB growth as an average of all countries, as a function of treatment costs and revenues. The response area represents the point in time after an average of 130 years at which the biomass of a released FCT is equal to the sum of the AGB of a non-released tree and the AGB of felled competitors. Compared to a non-released tree the required additional AGB growth per FCT, RAG_{agb} is between 0.6 and 22.7 Mg $tree^{-1}$. With carbon prices of US$ 40 to 100 Mg CO_2^{-1}, the slope of the response surface indicating the required additional AGB growth is consistently flat. At carbon prices of less than US$ 40 Mg CO_2^{-1} the slope of the response area becomes steeper and reaches a maximum at carbon prices of less than US$ 20 Mg CO_2^{-1}.

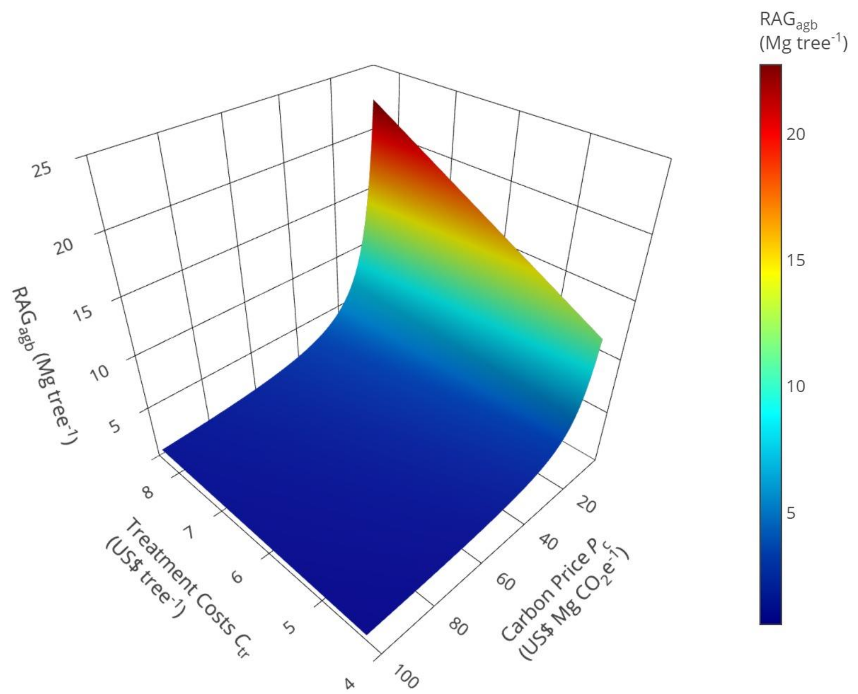

Figure 3. Required additional above ground biomass growth per tree (response–surface) after 130 years (recovery time). RAG_{agb} = required additional AGB growth per FCT, treatment costs C_{tr} = treatment costs per FCT, carbon price P_c = carbon price per Mg CO_2e^{-1}.

4. Discussion

By extending the REDD concept to REDD+, SFM has become part of the strategy for avoiding carbon emissions from forests. Since silvicultural treatments, such as FCTR, are often a critical component of SFM, we analyzed to what extent the loss of biomass due to the application of a liberation treatment can be compensated by the remaining stand and whether such treatment could be financed due to the possible increased biomass growth and the resulting carbon credits.

On average, about two FCTs per hectare were released under the treatment, with 1.4 competitors per FCT being felled. The removal of the competitors reduced the initial average biomass from 3.4 to 1.1 Mg per FCT released. Running a growth simulation, it was determined that the released FCT would need on average 130 years to compensate for the biomass loss of 2.3 Mg. This supports Rutishauser et al. [74], which found that the proportion of initial above-ground carbon stock lost at stand level best predicted the time to recover initial carbon stocks. However, the recovery times determined in our study are significantly higher than the harvesting cycles of 25 to 30 years which are common in Central and South America [75]. This confirms Zimmerman and Kormos [76], which propose an increase of the usual harvesting cycles by at least a factor of two. Under current harvesting cycles and harvesting intensities [75], which do not take site-specific conditions into account [77], the application of FCTR treatments may lead to carbon emissions. To avoid carbon emissions from FCTR treatments, felling cycles must be determined based on recovery times and site-specific conditions.

Even if a full balance on carbon stocks can be reached by extending the harvesting cycles, the question of economic viability must be addressed. REDD+ activities aim to achieve result-based payments. Therefore, the cost of releasing a FCT from competitors must be compared with the potential financial value of the C-gains achieved. The necessary increment gain is generated when the entire carbon loss from removed competitors is recovered and the additional C-gains correspond to the treatment costs. The revenues generated at the end of the recovery period are discounted carbon prices. The desired increment gain is thus the financial break-even point at which the expenditure for silvicultural treatments is exactly covered by the additional income generated by carbon credits. Only after the financial break-even point is reached, does the silvicultural treatment lead to a profit. We calculated the additional biomass growth that would be necessary to finance the treatment through the generation of carbon credits. We assumed treatment costs of US$ 4.2 to 8.4 per released FCT and carbon prices of US$ 5 to 100 per Mg CO_2e^{-1}. More than half of the carbon emissions covered by carbon price initiatives are priced at less than US$ 10 Mg CO_2e^{-1} [65]. At a carbon price of US$ 10 Mg CO_2e^{-1}, the required additional biomass growth after 130 years would be between 5.8 and 11.4 Mg per FCT, depending on treatment costs. Köhl et al. [78] investigated biomass growth of 61 individual trees with ages ranging from 84 to 255 y and stem diameters ranging from 36.7 to 99.2 cm at the time of harvest. The accumulated biomass per tree at the end of their lifetime ranged between 0.3 and 7.3 Mg and thus only partially achieves the required biomass growth rates determined by this study.

The additional biomass growth of released FCTs required to be in balance with a non-released tree is in the range of 5.8 to 11.4 Mg. Even after a period of 130 years, such an increase is not guaranteed, as it exceeds the biological growth potential of most individual trees. From a forest-growth perspective, there is a substantial risk that FCTR treatments investigated in this study do not lead to a carbon gain.

Due to the lack of long-term observations of the tropical forest populations, we chose the simplified approach of constant growth rates for the growth simulation. Mortality, recruitment, diameter distributions, neighborhood relations or the social position of the single tree were not considered. This limited modelling the variability of tree specific growth differences, which exists especially in tropical forests (e.g. Newbery and Ridsdale [79], Köhl et al. [78]).

5. Conclusions

The five activities of REDD+ that contribute to mitigation actions in the forest sector include the enhancement of forest carbon stocks and sustainable management of forests [80]. The release of FCTs per se does not guarantee a substantial increase in forest carbon stocks or sustainability in terms of AGB. Particularly critical is the fact that FCTR treatments within the regular intervention cycles of use of a few decades may lead to a C-loss compared to unreleased trees.

The approach with regard to the generation of payments must also be reviewed critically. One of the basic ideas of REDD+ is to reward activities that lead to the maintenance or enhancement of the forest C-pool through incentive payments. Our study shows that refinancing the costs of the treatments is a problem. The time period required for refinancing clearly exceed a reasonable economic planning horizon. Even significantly higher CO_2 prices do not really improve the economic appraisal. It should also be considered that incentive payments are subject to transaction costs, which further complicates the economic impact at the local level.

Our study reveals that no silvicultural treatments in which carbon losses are further increased are applied after selective logging takes place. The FCTR treatments investigated in this study are not recommended as an REDD+ activity, both from an economic point of view and with regard to the biological growth potential of trees. The avoidance of biomass losses during timber harvesting contributes substantially more to the conservation of the forest C-stock.

We present a first indication on the impact of FCTR treatments in tropical forests on carbon stocks and result-based payments. The variability of tree species compositions, stand structures and site factors in tropical forests shows that further studies on the long-term interactions between silvicultural measures and tree growth, natural regrowth after logging operations and differences in carbon recovery between different forest types and growth regions are urgently needed.

Author Contributions: Methodology, data curation, validation, formal analysis, investigation, writing—original draft preparation, visualization, S.G.; conceptualization, methodology, validation, writing—review and editing, supervision, project administration, funding acquisition, M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the German Federal Ministry of Food and Agriculture (BMEL) through the project "Ensuring long-term productivity of lowland tropical forests in the Caribbean" (GCP/SLC/205/GER). The main objective of this research project was to develop guidelines for the management of logged-over natural forests in the Caribbean. The project was implemented as a regional government trust fund project conducted in partnership with the University of Hamburg and partner organizations in the participating countries.

Acknowledgments: We would like to express our gratitude to Claus-Martin Eckelmann, Food and Agriculture Organization of the United Nations, Edilberto Romero and Ramon Pacheco, Programme for Belize, the Belize Forest Department, Quacy Bremner, Forestry Training Centre Inc., Guyana, the Guyana Forestry Commission, Maureen Playfair, Centre for Agricultural Research in Suriname, the Foundation for Forest Management and Production Control, Suriname, Mike P. Oatham, the University of the West Indies, Trinidad and Tobago, the Forestry Division of Trinidad and Tobago, for contributing their valuable time and sharing their knowledge and insights to the realization of this research. We are thankful to Thomas Hausmann and Matthias Schwörer, German Federal Ministry of Food and Agriculture, for their support and rewarding discussions. Philip Mundhenk deserves thanks for his patient assistance in the application of R. Three unknown reviewers carefully read the first draft of the manuscript and gave valuable hints for revision. We are deeply indebted to them for their contribution to improve the quality of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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