CAMILA THIEMY DIAS NUMAZAWA

**Material flow analysis and CO₂ footprint in lumber from managed
Brazilian Amazon rainforests**

São Paulo

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Brazilian Amazon rainforests**

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“Aos amores perdidos, aos amigos ausentes e aos velhos deuses”.
(Paulo Daniel Almada, *in memoriam*)

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A word after a word after a word is power.

(Margaret Atwood)

ABSTRACT

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Using wood produced under forest management in the Amazon has been proposed as a way of preserving the ecosystem, generating jobs and to aid in climate change mitigation by using wood products as carbon stock and through CO₂ uptake from the atmosphere during forest regrowth. However, the scarcity of research based on primary data of Amazonian lumber incorporated into construction can unknowingly lead to incorrect forest management and consequently forest destruction. Besides, it is necessary to verify the real environmental impacts. Two approaches were applied in this research to evaluate the wood product chain: material flow analysis and CO₂ footprint calculation of managed Amazonian lumber. The research quantified the resource efficiency and CO₂ footprint based on residue generation during the raw extraction in 5 forest plots in State of Pará, followed by the lumber production and the end-of-life phases, giving the CO₂ balance between the emissions from residue decomposition and the CO₂ uptake during forest regrowth, disregarding the energy consumption. Results indicated that the large quantities of logging residues are the main source of CO₂ emissions in the material flow from selective logging, ranging from 9% to 36% of the initial forest biomass, while timber logs represented between 4% and 11%. Logging residues ranged from 2.9 t t⁻¹ to 3.1 t t⁻¹ per tonne of log. Combined with an average sawmill lumber yield of 54%, wastage rate values increased to between 5.7 t t⁻¹ and 6.6 t t⁻¹, resulting in a CO₂ footprint of managed Amazonian lumber ranging between -6.6 tCO₂ t⁻¹ for reduced impact logging as carbon stock, to emissions of 6.1 tCO₂ t⁻¹ from cradle-to-gate for conventional logging. From cradle-to-grave the total CO₂ footprint of lumber is estimated to range from neutral to 7.5 tCO₂ t⁻¹. Resource efficiency ranged from 13% to 15%. In this study, only the forest under reduced impact logging was able to fully recover its initial aboveground biomass, showing that in most cases regulations in the New Forest Code for Amazon forest management may not ensure sustainable logging, leading to forest destruction. Policies need to be improved

and integrated with results from empirical research based on primary data to achieve sustainable exploitation of the Amazon forest.

Keywords: Material flow analysis. CO₂ footprint. Lumber. Amazonian forest management. Resource efficiency.

RESUMO

NUMAZAWA, Camila Thiemy Dias. **Análise do fluxo de massa e pegada de CO₂ da madeira nativa amazônica de manejo**. 2018. 166 f. Tese (Doutorado em Engenharia de Construção Civil e Urbana) – Escola Politécnica da Universidade de São Paulo, São Paulo, 2018.

O processo seletivo de utilização da madeira de manejo florestal na Amazônia tem sido proposto como forma de conservação e preservação do ecossistema, associada a geração de empregos e à mitigação de mudanças climáticas, pelo estoque de carbono dada a absorção de CO₂ da atmosfera durante o crescimento da floresta. No entanto, a limitação de pesquisas baseadas em dados primários sobre madeiras amazônicas incorporadas na construção civil pode levar, inconscientemente, ao manejo florestal incorreto e, conseqüentemente, à destruição da floresta no contexto original e de reais impactos ambientais provocadas por ações inadequadas. Duas abordagens foram aplicadas nesta pesquisa para avaliar a cadeia de produtos de madeira: análise de fluxo de material e cálculo da pegada de CO₂ da madeira manejada na Amazônia. A pesquisa analisou a eficiência dos recursos e a pegada de CO₂ com base na geração de resíduos durante a extração em 5 florestas no Estado do Pará, produção madeireira e o fim de vida, proporcionando o balanço de CO₂ entre as emissões da decomposição de resíduos e a absorção do CO₂ durante a recomposição florestal, desconsiderando a energia consumida. Os resultados indicaram que o expressivo volume de resíduos florestais é a principal fonte de emissões de CO₂ no fluxo de material proveniente da extração seletiva, variando de 9% a 36% da biomassa florestal inicial, enquanto os troncos de madeira representam entre 4% e 11%. Os resíduos de exploração florestal variaram de 2,9 a 3,1 t de resíduos por tonelada de tora. Combinado com um rendimento médio de madeira de serraria de 54%, os valores da taxa de desperdício aumentaram para entre 5,7 t e 6,6 t de resíduos por tonelada de tora e madeira serrada, resultando em uma pegada de CO₂ variando entre -6,6 tCO₂ t⁻¹ (exploração de impacto reduzido) considerado estoque de carbono e as emissões de 6,1 tCO₂ t⁻¹ do berço à porta. No final da vida útil, estima-se que a pegada total de CO₂ da madeira entre o berço e o túmulo é de neutra (exploração de impacto reduzido) a 7,5 tCO₂ t⁻¹, com uma eficiência de recursos variando de 13% a 15%. Neste estudo, apenas a floresta sob prática de extração de

impacto reduzido foi capaz de recuperar totalmente sua biomassa inicial acima do solo, mostrando que as regulamentações do Novo Código Florestal para o manejo da floresta amazônica pode não garantir a sustentabilidade de uso do recurso florestal para aquela exploração que não esteja alicerçada dentro desse contexto de conservação da floresta original. As políticas precisam ser melhoradas, integradas e dinâmicas com base em resultados derivados de pesquisas empíricas baseadas em dados primários garantindo a exploração sustentável na Amazônia.

Palavras chave: Análise de fluxo do material. Pegada de CO₂. Madeira serrada. Manejo florestal na Amazônia. Eficiência de recurso.

LIST OF GRAPHICS

Graphic 0.1 - Deforestation in the Brazilian Amazon from 2004-2016.....	2
Graphic 3.1 - Aboveground dry biomass (t ha^{-1}) on vertical data over 120 years' time horizontal data, considering extracting cycles of 30 years for L30 (a) and L15 (b). Conventional logging progressively loses biomass.....	64
Graphic 3.2 - Balance of CO_2 emissions. (a) Conventional Logging; (b) Reduced Impact Logging. CO_2 emissions are positives values.....	65
Graphic 4.1 – Total residue biomass distribution following its origins in each forest .	86
Graphic 4.2 – Resource efficiency results from the case studies in percentage of commercial timber logs, harvest tree residues and collateral damage.....	88

LIST OF FIGURES

Figure 1.1: Sustainable forest management (25-35 years cutting cycle)	12
Figure 1.2: Uses for timber products in construction	14
Figure 1.3: Life cycle assessment typical phases and variants	17
Figure 1.4: Combining MFA and Simplified LCA	18
Figure 1.5: Sankey diagram from Brazilian Amazon native lumber logged by conventional logging	19
Figure 2.1: Life cycle assessment phases in wood production.....	38
Figure 2.2: Net CO ₂ emissions from lumber (mitigating factors in blue, contributing factors in red)	47
Figure 3.1: Schematics of an extraction cycle for managed selective logging typical of the Amazon rainforest. Brown lines are residue converted in due time into CO ₂ . System Boundary is presented by the dark gray dashed line	59
Figure 4.1: Schematic of material flow of wooden building products from the Brazilian Amazon forest under selective logging. The System Boundary is presented by the area delimited by the dark blue dashed line.....	78
Figure 4.2: Illustration of the nomenclature adopted in this research. Harvested Tree Residues (HTR) comprising the tree Crown, Buttress Roots (BR) and Hollow Logs (HL). The commercial timber Logs (LOG) is the stem wood that was commercialized. The Collateral Damage (CD) is the biomass of other trees which were damaged around the logged stem during LOGs Felling or during transportation, including the residues from the Log Deck areas (LD), Primary Road (PRoad), Secondary Road (SRoad) constructions and Skid trails (Strails).	80
Figure 4.3: Sankey diagrams of biomass flow in F1, F2, and F3 before and after logging.	84
Figure 5.1: Simplified overview of the wood flow on lumber from managed forest in the Amazon forest and system boundaries from cradle-to-grave (dark blue dashed line) and cradle-to-gate (cyan dot line).....	100
Figure 5.2: Sankey diagrams from wood material flow in sawmill	106

LIST OF TABLES

Table 1.1 - Tree species for construction following physical properties and technical requirements	15
Table 2.1: Variance in carbon content in wood from literature.....	42
Table 2.2: Example of the tree species sample classification	44
Table 3.1 Biomass flow (dry basis) expressed as a percentage of total AGDB for the first cutting cycle for L30 and L15. For the L30 biomass never fully recovers.	63
Table 4.1: Raw data from each logging plots.	83
Table 4.2 Simplified biomass flow (dry basis) summary results expressed as a percentage of total AGDB and resource efficiency for F1, F2 and F3.....	84
Table 5.1: Basic data from material flow mass in 4 different forests.....	103
Table 5.2: Biomass balance and CO ₂ emissions from forest management in the Amazon forest after 30 years	104
Table 5.3: RE, WR and CO ₂ footprint per logs mass and volume in forestry operation	104
Table 5.4: Geometric volume of logs (V _{LOG}), lumber (V _{LUM}), residues (V _{RESIDUES}) and its mean (m ³).....	105
Table 5.5: Forest and sawmill biomass balance in metric tonne from cradle-to-gate	107
Table 5.6: Forest and sawmill CO ₂ balance in metric tonne of CO ₂ from cradle-to-gate	107
Table 5.7: Forest and sawmill results of resource efficiency and total CO ₂ emissions from cradle-to-grave.....	108

LIST OF ABBREVIATIONS AND SYMBOLS

AGDB	Aboveground Dry Biomass
AGSB	Aboveground Standing Biomass
bd	basic density
BR	Dry mass residues from Buttress Roots
C	Carbon
CD	Collateral Damage
CO₂	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
CONAMA	National Environmental Council
C_{LY}	Coefficient (%) of Lumber Yield
dbh	diameter at breast height
FM	Forest Management
FSC	Forest Stewardship Council
GV	Geometry Volume of logs
LI	Logging Intensity
HL	Dry mass residues from Hollow Logs
LR	Dry mass of total residues originating from the Logged Tree Felling
LTR	Logged Tree Residues
IBAMA	Brazilian Institute of the Environment and Renewable Natural Resource
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LD	Dry mass residues from Log Deck Area
LOG	Commercial timber Log
LR	Logging Residues
LR ≥ 10 cm	Logging Residues with diameter equal or superior to 10 cm

LR < 10 cm	Logging Residues with diameter above to 10 cm
MBD	Mean Basic Density
MFA	Material Flow Analysis
ppm	parts per million
Proad	Dry mass residues from Primary Road Area
RE	Resource efficiency
RF	Remaining Forest
RIL	Reduced Impact Logging
R_{transp}	Sum of dry mass of the residues related to transport of the harvested LOG
SEMAS	Para's Environmental and Sustainability Secretariat
Sroad	Dry mass from residues from Secondary Road Area
SFM	Sustainable Forest Management
SFMP	Sustainable Forest Management Plan
STrails	Dry mass from residues from Skid Trails Area
TA	Total forest Area managed
V_{LOG}	LOG volume in cubic meter conforms geometric solids shape
V_{LUM}	Lumber volume in cubic meter
W_{CO2}	Weight in metric tonnes of CO ₂
WR	Wastage rate

TABLE OF CONTENTS

INTRODUCTION.....	1
Purpose of the study	3
Reasons and Evidence	3
Summary.....	5
Reference.....	6
1 LITERATURE REVIEW	10
1.1 Aboveground dry biomass and carbon stock in the Amazon forest.....	10
1.2 Selective logging in the Amazon forest	10
1.3 Forest management in the Amazon forest	11
1.4 The current use of lumber in construction	13
1.5 Material flow analysis	17
1.6 Sankey diagram	19
1.7 CO ₂ emissions.....	20
1.8 Carbon stock	21
1.9 Reference.....	21
2 APPROACH AND METHODS	38
2.1 Literature review sources	39
2.2 Study areas and dataset	40
2.3 CO ₂ uptake by biomass and emissions from managed wood	40
2.4 Logging residues from forest management.....	43
2.5 Material flow analysis from Amazon wood: cradle-to-grave	45
2.6 Resource efficiency and wastage rate.....	46
2.7 Conversion of dry biomass and CO ₂ generation and carbon allocation	46
2.8 Net CO ₂ emissions.....	47
2.9 Reference.....	47

3	LOGGING RESIDUES AND CO₂ OF BRAZILIAN AMAZON TIMBER: TWO CASE STUDIES OF FOREST HARVESTING	55
3.1	Introduction	56
3.2	Materials and Methods	58
3.3	Results	62
3.4	Discussion.....	66
3.5	Reference.....	68
4	BRAZILIAN AMAZON LOGGING RESIDUES: MATERIAL FLOW ANALYSIS FOR THREE DIFFERENT FOREST MANAGEMENT OPERATIONS	74
4.1	Introduction	75
4.2	Materials and Methods	76
4.3	Results	82
4.4	Discussion.....	89
4.5	Reference.....	91
5	MATERIAL FLOW ANALYSIS FROM AMAZON MANAGED LUMBER: RESIDUES AND CO₂ FOOTPRINT	98
5.1	Introduction	99
5.2	Materials and Methods	101
5.3	Results	102
5.3.1	Forestry operation.....	102
5.3.2	Processing in sawmill	104
5.3.3	Mass balance and CO ₂ footprint: from cradle-to-gate.....	106
5.3.4	Cradle-to-grave.....	107
5.4	Discussion.....	108
5.5	Reference.....	109
	CONCLUSION	112
	Future work and research needs.....	117
	Appendix A – Statistics results of logs volume conversion in logging residues ≥ 10 cm	118
	Appendix B – Descriptive statistics equations and results of logs sample on sawmill data	119

INTRODUCTION

For several decades logging in the Amazon forest has been promoted to meet the timber demand in national and international markets. Forest logging intensified mainly because of increasing availability of highways and housing spaces, the expansion of the agricultural frontier and the depletion of forest reserves (BROWN; PEARCE, 1994; GEIST; LAMBIN, 2002; HOLMES et al., 2005; HOMMA, 2015; REPETTO, 1990; RUDEL; ROPER, 1996).

Although through most of human history the Amazon forest was primarily providing local livelihoods of forest dependent people, in the later part of the 20th century, the primary motivation for more than three-quarters of forest logging was for clearing areas for cattle-ranching, industrial activities and large-scale agriculture as forest conversion was financially more attractive (HOUGHTON et al., 2000; LAURANCE et al., 2001). Hence, unmanaged wood¹ in the Legal Amazon may be the risk catalyzing the first of a sequence of economic activities that, as a rule, leads to the destruction of the forest (CEDERBERG et al., 2011; MALHI et al., 2008; NEPSTAD et al., 2009).

However, from 2004 to 2016 there was a reversal in the trend of the previous decade as deforestation rates fell steadily, decreasing 71% as illustrated in Graphic 0.1 (INPE, 2018). The drop has been a result of more effective law enforcement, caused by the Copenhagen accord including an Amazon deforestation reduction target, and other factors such as new satellite-based monitoring systems, expansion of the size and number of protected areas, market interventions (soy and beef supply chains), restrictions on access to credit for action resulting in deforestation, macroeconomic trends, etc. (NEPSTAD et al., 2009, 2014).

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¹ According to the Forest Code (Law 4.771 / 65, modified by Law 7.803 / 89) and the New Forest Code (Law 12.651 / 12) unmanaged exploration in the Legal Amazon is illegal.

Graphic 0.1 - Deforestation in the Brazilian Amazon from 2004-2016

Source: adapted by the author from Inpe (2018)

It is worth pointing out that after August 2014, austerity measures introduced to reduce Brazil's budget deficit led to a 72% budget cut for forest protection and the control of deforestation, which contributed once again to the increased clearing of new areas, mostly for cattle pastures and farming space, and increased the deforestation rate for 3 years in a row (yellow arrow in Graphic 0.1) (MMA, 2018).

After fossil fuel combustion, global deforestation is the second largest anthropogenic source of carbon dioxide (CO₂) in the atmosphere ranging between 12% to 20% of the total emissions (HARRIS et al., 2012; CHATHAM HOUSE, 2010; WERF et al., 2009).

In Brazil, these emissions are caused by the destruction and burning of native vegetation, representing 70% of the national CO₂ emissions to the atmosphere in 2016 (SEEG/OC et al., 2018). Consequently, deforestation and degradation of the Amazon, as well as other tropical forests, implies the release of carbon into the atmosphere, significantly contributing to climate change.

The preservation of the Brazilian Amazon forest requires the development of economic alternatives for more than 25 million inhabitants of the region (IBGE, 2010. p.74), improving livelihood conditions especially for poor forest dwellers.

Commercial logging of native wood is an unquestionable source of income (IMAZON, 2010). It's able to generate market access and income for a significant portion of the Amazon's population and provides a way to satisfy physical and material needs, including those of the indigenous and traditional population (BARROS; VERÍSSIMO, 1996; BROWN; ROSENDO, 2000).

Sustainable forest management (SFM) in the Amazon forest has been proposed as a way of preserving and maintaining biodiversity, besides generating jobs, income and forest services (BARROS; UHL, 1995; GIBBS et al., 2007). Since most of the forest remains intact, forest management (FM) not only prevents global land use change and the use of natural resources for predatory purposes (BRASIL, 2004), but also preserves the terrestrial carbon stock (PUTZ et al., 2008).

Scientific and technological knowledge based on primary data that can be used to improve to the sustainability of forest enterprises remains scarce in most tropical countries due to the limited availability of surveys and diagnoses on the impact of activities (MURPHY et al., 2004). The first step towards gaining this knowledge would be to quantify the CO₂ footprint of timber products from managed Amazon forests using primary data.

Purpose of the study

To estimate the material flow and the carbon dioxide balance associated with the sawed wood from 5 managed forest plots of the Western Brazilian Amazon, based on its resource efficiency from raw material acquisition to the final disposal.

Reasons and Evidence

Previous studies support the assumption of non-conservation of the forest and/or the non-recovery of logged commercial tree species between the cutting cycles (DEKKER; DE GRAAF, 2003; GROGAN et al., 2008; HOLMES et al., 2002; HUTH; DITZER, 2001; JOHNS; BARRETO; UHL, 1996; MACPHERSON et al., 2010; PUTZ; DYKSTRA; HEINRICH, 2000; SCHULZE et al., 2008; SCHULZE; GROGAN; VIDAL, 2008; SIST et al., 1998; SIST; PICARD; GOURLET-FLEURY, 2003; ZARIN et al., 2007).

On one hand, Public Policies on logging tend to underestimate or neglect environmental impacts and their consequences, while on the other hand they overestimate sustainability of low impact forest management plans.

Therefore, it is necessary to examine how environmental indicators of forest management can influence the process of conservation, maintenance and renewal of the forest within cutting cycles, reinforcing sustainability and the value of inheritance and existence (FEARNSIDE, 2004), and to point towards the right direction for the mitigation of deforestation.

For instance, Amazon forest management indicators could create and help decision makers by giving practical guidance in creating awareness of the CO₂ footprint of lumber while at the same time providing a tool that can pressure industries to find new strategies in reducing product CO₂ footprint.

Several researchers (CHENG et al., 2010; LINDNER et al., 2010, 2011; PAROBK et al., 2014; ZHAO; WANG; ZHANG, 2008) have identified material flow assessment (MFA) as an important tool to validate these indicators. Applying MFA on forest management for timber production in the Amazon could demonstrate and quantify the relationship between raw materials, wood products for the construction industry and the generated residues.

Main methods of green building certification systems recommend the use of timber in construction, probably based on Northern Hemisphere forest harvesting data (ESPINOZA; BUEHLMANN; SMITH, 2012; GUSTAVSSON; SATHRE, 2010; RITTER; SKOG; BERGMAN, 2011; WANG; TOPPINEN; JUSLIN, 2014).

Throughout all life cycle phases of unmanaged timber in European forests (raw material extraction, material processing and manufacturing of timber products assembly, product use and end-of-life) the CO₂ emissions are estimated to be between 6.35 and 10.36 tCO_{2eq} t⁻¹, including all related energy consumption as input and the residues generated as output (WEIGHT, 2011).

In contrast, a study related to Brazilian Amazon native wood incorporated into construction and logged by conventional intensive and unplanned logging shows a different picture, with emission factors from cradle-to-gate between 7.5 tCO₂ t⁻¹ and

28.6 tCO₂ t⁻¹ of lumber, including fuel and energy consumption (CAMPOS, 2012), depending on forest conditions like logging intensity and forest density. These last values do not include the assembly, use and end-of-life product phases.

These emissions are much greater than in Europe and clearly justify thorough investigation into data related to forest management in the Amazon, for which, at the moment, reliable reference data and/or scenarios have not yet been established. Besides, it is necessary to verify in fact if FM is more environmentally friendly than conventional logging and how much.

Summary

All chapters provide data related to activities involving managed Brazilian Amazon lumber, proposing a framework for MFA of CO₂ emissions and uptake, as well as carbon stock related to wood as a construction material.

Chapter 1 is dedicated to the **literature review** with a brief overview of fundamentals such as the biomass properties of the Brazilian Amazon, carbon stock, the concept of forest management, the principal tree species and wood use in construction.

Chapter 2 describes the MFA **methods adopted in the thesis**. In addition, the different kinds of wood residue are explained and how to calculate CO₂ emissions and uptake defined in metric tonnes per hectare.

Chapter 3 comprises the first synthesized essay on the subject and the methodology. The chapter presents the **MFA of biomass and CO₂ emissions** from two managed forests. Despite both having the same aboveground dry biomass, the first one has a logging intensity of 30 m³ ha⁻¹ and the second of 15 m³ ha⁻¹. The biomass flows, CO₂ emissions and the forest regrowth were calculated.

Chapter 4 focuses on revealing the **total amount of residues produced under forest management, which so far have been considered hidden flows**. The chapter includes 3 different case studies and outlines the different sources of harvesting residues and the CO₂ emissions for each of these logging operations.

Chapter 5 presents case studies of **wood flow in sawmill operation**. This chapter includes the material flow and CO₂ footprint results of sawmill processing.

Chapter 6 presents the **highlights of the main chapters** and **conclusions, discussion and suggestions for further research**.

The thesis structure and citation style follow the **USP Structure Guidelines** (USP, 2016) and the **Associação Brasileira de Normas Técnicas** (ABNT – Association of Brazilian norms).

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1 LITERATURE REVIEW

The purpose of this chapter is to provide a brief understanding of the general terms and principal concept related to the thesis subject.

1.1 Aboveground dry biomass and carbon stock in the Amazon forest

Aboveground dry biomass (AGDB) estimation is critical to quantify MFA and CO₂ emissions from forest management. In the Amazon forest, the aboveground dry biomass is estimated to be between 200 to 562 t ha⁻¹ (with an uncertainty of 47,5%), it is calculated by multiplying the average of wood species' basic density and the volumetric data of live biomass found in literature and compared to remote sensed satellite images (CAMPOS, 2012; MTC, 2010; SAATCHI et al., 2007).

These average values may vary according to the species' average density, species' frequency, basal area of the stem, moisture present in the wood, topography, solar incidence, climate, age of trees, grade of forest conservation, among others (CHAMBERS et al., 2001; CUMMINGS et al., 2002; MALHI et al., 2006; NASCIMENTO; LAURANCE, 2002).

The CO₂ uptake and CO₂ emissions are of paramount importance to obtain a model comparable to other construction materials and it is directly connected with the biomass stock. In the South America forest scenario, it is estimated that the forests retain around 796 tCO₂ ha⁻¹ total, against 560 tCO₂ ha⁻¹ in North and Central America, 590 tCO₂ ha⁻¹ in Europe, 534 tCO₂ ha⁻¹ in Africa and 461 tCO₂ ha⁻¹ in Asia (FAO, 2010).

1.2 Selective logging in the Amazon forest

Forest logging in the Amazon, whether managed or not, is done differently than harvesting in temperate forests with coniferous tree species. Despite the high value of AGDB with up to 562 t ha⁻¹ in the Amazon forest (CAMPOS, 2012; MTC, 2010; SAATCHI et al., 2007) against the maximum value of 262 t ha⁻¹ from temperate forests (KUPLICH, 2003), unlike with coniferous forests only some species of trees are commercial, making it necessary to use selective logging.

More than 90% of the legal timber forest products in Brazil come from selective cutting in the Amazon (PERES et al., 2010). This activity is considered as one of the land uses

that is less damaging to the biome, which should ensure that forest resources are preserved to meet the needs of future generations (GIBSON et al., 2011; KUDAVIDANAGE et al., 2012).

However, each main commercial species with a diameter at the breast height (dbh) equal or greater than 50 cm is sited in a low density distribution of less than or equal to 1 tree per hectare (GROGAN et al., 2008; RANKIN-DE-MÉRONA et al., 1992; SCHULZE et al., 2008; SIST et al., 2003). Hence, forest management produces skid trails and access roads, log decks, but also canopy disturbance implying more destruction of biomass than just the commercialized timber log and, consequently, a greater CO₂ emission rate embedded in the final product.

1.3 Forest management in the Amazon forest

In the Legal Amazon² there are only two legal ways to exploit timber resources. The first one is by an elaborated Sustainable Forest Management Plan which entails the management of forests to maintain their full range of environmental, social and economic value. Secondly, with authorization to deforest or suppress vegetation, which may be granted for research and for mining³, for hydroelectric construction⁴ etc.

The Sustainable Forest Management phases are defined in Figure 1.1, including pre-logging, logging and post-logging activities (LAURANCE et al., 2001; FREITAS, 2006 SABOGAL et al., 2009; UHL et al., 1997).

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² Brazilian Government official designation that encompasses 9 states: Acre, Amapá, Amazonas, Maranhão, Mato Grosso, Pará, Rondônia, Roraima and Tocantins (Federal Law N°5.173/1966, Article 2).

³ Normative Instruction N°152/2007 by the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) .

⁴ Normative Instructions N°6/2009 and N°06/2006 (IBAMA and Ministry of the Environmental); Federal Consent Decree N°975/2006.

Figure 1.1: Sustainable forest management (25-35 years cutting cycle)

PRE-LOGGING ACTIVITIES		LOGGING ACTIVITIES	POST-LOGGING	
Completion of studies on flora, fauna, hydrography, landscape, social and economic		Pre-logging liana cutting (≈ 1 year before the operation)	Monitoring of forest regeneration	Silvicultural treatments: Carrying out treatments that encourage the development of the forest already thinking about the next cutting cycle
100% Forest Inventory and Forest census (as identification and tagging of trees interest)		Infrastructure planning: definition of the road tracings (grid of 250 x 250 m) and log decks (25 x 25 m), and construction		
Setting boundaries of forest management areas and at Annual Production Unity (Grid 50 x 50 m)		Harvesting (felling of selected trees and tagging of stumps)	Assessment of damage	
Mapping	Opening of direction trails	Skidding	Survey of species	Measurement of permanent sample plots
Definition of permanent sample Plot	Approval by relevant institution (SEMAS/IBAMA)	Bucking	Analysis of tree growth	
		Cutting and removal of logging residues		

Source: adapted by the author from Freitas (2006)

According to the Brazilian New Forest Code regulations⁵ under 25-35 year cutting cycles the Sustainable Forest Management Plan must respect a minimum tree diameter of 50 cm dbh for harvesting and the two categories of maximum cutting intensities with up to 30 m³ ha⁻¹ as full logging intensity (LI) using forestry machines and 10 m³ ha⁻¹ as low intensity carried out by small scale farmers without using machines (ROMERO et al., 2015). These parameters were established focused on benefits, respecting the ecosystem sustaining mechanisms and considering differences of tree species, in dioecious and monoecious trees, and biodiversity (BRASIL, 2006).

Reduced Impact Logging (RIL) is considered the most favorable logging technique (LI average around 15 m³ ha⁻¹) due the intensively planned and carefully controlled implementation of the timber logging operation to minimize the environmental impact on forest stands and soils (ITTO, 2018).

This activity provides better planned road openings, log decks and skid trails; the cutting of vines and lianas around the commercial tree that will be logged, in order to improve the safety of the employees and to eliminate probable damages to

⁵ Brazilian legislation at Federal Level: The Brazilian Forest Code Law #4,771/65 #12,651/12 and corresponding normative instructions; Approval of the Management Plan by IBAMA; Federal Law nº 9,605, Article 17, in February 12th, 1998; Federal Decree nº 5,975, in November 30th, 2006 and Federal Decree nº 6.514, in July 22th, 2008; AUTEF for forest harvesting; Ruled nationwide by Resolution 406/2009 of the National Environmental Council (Conama).

surrounding trees; the planned directional cut to minimize damage to future crops and reducing residue generated during logging (PEREIRA JR. et al., 2002; PUTZ et al., 2008b; VIDAL et al., 1997).

However, even under these conditions, there is a large gap because even if the biomass is able to recover after 35 years, these estimates do not take into account the logging impacts on timber species populations or population recovery rates (SCHULZE et al., 2008), i.e. *Cedrela odorata* L. or *Handroanthus* populations (BECERRA-MONTALVO; POLLITO, 2013; SCHULZE; GROGAN; VIDAL, 2008).

1.4 The current use of lumber in construction

Civil construction is the main consumption sector for Amazon wood (CAMPOS, 2012). The industrial yield in sawmill ranges from 35 to 60% in hardwoods, and from 55% to 65% coniferous wood (CAMPOS, 2012; GOMIDE, 1974; NUMAZAWA et al., 2017; ROCHA, 2002), which leads to a low resource efficiency due to an unavoidable decrease in final product quantity and a large generation of residues.

The yield depends on factors such as sawmill processes, technology and equipment, wood density and moisture, physical and mechanical properties of the species, trunk geometry and conicity, final dimensions of sawn products, thickness, width and tension of the cutting blade equipment and workmanship (CAMPOS, 2012; OLIVEIRA et al., 2003; ROCHA, 2002).

In 2009, 79% of the 5.8 million cubic meters of processed native wood from the Legal Amazon was destined for the national market. Of this percentage, 72% consisted of sawn wood, 15% went towards the production of doors, windows, floors etc., and only 13% was for laminated and plywood (IMAZON, 2010; ZENID et al., 2009). Consequently, the larger the generation of waste, the greater the forest suppression.

The most common uses of native wood are in roofing structures, forms and scaffolds for concrete, linings, floor covering, frames, structures including glued laminated timber, piles, bridges, foundation piles, prefabricated houses, etc. (NUMAZAWA, 2009; SOBRAL et al., 2002; ZENID, 2009), as can be seen in the following figure.

Figure 1.2: Uses for timber products in construction

Source: adapted by author. a: roof structure (author, 2008); b: concrete formwork (Apawood, 2018); c: timber scaffolds (Flirck, 2018); d: UBC Brock Commons Building, World's tallest wood building since 2017 18 floors (Actonostry, 2018); e: wooden structure (Szücs, 2008); f: Allgäu open-air theater, Altusried (Wege Zum Holz, 1999); g: wood pile (Barrier, 2018); h: Leonardo da Vinci Golden Horn bridge (Forbes, 2018); i: UBC Brock Commons Building framing (Science, 2018); j: wood plans (EDF, 2018).

Tree species must be chosen according to the need of the project and its risk class. In Table 1.1 identifies the most harvested species for construction based on the components and technical requirements for good performance and in acceptable dimensions, forms and defects (ABNT, 1996; NAHUZ (COORD.), 2013; NUMAZAWA, 2009). It is worth mentioning that information on the use of applied constructive elements is based on research in the national market by consultation of several native wood dealers, architecture offices using the material and the author's experience.

Table 1.1 - Tree species for construction following physical properties and technical requirements

Common name of tree species Botanical (Scientific) name	Wood Sample	Basic density (t m ⁻³)	Carbon stock (tC m ⁻³)	Applying		Durability			Wood as a building material								
				for na external area	for na internal area	Longstanding	Temporary	Shortstanding	Foundation	Column and beam	Roof framing	Bridge (submerged logs)	Wall framing, Framing	Ceiling	Flooring	Plywood laminate, etc.	Wood forms for concrete
Acapú		.79	0.4		•	•			•	•	•	•			•		
<i>Vouacapoua americana</i> , Aubl.																	
Amapá		.53	0.3		•		•							•			•
<i>Brosimum parinarioides</i> , Ducke																	
Angelim Vermelho		.83	0.4		•	•				•	•		•	•	•	•	
<i>Dinizia petreum</i> , Ducke																	
Angelim Pedra		.83	0.4		•	•				•	•		•	•	•	•	
<i>Dinizia excelsa</i> , Ducke																	
Breu		.50	0.2		•		•						•			•	•
<i>Trattinnickia cf. burseraefolia</i> Mart.																	
Cumarú		.91	0.4	•	•	•			•	•	•		•		•		
<i>Dipteryx odorata</i> Aubl. Wild.																	
Cupiúba		.71	0.3		•	•							•	•			
<i>Goupia glabra</i> , Aubl.																	
Faveira		.44	0.2		•			•						•		•	•
<i>Parkia paraensis</i> , Ducke																	
Guarapa		.67	0.3		•		•						•	•	•	•	•
<i>Apuleia leiocarpa</i> (Vogel) J.F. Macbr																	
Freijó		.75	0.4	•	•	•					•		•	•			
<i>Cordia goeldiana</i> . Huber.																	
Jarana		.79	0.4		•	•				•	•		•				
<i>Lecythis lurida</i> Miers S.A.Mori																	
Jatobá		.76	0.4	•	•	•			•	•	•	•	•		•		
<i>Hymenaea courbaril</i> , L.																	

Common name of tree species Botanical (Scientific) name	Wood Sample	Basic density (t m ⁻³)	Carbon stock (tC m ⁻³)	Applying		Durability		Wood as a building material											
				for na external area	for na internal area	Longstanding	Temporary	Shortstanding	Foundation	Column and beam	Roof framing	Bridge (submerged logs)	Wall framing, Framing	Ceiling	Flooring	Plywood laminate, etc.	Wood forms for concrete		
Louro		.55	0.3		•		•							•			•	•	
<i>Nectrandra rubra</i> , Mez																			
Massaranduba																			
Maçaranduba (pt)		.83	0.4	•	•	•			•	•	•	•				•			
<i>Manilkara huberi</i> , Ducke																			
A. Chevalier																			
Marupá		.37	0.2		•			•						•		•	•	•	
<i>Simarouba amara</i> , Aubl.																			
Matamatá																			
<i>Eschweilera grandiflora</i> (Aubl.)		.76	0.4		•	•					•		•	•					
Sandwith																			
Muiracatiara																			
<i>Astronium lecontei</i> , Ducke		.79	0.4	•	•	•							•	•	•				
Pau amarelo																			
<i>Euxylophora paraensis</i> , Huber.																			
Pau roxo		.69	0.3		•	•							•				•		
<i>Peltogyne lecontei</i> , Ducke																			
Piquiá																			
<i>Caryocar villosum</i> , Aubl Pers		.63	0.3		•		•				•	•							
Sucupira																			
<i>Bowdichia nitida</i> Spruce ex Benth																			
Tachi		.85	0.4		•	•			•	•	•	•				•			
<i>Tachigalia myrmecophyla</i> , Ducke																			
Tatajuba																			
<i>Bagassa guianensis</i> , Aubl.		.70	0.3		•	•								•			•		
Tauari																			
<i>Couratari guianensis</i> , Aubl																			
Timborana		.50	0.2		•		•							•	•		•	•	
<i>Piptadenia suaveolens</i> , Miq																			

Source: author's database (2016)

1.5 Material flow analysis

Each building material has several potential environmental impacts, including timber. Although it is considered renewable, biodegradable and carbon stock, wood generates impacts associated with transportation, processing, use and disposal that need to be quantified (JOHN, 2010. p.130).

Life cycle assessment (LCA) of a product it is a methodology (ISO 14.044:2006) that aims to collect and quantify environmental, economic and social damages, including the design phase (JACOVELLI; FIGUEIREDO, 2003), presenting all consumed resources and emissions generated in each phase of life (ASHBY, 2009). In Figure 1 the typical phases and variants of the LCA are shown.

Figure 1.3: Life cycle assessment typical phases and variants

Source: adapted by author from ISO 14040 (2018)

However, LCA implementation is expensive and complex, requiring large-scale measurements of apparatus-based variables and highly specialized human resources,

while various regions of study, mainly in the Amazon forest are not readily accessible (CBCS, 2012).

Simplified LCA has been extensively applied in building materials and technologies and incorporated into environmental product declarations (PACCA, 2012). It is based on the sum of all flows and allows us to estimate the contribution to the increase of environmental problems such as climate change, pollution, etc. (BRINGEZU; MORIGUCHI, 2002; CHILDERHOUSE; TOWILL, 2003).

One of the LCA analysis tools, the material flow analysis (MFA), is used on industrial ecology to evaluate the throughput of process chains comprised of extraction or harvest, manufacturing, consumption, recycling and disposal of materials based on accounts in physical units and quantifying the inputs and outputs of those processes (BRINGEZU; MORIGUCHI, 2002).

Hence, combining material flow analysis and simplified life cycle assessment (Figure 1.4) is proposed as an evaluation method where MFA is used for the qualitative and quantitative assessment of material flows, while additionally LCA is performed for the environmental assessment through the quantification of environmental effects (BINDER et al., 2004; ROCHAT et al., 2013).

Figure 1.4: Combining MFA and Simplified LCA

Source: adapted by author from ISO 14040 (2018)

1.6 Sankey diagram

The Sankey diagram has mainly been used in material flow analysis and life cycle assessment as a tool to present energy and material flow by showing quantitative information. It has also reportedly been useful in demonstrating the efficiency of the material production (CHRISTOFOROU et al., 2016; SCHMIDT, 2008; SHUAIB et al., 2015).

The larger the width of a line (links), the larger the energy or the material flow. The lines show flows from one node (source or process) to another node, presenting production systems or value chain results clearly, which cannot be achieved using standard tables, bar charts or pie charts.

For instance, Campos (2012) used the Sankey diagram to show lumber flow (Figure 1.5). In this case, the diagram is oriented left-right (inputs-processes-outputs) showing wood biomass flow from conventional logging in the Amazon forest. The width or thickness of the line indicated the values that represent the flow and arrows show the relation between the processes (SHUAIB et al., 2015).

Figure 1.5: Sankey diagram from Brazilian Amazon native lumber logged by conventional logging

Source: adapted by author from Campos (2012. p. 120)

1.7 CO₂ emissions

Carbon dioxide (CO₂) is one of the most important greenhouse gasses emitted by human activities. Its concentration in the atmosphere has significantly increased after the pre-industrial era, reaching an average concentration of 408 ppm in 2018 (NASA, 2018).

CO₂ emissions can be divided in two main categories: the total net anthropogenic release due to land change use by (tropical) deforestation, making up almost 14% of the emissions, and the global emissions of gas, caused mainly by the burning of fossil fuels, accounting for the remaining 86% of emissions (FEARNSIDE, 2003; IPCC, 2015).

In Brazil, a study based on simplified LCA focused on material flow to calculate CO₂ emissions from conventional lumber logging in the Amazon estimated it was responsible for a range between 3.5% and 13.1% of the total CO₂ released in 2005 in Brazil (CAMPOS, 2012). These values are fundamental for professionals and consumers as a reference for management and to raise awareness of sustainability in civil construction.

It is known that wood residues are composed of branches, treetops, furs, barks, roots, damaged logs and sawdust, among others. However, its quantification in Brazil is still not precise and its use is only incipient. It is believed that 60% of wood residues abandoned in the forest could have a potential use. Besides, about 50% of the wood volume of logs processed by sawmills is discarded at the end of production (NOLASCO; VIANA, 2004) while part of these residues could have a use, i.e. as bioenergy.

Inadequate disposal of waste can cause several problems, among them social ones i.e. damaging human health, environmental ones, as a pollution source, and economic ones motivated by companies' lack of interest in their use, believing there is no profitability (NASCIMENTO; DUTRA; NUMAZAWA, 2006).

In an unplanned area under conventional logging in Paragominas in Pará State, for each commercial tree logged there was a range between 27 to 29 other trees with ddb ≥ 10 cm that were damaged (JOHNS; BARRETO; UHL, 1996), representing ≈ 1.2 m³

of damaged timber for each cubic meter of commercial log logged, which justifies CO₂ emissions research into the subject.

Thus, it is observed that the production of wood residues is inevitable and of great inconvenience to most forest exploiters and is directly related to the technology and the type of forest management technique applied. Moreover, the final disposal could be done in a more sustainable and profitable way, through its use for energy generation, i.e. charcoal or pellets production.

1.8 Carbon stock

Timber products are considered as carbon stock. On average, between 48% and 50% of its dry weight is composed of carbon belonging to the CO₂ that was sequestered from the atmosphere by photosynthesis during the growth of the tree (PACHECO-TORGAL et al., 2014) and stored in the product.

For the IPCC, the carbon stock during the lifespan of a product may vary according to how the wood was treated and used (IPCC, 2014). Taken into account should be the natural durability, the applied protection treatments, the water flow, the necessary ventilation in the environment where the products is found, respect for physical properties, maximum safety load limits and, finally, the minimum dimensions of parts (ABNT, 1996).

During the complete life cycle of a timber product used in buildings the carbon remains stored and does not cause any changes in the atmospheric carbon balance. For that reason, a longer lifespan of timber products increases the amount of carbon stock by extending the amount of time before, eventually, the building products reach their end-of-life and it is assumed that 100% of this carbon stock is oxidized and released back into the atmosphere as CO₂.

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2 APPROACH AND METHODS

The main objective of this study was to estimate the material flow analysis and CO₂ footprint of the Brazilian native wood used in civil construction based on the resource efficiency. To achieve this objective, we focused on a systematic view from an environmental perspective by applying material flow analysis and estimating the CO₂ balance and emissions from residues. We detailed the value chain inventory including the raw material extraction, the production, the installation, use and maintenance until the end of life (Figure 2.1). The simplified life cycle assessment scope was defined from the raw material extraction to the final disposal of the material (cradle-to-grave).

Figure 2.1: Life cycle assessment phases in wood production

Source: adapted by author from ISO 14040 (2016)

The most relevant variables considered during the LCA were the forest biomass concentration, the logging intensity and logging and sawmill residue generation ratio. Scenarios were based on examples by Campos (2012) and Punhagui (2014) already applying the calculation of CO₂ emissions, which incorporated typical scenarios for the studied forests and parameters in minimum, maximum and median values for simplified LCA on both non-managed and planted forests (eucalyptus forest) providing Brazilian lumber.

Regarding the net CO₂ emission calculation based on the IPCC (2007) reports, the carbon stock in wood products is considered a mitigating factor and as such has a positive influence on CO₂ emissions, in contrary carbon into residual forest biomass and / or industrial production process released into the atmosphere.

Energy consumption during logging, transportation and sawing processes contributing to the carbon footprint of lumber was not included in this research considering that the system boundary of the thesis only comprises the material flow and emissions from residues. However, emissions related to energy consumption can be found in literature (CAMPOS, 2012; CAMPOS; PUNHAGUI; JOHN, 2011). The average amount represents a range between:

- Logs harvesting and transportation: from 0.02 tCO₂ t⁻¹ to 0.12 tCO₂ t⁻¹;
- Lumber transportation admitting 1,956 km distance from sawmill and consumers: from 0.03 tCO₂ t⁻¹ to 0.12 tCO₂ t⁻¹;

As mentioned earlier, the lumber material and residue flow emissions found in literature represent from 7.5 tCO₂ t⁻¹ to 28.4 tCO₂ t⁻¹. The energy consumed during logging, transportation and sawing process represented only 1% of the total CO₂ emissions (CAMPOS, 2012).

Biomass residues were not considered to be used and/or recycled in this research. However, an ongoing study⁶ is considering these possibilities by researching the benefits of charcoal coproduction.

2.1 Literature review sources

As a theoretical basis for documental and bibliographical research, both printed and digital sources were used in this research. In the final part of each chapter references related to the subject are presented.

References have been taken from a variety of databases and sources, i.e. articles from journals, national and international dissertations and theses, as well as book chapters, satellite images, maps, etc. Scientific breakthroughs as UNEP publications, IPCC and IBGE reports were applied to complement.

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⁶ Working in progress "Numazawa, C. T. D.; Numazawa, S.; Pacca, S. A.; John, V. M. Brazilian Amazon logging residues: material flow analysis from 3 different forests management operations". Article manuscript to be submitted for publication March 2019.

Portals such as Scopus Database and Web of Science were used to uncover a wide range of journals and conference proceedings, ranked by number of citations and impact factor found using main keywords in the subject area.

Through reference sources it was possible to create scenarios, select and refine the possible indicators of the impact categories, as well as to build a database of the impacts of the managed wood extraction in the Amazon forest using data available in the literature.

2.2 Study areas and dataset

This research uses primary data on the total amount of logs extracted and logging residues (≥ 10 cm) generated by five managed forests in the Western Amazon during one cutting cycle. The sites are located in Baião (1), Portel (1), and Paragominas (3), all municipalities in the Pará State. The areas were logged by 3 different companies in the Western Amazon and identified by letter codes to protect their anonymity.

The forest management plans followed the Brazilian Forest Code legislation (Federal Law nº 12,651/2012) and were analyzed and approved by Pará's Environmental and Sustainability Secretariat. The forest plots were logged in Baião 2007, in Portel 2007 and in Paragominas 2002, 2005 and 2016. Total area of managed forest was 11,506 ha, with an extraction of 331,201.00 m³ (geometric volume) of logs with more than 50 different species and with an average basic density of 0.67 t m⁻³.

The aboveground standing biomass was estimated according to Saatchi's satellite data (SAATCHI et al., 2007) and verified in the study areas. It is known that the value of aboveground dry biomass represents 60.28% of total standing biomass (HIGUCHI et al., 1998), therefore, values ranging from 166 to 226 t ha⁻¹ were found (with an uncertainty of 15%), with an average of 196 t ha⁻¹. These data were validated by forest engineers who worked during management planning, based on their direct observations in the field and on the forestry inventories.

2.3 CO₂ uptake by biomass and emissions from managed wood

All organic matter accumulated in a tree during its growth has its origins in the photosynthetic process of atmospheric carbon fixation by hydrogen electrons. Photosynthesis (Equation 2.1) is responsible for the origin of glucose, water and

oxygen which derives from the transformation of carbon dioxide, water and solar energy (Equation 2.2).

Wood composition consists essentially of cellulose ($\text{C}_6\text{H}_{10}\text{O}_5$) ranging from 40 to 50%, hemicellulose ($\text{C}_5\text{H}_{10}\text{O}_5$; or $\text{C}_6\text{H}_{12}\text{O}_6$) of 20 to 30% and lignin ($\text{C}_9\text{H}_{10}\text{O}_2$; or $\text{C}_{10}\text{H}_{12}\text{O}_3$; or $\text{C}_{11}\text{H}_{14}\text{O}_4$) of 20 to 30%.

CO_2 uptake by biomass in the Amazon forest corresponds to the product between the dry mass above the soil, the average carbon content in the wood and the carbon conversion factor in CO_2 emissions, according to Equation 2.3:

$$\text{CO}_2 \text{ uptake} = \text{AGDB} \times \text{Carbon}_c \times 3.67 \quad (2.3)$$

Where:

$\text{CO}_2 \text{ uptake}$ = amount of carbon dioxide uptake by the living biomass aboveground;

AGDB = mass of aboveground dry biomass;

Carbon_c = average on the carbon content in wood in percentage (Table 2.1); and

$3.67 = ((12 + 2 \times 16)/12)$, which is the carbon conversion factor in CO_2 emission by stoichiometric ratio where 12 is the molecular weight of carbon and 16 is the molecular weight of oxygen.

Carbon content is defined from the organic polymer composition of the wood. Carbon and oxygen are distinguished as the main chemical elements of their constitution. In the literature there is a small variation in the percentage of carbon content in the dry biomass, as can be seen in the table below.

Table 2.1: Variance in carbon content in wood from literature

Author and year	Percentage of carbon on dry wood mass
(HIGUCHI et al., 1998)	48
(SANQUETTA et al., 2013)	48
(CAMPOS; PUNHAGUI; JOHN, 2011)	49
(IPCC, 2015)	49
(BRITO; BARRICHELO, 1981)	49-50
(DUTRA; NASCIMENTO; NUMAZAWA, 2005)	50
Average	49

Source: by author (2018)

Therefore, it was determined that for the quantification of CO₂ emissions, the total carbon fraction in trees was considered as the average percentage of carbon content in the wood of 49% of the biomass dry weight.

It is assumed that the total woody biomass will progressively decompose into CO₂ (FEARNSIDE, 1997) and therefore methane emissions will not be the focus of the study. The factors for the methane emission calculation are difficult to estimate due the large numbers of variance, e.g. methanobacteria, termites, radiation regime, precipitation etc. (GARCÍA, 2014) and it would demand a complex and diverse knowledge in different areas.

Moreover, there is, as of yet, insufficient in situ field evidence to determine what proportion of carbon from wood products is emitted as carbon dioxide and as methane (FERREIRA-LEITÃO et al., 2010), since methane yield estimates are highly varied and have been derived from theoretical stoichiometric calculations and laboratory measurements of small-scale simulations (MICALES; SKOG, 1997).

A data set with 315 trees with a dbh > 5 cm were analysed using four different statistical models (linear, non-linear and two logarithmic) to estimate the average composition of aboveground standing biomass for these trees. The resulting error between observed and estimated biomass was below 5%, resulting in the following percentage of each tree component in the total weight of a standing tree (HIGUCHI et al., 1998):

- 65.6% from log; and
- 34.4% from tree crown: with 17.8% from branches (≥ 10 cm); 14.5% from twigs; 2.03% from leaves; 0.01% from flowers and fruits.

2.4 Logging residues from forest management

In general, logging residue (LR) generation is dependent of logging intensity, the technique applied, and the natural shape of the commercial tree species being cut (i.e. presence and size of buttress roots or canopy size), justifying the importance of knowledge of the relationship between residues and logged stems.

In this study, the logging damage or logging residues produced by the harvesting were:

- from canopies of harvested trees and by other trees felled along in the cutting process, including coarse woody debris as well leaves, flowers, fruits;
- biomass damage during opening of the infrastructures and log deck areas; and
- buttress roots and hollow logs from the harvested trees.

The quantity of residues with a diameter equal to or greater than 10 cm generated during forest management was obtained from the primary data reports which were collected and measured on site. These data were gathered on the demand of foresting companies by forest engineers as part of the exploration authorization report required by Para's Environmental and Sustainability Secretariat (SEMAS) to explore the possibility of using the residues for charcoal co-production.

The ratio was calculated between the total damaged biomass geometric volume and the total timber logged geometric volume. Statistics results for each forest with the mean, standard deviation and coefficient of variation are described in Appendix A.

In order to determinate the logged timber volume, a sample from the forestry inventory was taken of species representing at least 80% of the total stems logged (between 100 and 157 trees) in the total managed area to determine stem volume. The logs were classified according to diametrical classes and the number of trees, as in the example of table 2.2 for one plot:

Table 2.2: Example of the tree species sample classification

Species	Number of trees	Class 1: from 50 to 70 cm	Class 2: from 71 to 90 cm	Class 3: ≥ 91 cm
<i>Vouacapoua americana</i> , Aubl.	4	4	0	0
<i>Euxylophora paraensis</i> , Huber	9	2	4	3
<i>Protium sagotianum</i> March.	3	1	1	1
<i>Micropholis</i> sp.	7	2	2	3
<i>Guatteria olivacea</i> R.E.Fr.	4	4	0	0
<i>Parkia</i> sp.	8	1	1	6
<i>Handroanthus serratifolia</i> , (G.Don) Nichols	8	3	3	2
<i>Lecythis lurida</i> (Miers) S.A.Mori	10	7	3	0
<i>Hymenaea courbaril</i> , L.	8	2	6	0
<i>Caraipa grandiflora</i> , L.	2	2	0	0
<i>Simarouba amara</i> , Aubl.	4	4	0	0
<i>Alexa grandiflora</i> , Ducke	17	8	8	1
<i>Astronium lecointe</i> , Ducke.	8	2	5	1
<i>Brosimum parinarioides</i> , Ducke	4	3	1	0
<i>Ceiba samauma</i> , K.Schum	7	2	1	4
<i>Tachigalia</i> sp.	4	4	0	0
<i>Bagassa guianensis</i> , Aubl.	2	0	0	2
<i>Couratari oblongifolia</i> , Ducke & R.Knuth	6	3	3	0
Total	115	54	38	23
Percentage	100	47	33	20

Source: by author (2018)

After cutting, each residue (≥ 10 cm) generated during the felling of the selected tree samples were measured individually to obtain its geometric volume. In the reports from the study areas, the residue volume found for each cubic meter of commercial timber was between 1.6 m³ to 1.8 m³.

Commercial timber logs' dry biomass (in metric tonne per hectare) were based on the factor between basic mean density of logged trees (metric tonne per cubic meter) and its logged volume (cubic meter from primary data obtained by the Sustainable Forest Management Plan), the volume from the tree's base to the first branch of the crown. Then, it was possible to obtain the canopy biomass by Higuchi's allometric equation and, therefore, the quantity of tree crown residues.

Total logging residues include residues from logged trees (logged tree crown + buttress roots and hollow logs) and the collateral damage. The collateral damage consists of i.e. broken or fallen trees during logging, residues generated by the opening of roads (primary and secondary), skid trails, etc.

Lastly, logging residues < 10 cm due to collateral damage need to be estimated as these were not collected and measured. This is done using the allometry equation by Higuchi (HIGUCHI et al., 1998) which showed that 16.6% of an average tree's weight is made up of twigs, leaves, flowers and fruits, resulting in residues < 10 cm. The other 83.4% belongs to the stem and branches, resulting in residues $\geq$ 10 cm which have been collected and measured. Therefore, the amount of logging residues < 10 cm is 16.6 / 83.4 times the amount of logging residues $\geq$ 10 cm.

Although rainforest lianas (wood vines) can reach a diameter of 15 cm and a length of 70 meters (JACOBS, 1990) and can represent up to 5,500 individuals per hectare (GERWING; VIDAL, 2005) they were not included due the lack of primary data. Moreover, the study about this subject it is still very incipient (BUSTAMANTE et al., 2016; GERWING, 2001; VIDAL et al., 1997).

2.5 Material flow analysis from Amazon wood: cradle-to-grave

Wood flow is quantified and evaluated using material flow analysis based on dry mass transfers (OECD, 2008) and focuses on evaluating the environmental impacts of CO₂ emissions associated with commercialized lumber.

The units used in MFA are mass in metric tonnes (t), with a system area of 1 hectare (ha). The wood flow analysis for the production cycle is sub-divided into several parts:

- Forest: raw material extraction in the Amazon forest;
- Logs: commercial timber logs;
- Logging residues: residues generated during the logging such as branches, leaves, etc.;
- Logging residues with a diameter equal or greater than 10 cm: including those from the logged tree;
- Logging residues < 10 cm: all residues with a diameter smaller than 10 cm, such as twigs, leaves, fruits and flowers;
- Harvested tree residues: all residues bellowing to the commercial tree;
- Collateral damage: all residues from damaged biomass not belonging to the commercial tree, caused by the felling and transportation of the logged stems;
- Lumber: as wood product to be applied in construction;

- Sawmill residues: such as sawdust, wood chips, etc.;
- Wooden products: as wooden products for building, i.e. wooden floor etc.; and
- End-of-life: lifespan of the wood product until it goes to landfill or is burnt.

Information relevant to the discussion on wood lifespan was obtained by primary data, given by the literature, and by data from the dissertation on wood durability applied in architecture (NUMAZAWA, 2009).

2.6 Resource efficiency and wastage rate

Resource efficiency was applied as a performance indicator in the lumber supply chain, focusing on the resource productivity (OECD, 2015) by analyzing the material flows in production and consumption. This is done in order to give insight into the creation of products and services that provide consumers with the same level of performance, but with an inherently lower environmental burden (MONT, 2002). The estimated resource efficiency is given by the ratio of dry product biomass to the total withdrawn dry biomass. The value ranges from 0 to 1 (or 0% to 100%) where a higher rate is better and reflects a greater resource efficiency and lower environmental impact. A value of 1 represents the ideal situation where all withdrawn biomass belongs to the product and there is no waste.

The wastage rate was calculated based on the cumulative residue biomass generated during the production. It presents the ratio between residue biomass and the biomass of the final product. A lower rate is better with 0 representing no waste generated and values > 1 representing the generation of more residue biomass than product biomass.

2.7 Conversion of dry biomass and CO₂ generation and carbon allocation

The units used for the conversion of biomass into CO₂ are in mass of carbon or carbon dioxide with the following basic conversion factors (CAMPOS, 2012):

- Density of wood with moisture in equilibrium with air ($\approx 15\%$ humidity): 0.81 g cm^{-3} ;
- Density of green wood (about 40% humidity): 1.15 g cm^{-3} ;
- Carbon content in dry wood mass: 49% ;

- Conversion between carbon (C) and carbon dioxide (CO₂): based on molecular weight, C=12 and CO₂=44.

2.8 Net CO₂ emissions

The net CO₂ emissions were calculated at three different times: at the end of the logging operations with the logs as products, at the end of sawmill process with lumber as the final product and at the end-of-life when the wood product lifespan expired.

The carbon present in wood products and the absorption of CO₂ during forest regeneration was considered as a mitigating factor (CO₂ uptake or Carbon stock), and the carbon present in the residual biomass to be released into the atmosphere as a contributing factor (CO₂ emission), as in the following figure.

Figure 2.2: Net CO₂ emissions from lumber (mitigating factors in blue, contributing factors in red)

Source: by author (2018)

A study showed the possibility of incomplete biomass recovery within the 30 year cutting cycle (VIDAL; WEST; PUTZ, 2016). Here, it was taken into account that if the forest biomass did not recover to the value of the initial biomass, the quantity of missing biomass would be considered an emission factor.

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3 LOGGING RESIDUES AND CO₂ OF BRAZILIAN AMAZON TIMBER: TWO CASE STUDIES OF FOREST HARVESTING

Abstract

Forest Management has been repeatedly mentioned as a strategy to reduce damage caused by logging when compared with conventional logging. Much has been learned about logging impacts and prospects for forest management, but there are still too many gaps regarding the CO₂ emissions in logging, due to residues. Here we compare CO₂ emissions between two timber harvesting strategies, a conventional logging management intensity of 30 m³ ha⁻¹ (L30) and reduced impact logging management intensity of 15 m³ ha⁻¹ (L15) were compared over 4 rotation periods (four 30-year cutting cycles over 120 years). Primary logging residue (LR) data was used to determine emissions by residue decomposition. On average, L30 has produced more LR (47.58 t ha⁻¹), than L15 (25.50 t ha⁻¹); for each tonne of commercial stem 2.48 tonnes of logging residues were generated for L30 and 2.50 tonnes of residues for L15. Moreover, we have analyzed the net biomass balance over time to evaluate the recovery time for the vegetation mass for each logging intensity. We found that complete biomass recovery will take about 42.3 years under L30; whereas 21.2 years were required in the case of L15. The L30 recovery time is longer than the cutting cycle, which means that aboveground standing biomass is not able to fully recover until the next cutting cycle. Full biomass recovery was only achieved when L15 was applied. Furthermore, there is a reduction over time of commercially viable specimens as the diameter of the commercial tree species takes a longer time to recover than the cutting cycle allows for. Finally, ignoring the post harvesting life cycle phases, both CO₂ balances were negative, which means that both practices ended up fixating more CO₂ from the atmosphere than the decomposing residues emitted.

Keywords: CO₂; Forest residues; Forest management; Climate change; Amazon rainforest.

3.1 Introduction

The old-growth Amazon rainforest stores approximately 290-367 Gt of carbon dioxide (ASNER et al., 2004, 2006; MALHI et al., 2006, 2008) in aboveground standing vegetation, which represents a value about 6 times higher than the total anthropogenic greenhouse gas emissions estimated by the IPCC ("IPCC Fifth Assessment Synthesis Report", 2014) up to 2010. As a result, the destruction of the Amazon rainforest, as well as other tropical forests, would greatly contribute to carbon release into the atmosphere and exacerbates climate change (LAURANCE; WILLIAMSON, 2001).

Nowadays, one fourth of the remaining Amazon rainforest could be exploited for wood production (SIST; PICARD; GOURLET-FLEURY, 2002). Sustainable forest management (SFM) allows for the preservation of most of the forest and its biodiversity (LINDENMAYER; MARGULES; BOTKIN, 2000; SHEIL; WUNDER, 2002; SIKOR, 2006) by exploiting the forest under selective logging and taking advantage of non-timber products as well (GUARIGUATA et al., 2010; TICKTIN, 2004). Such a model offers concurrent social, economic, and environmental benefits, because it brings about jobs and revenues, and at the same time protects biodiversity and carbon stocks (BOLTZ; HOLMES; CARTER, 2003; UHL et al., 1997).

Nevertheless, harvesting timber in tropical rainforests is substantially different from exploiting temperate coniferous forests because marketable tropical tree species are a small fraction of total aboveground biomass (PALACE et al., 2007; SCHULZE et al., 2008). Most commercial timber tree species occur at low densities (≤ 1 adult tree ha⁻¹) making selective logging mandatory (PITMAN et al., 1999; SCHULZE et al., 2008; VAN GARDINGEN; VALLE; THOMPSON, 2006). As a result, timber harvesting requires opening up space for felling, bucking, roads for skidding and log decks. This implies that only some of the felled trees and part of the affected biomass becomes commercial timber.

The process typically results in a relatively low stem yield, because most stems have a heterogeneous shape due to tree anatomy (i.e. prop roots and different branch diameter distribution). Such tree diversity contributes to biomass residue generation during extraction (SANTOS et al., 2014). Nevertheless, SFM not only generates income but also prevents total deforestation (ASNER et al., 2006).

The Brazilian government supports harvesting systems in which the purpose is producing goods (timber and non-timber products) while maintaining environmental services. Under Brazilian law ("Instrução Normativa nº 5 de 11/12/2006 / MMA) SFM implies a maximum logging intensity (LI) of 30 m³ of extracted timber per hectare observing a cutting cycle of 30 years, and a minimum diameter at breast height (dbh) of 50 cm. This is known as conventional logging (L30), and it prevents the destruction of forests while allowing timber production and income generation.

Voluntary green market-based incentives, such as the Forest Stewardship Council (FSC) certification, requires harvest practices complying with a Reduced Impact Logging (L15) standard, which focuses on measures to improve forest preservation, with requirements for pre-harvesting, harvesting, and post-harvesting operations.

Requirements includes a 100% botanic inventory, road and track planning, and forest management activities aiming to minimize canopy disturbance, such as cutting vines that are interconnecting trees (VIDAL et al., 1997). It reduces the impact of harvesting by limiting LI to 15 m³ of timber per hectare respecting a cutting cycle of 30 years, and individuals with dbh greater than 50 cm (GROGAN; VIDAL; SCHULZE, 2005).

Lumber is widely applied in several construction applications (e.g. floor covering, roof structures, and windows frames) representing 403 million hectares of tropical forest designated for timber production (THE INTERNATIONAL TROPICAL TIMBER ORGANIZATION, 2011). Such applications preserve the carbon fixated in the product and avoid carbon dioxide emissions for decades (PROFFT et al., 2009).

Therefore, it is possible to consider harvested wood products as carbon stock (BRUNET-NAVARRO; JOCHHEIM; MUYS, 2016; LIM; BROWN; SCHLAMADINGER, 1999; WINJUM; BROWN; SCHLAMADINGER, 1998) to the quantity of carbon stored in long-lived wood products (CÔTÉ et al., 2002; KARJALAINEN et al., 2002; MASERA et al., 2003; PINGOUD; PERÄLÄ; PUSSINEN, 2001; SASAKI et al., 2016; WINJUM; BROWN; SCHLAMADINGER, 1998), remaining constant over time (IPCC, 2006).

However different technical approaches, i.e. in terms of their system boundaries, debits for CO₂ flows and carbon stock in wood products, are applied among countries that produce or consume wood (LIM; BROWN; SCHLAMADINGER, 1999). Therefore,

forest management affects carbon storage (PUTZ et al., 2012) and environmental quality of its products, but reliable data is required for proper quantification.

Some studies dedicated to CO₂ emissions of harvesting in coniferous forest have been done in the past (BACKÉUS; WIKSTRÖM; LÄMÅS, 2005; FAHEY et al., 1991; HYVÖNEN et al., 2000; KELLER; KAPLAN; WOFSY, 1986; LITVAK et al., 2003; SEIDL et al., 2007). They focus on net greenhouse gas emissions due to energy production using logging residues, impacts on soil carbon, and emissions from harvest residue decomposition.

Estimations of emissions from deforestation and forest degradation are found in literature (ASNER et al., 2009; HOUGHTON et al., 2000; MALHI et al., 2008; PEARSON; BROWN; CASARIM, 2014). However, CO₂ emission studies associated with timber production from selective tropical forest logging are scarce (SASAKI et al., 2016).

Eshun et al. (ESHUN; POTTING; LEEMANS, 2010), present an estimation for Ghanaian rainforests, but it does not include CO₂ emissions from the decomposition of logging residues, which are expected to decompose and release considerable fluxes of CO₂ to the atmosphere (PALVIAINEN et al., 2004; REPO et al., 2012). Studies involving CO₂ emissions from Amazon rainforest timber are not available, and lack of data is still an important constraint for a more realistic estimation of carbon stocks and fluxes.

In this paper, we compare CO₂ emissions of conventional logging (L30: 30 m³ ha⁻¹) and of reduced impact logging (L15: 15 m³ ha⁻¹). We have created a 120-year long model to determine biomass recovery and residue decomposition for both harvesting intensities.

3.2 Materials and Methods

The case study was based on primary data collected from 2 logging areas in the Paragominas region of Pará State, Brazil (GPS localization between 02° - 04° South and 46° - 49° West). The climate in these forests is humid tropical and is classified as tropical. The average temperature is 26.6 C°. Total annual average precipitation is 1,805 mm (SOUZA et al., 2015). The topography is flat to mildly undulating (PINTO,

ANDRÉIA et al., 2009). Usually, logging operations occur during the dry season which takes place between June and November.

We have assessed two logging methods: L30 and L15. Both logging operations were carried out by chainsaw and cable skidder. The total authorized exploitable area was 4,330 ha and the maximum extractable timber volume was 120,900 m³ of stems, out of which 111,900 m³ under L30 and 9,000 m³ under L15.

The system boundary of this study was limited to fluxes related to logging operations, focusing on CO₂ emissions by logging residues, carbon storage in forest products (stems), and the potential of CO₂ uptake by biomass recovery as indicated in Figure 3.1. We have adopted a 120 year long analytical period, which comprises 4 harvesting cycles spaced by 30 years. Lumber manufacturing, industrial processing, use phase, and end-of-life were not considered in the accounting of CO₂ emissions.

Figure 3.1: Schematics of an extraction cycle for managed selective logging typical of the Amazon rainforest. Brown lines are residue converted in due time into CO₂. System Boundary is presented by the dark gray dashed line

Source: by author (2016)

For each area, the extraction of a sample of 102 (L30) and 157 (L15) commercial trees were evaluated. These trees represent at least 80% of the authorized exploited volume for the area. In each case, the stere volume of harvesting residues with diameter equal or above 10 cm was measured. The commercial tree species was identified and its diameter was measured.

The selective timber logging intensities (LI) were respectively $30 \text{ m}^3 \text{ ha}^{-1}$ for L30, and $15 \text{ m}^3 \text{ ha}^{-1}$ for L15. L15 LI was established by property owners based on a site-specific survey of the amount of commercial species per hectare (SAATCHI et al., 2007). In each area, the total mass of harvested timber was calculated multiplying the average wood density (t m^{-3}) by the LI ($\text{m}^3 \text{ ha}^{-1}$).

In order to estimate the average density of harvested boles, the basic density of each detected species was obtained from literature (ARAÚJO, 2007; IPT, 2017) and multiplied by the volume fraction estimated for each species. We have estimated mean basic densities of the commercial biomass at 0.64 t m^{-3} (L30) and 0.68 t m^{-3} (L15), which is consistent with the typical values for the entire forest reported in the literature (BROWN; LUGO, 1992; FEARNside, 1997; KINDERMANN et al., 2008; NOGUEIRA et al., 2007, 2008; PALACE et al., 2007).

Under selective logging, residues result not only from harvested trees, but also from damage to the surroundings of harvested trees, due to (improper) felling, bucking, opening roads for skidding, and log decking practices. Logging residues (LR) with a diameter equal or superior than 10 cm were directly collected, measured, and piled on site, providing a ratio of residue stere volume to their geometric volume. The ratio between residues above 10 cm and boles was $1.78 \text{ m}^3 \text{ m}^{-3}$ for L30 and $1.71 \text{ m}^3 \text{ m}^{-3}$ for L15, equivalent of $54.40 \text{ m}^3 \text{ ha}^{-1}$, and $25.65 \text{ m}^3 \text{ ha}^{-1}$, respectively.

We estimate the harvested trees' LR under 10 cm to be 16.6% of the trees' biomass. LR under 10 cm from collateral damage (i.e. leaves, flowers or branches) are calculated as 20% of $\text{LR} \geq 10 \text{ cm}$ dry mass as defined by an allometry equation originating from Higuchi (HIGUCHI et al., 1998) (65% stem of the tree; $\text{LR} \geq 10 \text{ cm}$ 17.8% of the tree, $\text{LR} < 10 \text{ cm}$ 16.6% of the tree), making $\text{LR} < 10 \text{ cm}$ equal to 20% of the combined biomass of the stem and $\text{LR} \geq 10 \text{ cm}$. This value for LR under 10 cm by collateral damage is a good approximation under the assumption that, on a dry

biomass basis, the collateral damage consists mostly of other large trees for which the allometry equation is valid.

The aboveground standing biomass (AGSB) from each site was obtained from Saatchi (SAATCHI et al., 2007). Aboveground dry biomass (AGDB) represents 60.28% of total AGBS (HIGUCHI et al., 1998). In the assessed area AGDB values vary from 211 to 241 t ha⁻¹, with an average of 226 t ha⁻¹. These data were validated by one of the authors (SN), based on his direct field observations.

We assumed that the total dead aboveground wood biomass will progressively decompose to CO₂, considering that bacterial decomposition and termite activity emissions of methane from decay of unburned biomass are substantially lower than CO₂ emissions. The estimates of the number of termites in managed forest indicate that the populations are insufficient to consume the quantity of wood that had previously been assumed.

Estimates of CH₄ emissions are scarce, and the values are as low as 0.002 t t⁻¹ of dry wood consumed (FEARNSIDE, 1991, 1992; MARTINS et al., 1996). Even considering the global warming potential of 25, this leads to 0.05 t t⁻¹ CO_{2eq} to about 3.67 t t⁻¹ for CO₂ decomposition. We have calculated CO₂ emissions by multiplying dry mass of LR by 0.49, which corresponds to the total carbon fraction in trees (HIGUCHI et al., 1998), then multiplying by 3.667, to determine the carbon dioxide mass.

In order to estimate CO₂ emissions from logging residue biological decay, we have assumed the decay of dead wood (residues) left on site according to an exponential model (Equation 3.1) with a constant of $k_d = 0.1 \text{ yr}^{-1}$ (HOUGHTON et al., 2000). This is the slowest carbon mineralization rate identified in the literature for biomass (CHAMBERS et al., 2000; PALACE et al., 2007). This includes all non-living woody biomass, standing or lying on the ground, or within buttress roots, excluding the soil content such as underground roots.

$$R_t = R_0 \times e^{k_d \times t} \quad (3.1)$$

Where R_t is the remaining biomass of dead wood over time; R_0 is the woody material residue on the site after extraction (time=0); k_d is a rate constant of 0.1 yr⁻¹; t is time after extraction.

The post-logging forest recovery per year was assumed to be linear with time (RUTISHAUSER et al., 2015). It was calculated by the quotient between the biomass withdrawn and time necessary to recovery the total biomass (Equation 3.2). As a general rule we assumed that the recovery rate will never surpass the initial biomass, something that may happen in some cases (RUTISHAUSER et al., 2015).

Besides, as we are evaluating the CO₂ emissions and CO₂ uptake, we focus only on biomass recovery, without considering if dbh of individual species reached the initial values or considering the specific recovery of commercial biomass. We defined time for biomass recovery using the percentage of initial AGDB lost from Rutishauser et al.⁴⁹ which include the natural mortality. Posteriorly, we calculated the AGDB recovery over time after each rotation (Equation 3.3).

$$R_{rc} = w(100 \times w/AGDB_c)^{-1.106} \quad (3.2)$$

$$AGDB_{(tc)} = w \times t_c + AGDB_c \quad (3.3)$$

Where R_{rc} is the biomass recovery rate for each cutting cycle; w is the total biomass withdrawn; $AGDB_{tc}$ is related to aboveground dry biomass recovery tc years after each cutting cycle; $AGDB_c$ corresponds to aboveground dry biomass before each harvesting. All values are on dry biomass basis.

In our model we have not considered the effect of climate variables, such as droughts, which might decrease biomass recovery rates. This effect might be even more prevalent in the future (IPCC, 2014).

3.3 Results

Each logging operation can be analyzed based on the aboveground biomass variation over time. This variation results from a combination of biomass withdrawn at each cutting cycle, composed of the harvested stem volume plus residue volume due to biomass damage, and forest recovery between cycles.

The total volume of harvested timber was 19.2 t ha⁻¹ for L30, and 10.2 t ha⁻¹ for L15. Total biomass withdrawn, including mass of logs, was 66.78 t ha⁻¹ (L30), and 35.70 t ha⁻¹ (L15), which implies the production of 47.58 t ha⁻¹ of LR for L30, and 25.50 t ha⁻¹ for L15. LR are comprised of logging disturbance and damaged trees caused by the

harvesting operation. LR < 10 cm was 11.08 t ha⁻¹ for L30 and 5.93 t ha⁻¹ for L15 (Table 3.1).

Table 3.1 Biomass flow (dry basis) expressed as a percentage of total AGDB for the first cutting cycle for L30 and L15. For the L30 biomass never fully recovers.

Logging methods	Units	Initial Biomass	Stems t=0	Residue t=0	Remaining forest t=0	Biomass after recover t=30 years	Recover time (y)
L30	t ha ⁻¹	226.1	19.2	47.58	159	206.7	42.3
	%	100	8.5	21	70.5	91	
L15	t ha ⁻¹	226.1	10.2	20.9	195	226.1	21.2
	%	100	5	9	86	100	

Source: by author (2016)

Differences between L30 and L15 were more pronounced with respect to the time to recover the initial biomass. Growth simulation models (VALLE et al., 2006; WEST; VIDAL; PUTZ, 2014) indicate that time required for total volume recovery following L15 is much less than when following L30. It takes 42.3 years to recover the total biomass under L30 while under L15 it takes 21.2 years.

Assuming that cutting cycles occur every 30 years and the same logging intensity is applied, the forest logged using L30 techniques wouldn't recover its full initial biomass (Graphic 3.1). Meanwhile when L15 is applied biomass is fully recovered about 8 years before the next logging cycle, which helps biodiversity and forest preservation.

Graphic 3.1 - Aboveground dry biomass (t ha^{-1}) on vertical data over 120 years' time horizontal data, considering extracting cycles of 30 years for L30 (a) and L15 (b). Conventional logging progressively loses biomass

Source: by author (2016)

Differences in standing biomass between L15 and L30 cannot be attributed to intrinsic floristic characteristics, nor climate change, since we maintained the same background over the 120-year long horizon in our models.

In L30, higher number of skid trails, roads, and log landing densities combined with no optimized forestry technique resulted in a greater number of damaged trees. This larger logging impact on the forest under L30 is the most probable reason for its slower standing biomass recovery after logging.

L15 logging is effective in reducing the total amount of wood residues relative to the L30 operation, although both L30 and L15 produced a notable logging damage. For each tonne of commercial stem, we found 2.48 tonnes of logging residues following L30 and 2.50 tonnes of residues following L15 (logs were considered as carbon stock). L15 activities did not result in increased timber utilization efficiency.

Graphic 3.2 - Balance of CO₂ emissions. (a) Conventional Logging; (b) Reduced Impact Logging. CO₂ emissions are positives values

Source: by author (2016)

CO₂ emission balance over time represents the difference between logging residues emissions and carbon sequestration due to standing forest biomass recovery (Graphic 3.2). The carbon mass of stems logged were considered as a carbon stock in the CO₂ emissions balance because carbon remains trapped in wood products. Only in L15 we have found a negative value because the C uptake is higher than emissions.

Note that biomass recovery includes the carbon fixed in stems, whereas residue emissions do not account for CO₂ release from lumber used in long lasting construction applications. In respect to CO₂, L15 provides better results than L30. However, the negative CO₂ emissions are obtained within the system boundary, which is limited to timber's harvesting and disregard subsequent life cycle phases, e.g. industrial processes, use phase, and the end-of-life, as well as fossil fuel consumption.

L15 techniques increase forest carbon retention (sequestration) relative to L30, and consequently, decrease CO₂ emissions. L15 is also better than L30 to preserve the ecosystem including commercially viable species.

3.4 Discussion

We have estimated that forest management using L30 techniques (up to 30 m³ ha⁻¹), considering the initial AGSB of the area, the minimum annual recovery rate recommended for this biome, and a 30-yr rotation cycle, results in a progressive decrease of the AGSB. Thus, it jeopardizes the ecological carrying capacity of the area because the forest will be progressively destroyed. In comparison, we have estimated that logging the forest using L15 techniques (15 m³ ha⁻¹), results in the full recovery of the original AGSB after 22 years. Such practice supports the sustainability of the carbon stock and the biodiversity of mature tropical forests. Although L15 is best for environmental purposes, L30 yields twice as much logs; therefore, it may generate twice as much revenue, considering present values.

In order to grant the full recovery of the area between rotation cycles, it is possible to either extend the rotation period of L30 to 43 years or decrease the logging intensity to 21.3 m³ ha⁻¹. This strategy maximizes revenues and allows for the full recovery of the AGSB, which supports biodiversity.

We have not considered that several exploited species are not able to recover to the

minimum dbh between cycles. However, a study in the same area (WEST; VIDAL; PUTZ, 2014) shows that although the initial aboveground standing biomass was completely recovered after 16 years, stock of commercial trees with dbh greater than 50 cm was not yet recovered. It is worth noting that although some species may be negatively affected by logging (SCHULZE et al., 2008; SEBBENN et al., 2008), many others can persist in forests that have been selectively logged at low LI. Nevertheless, this scenario might compromise long term harvesting of commercial species and affects economic results. Consequently, long term studies on biomass recovery of commercial trees are needed.

It is a fact that for each harvest L30 will result in double the total amount of commercial logs than L15. However, higher intensity resource extraction may result in a progressive depletion of high value timber with a large dbh. The increased logging intensity implies an increased amount of biomass destroyed per cubic meter of commercial logs. There is also a higher cost associated with labor, machines, and fuel for logging activities. However, the easiest way to raise profits is increasing logging intensity, which results in larger CO₂ emissions.

All considered, it is clear that higher intensity logging will result higher profits, at least in the first cycles. The pure economics encourages destruction. Besides that, interests of traditional and local population of the Brazilian Amazon focus on profitability in the total timber harvest cycle. Maximizing short-time private profits conflicts with the public interest of moderated logging to reduce CO₂ emissions and ensure the long-term forest survival, a revisit on the Tragedy of Commons.

SFM basic hypothesis is that it allows forest to be preserved indefinitely. This depends on economic results from SFM activity as well as legal enforcement. However a decrease in the total area exploited by L15 methods, with voluntary certification schemes was reported by Chatham House (WELLESLEY, 2014) in the years 2009 and 2010, a period of time with high demand for building products in Brazil. This implies that the certification scheme of forest areas under L15 was abandoned, which was probably driven by an economic decision that lowered the probability of their long-term preservation.

Under L15 the CO₂ balance becomes stable and it is possible to account for a forest

carbon stock. Indeed, L15 demonstrates that atmospheric emissions due to deforestation and forest degradation are concurrently reduced with the enhancement of forest carbon stocks, and the maintenance of ecosystem services. But because L15 decreases the economic output, the conversion from L30 to L15 and continuity of L15 forest management should be supported by appropriate economic carbon-based incentive schemes.

A change on inventory boundaries (Figure 3.1) to include residue generation at sawmills (greater than 54% of the bole mass (BIASI; ROCHA, 2006)), during industrial activities and product end-of-life will affect the emissions balance. Over the long term, all withdrawn biomass will decompose and the CO₂ balance of the forest will be neutral. However, in the case of L15 the carbon stock comprising timber products in use, residues not yet decomposed, and the standing forest could provide a negative carbon balance for the system. Moreover, a proper LCA of timber products will require considering fuel consumption of typical logging equipment and emissions from transportation and industrial operations.

3.5 Reference

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4 BRAZILIAN AMAZON LOGGING RESIDUES: MATERIAL FLOW ANALYSIS FOR THREE DIFFERENT FOREST MANAGEMENT OPERATIONS

Abstract

Logging residues in the Amazon forests are an important indicator of wood resource efficiency. This study quantifies wood flows in individual logging operations that generated residues in 3 managed forests plots in the Western Amazon in order to analyze resource efficiency from timber production and to present the main origins of logging residues. The forest management operations were identified and evaluated, with results calculated by a material flow analysis using primary data. Logging intensities ranged from 27 m³ ha⁻¹ to 30 m³ ha⁻¹ and aboveground dry biomass from 165.77 t ha⁻¹ to 226.05 t ha⁻¹. The resource efficiency was found to be between 25% to 26%. The average flow results found for the total dry biomass withdrawn consist of 25% for the commercial timber logs, 20% residues belonging to logged commercial tree (crown, hollow logs and buttress roots), and 55% residues due to forest damages not belonging to the commercial tree, collateral damage. Results indicate collateral damage as the largest hidden flow being up to 73% of the total logging residues. Hence, reducing collateral damage is the key to logging residue flow reduction and it would increase the resource efficiency and improve the capacity of the remaining stand.

Keywords: Material flow analysis; Wood flow; Logging residues; Amazon forest management; Resource efficiency.

4.1 Introduction

There is ample evidence that the Amazon forest is the most species-rich region in the world. Although the exact number of tree species is unknown, an estimate based only on trees with a dbh (diameter at breast height) greater than 10 cm showed that their number is assessed at 11,120 (HUBBELL et al., 2008), with a frequency distribution of between 100 - 300 trees species over a single hectare (GENTRY, 1988; JOHN et al., 2007; TER STEEGE et al., 2000; VALENCIA et al., 2004). However, most merchantable commercial timber species are rare occurring at low densities (≤ 1 adult tree ha⁻¹), which leads to selective logging operations (CLARK; CLARK, 1999; GENTRY, 1988; SCHULZE et al., 2008; VAN GARDINGEN; VALLE; THOMPSON, 2006) resulting in logging operations generating greater quantities of residue biomass than commercialized stem wood biomass (SANTOS et al., 2014; NUMAZAWA et al., 2017).

Logging residues (LR) generated under forest management are an unavoidable part of the supply chain and are, usually, left in the forest to decompose. Consequently, LR impacts are one of the major forms of disturbances in the carbon flux (ASNER et al., 2005; BICKNELL et al., 2014, 2014; BLANC et al., 2009; BUSTAMANTE et al., 2016; CAMPOS; JOHN, 2012; CRUZ FILHO; BARROS; SILVA, 2013; EDWARDS et al., 2014; FELDPAUSCH et al., 2005; GERWING, 2002; KELLER et al., 2004; NUMAZAWA et al., 2017; PUTZ; PINARD, 1993) and the efficiency of the forestry operations need to be investigated.

In general, logging residues are related to the logging intensity, to the logging practices (i.e. conventional or reduced impact logging) (ASNER et al., 2002; HAWTHORNE et al., 2011; HOLMES et al., 2002; PEREIRA et al., 2002), to the quantify of aboveground biomass (CUMMINGS et al., 2002; MAZZEI et al., 2010) as well as the selected tree species (ANDRÉ et al., 2008; GROGAN et al., 2008; LACERDA; KANASHIRO; SEBBENN, 2008; SCHULZE et al., 2008), the skill level of the workforce and to the tools and logging equipment (SILVERSIDES; SUNDBERG, 2013).

Selective logging in the Amazon forest requires openings for felling the trees, skidding the logs, forest roads and areas for log decking practice. It also causes canopy disturbances, top logs and broken trunks resulting in LR quantities 1 to 5 times the

amount of roundwood logged (ASNER et al., 2002; BARRETO et al., 2006; BRAZ et al., 2014; CAMPOS, 2012; CUMMINGS et al., 2002; GERWING, 2002; GERWING; JOHNS; VIDAL, 1996; JOHNS; BARRETO; UHL, 1996; NUMAZAWA et al., 2007, 2009, 2014; RATNASINGAM; NJANKOUO, 2002; SASAKI et al., 2016; TRITSCH et al., 2016; VERÍSSIMO et al., 1992; VIDAL et al., 1997). Most LR estimates only consider trees ≥ 10 cm dbh so there is a need for additional research to better quantify the smaller residues. So far there is a lack of primary data that quantifies the residues generated by logging operations.

Material flow analysis is an analytical method regarding physical material flows into, through and out of a given system, using a mass approach. It has been used to analyze the relationship between material flows, environmental changes and human activities (OECD, 2015). It is applied to identify and to optimize resource flows by accounting for physical material units from the extraction until the disposal of the materials towards minimum residue and resource expense (BRINGEZU; MORIGUCHI, 2002; CHILDHOUSE; TOWILL, 2003; HINTERBERGER; GILJUM; HAMMER, 2003; KNOERI et al., 2013; MORIGUCHI; HASHIMOTO, 2016; MUÑOZ; GILJUM; ROCA, 2009; TOWILL, 1997).

It has also been increasingly used to assess the sustainability of wood products (MÜLLER, 2006; BERGERON, 2016; BINDER et al., 2004; HASHIMOTO et al., 2004; LAFLEUR; FRAANJE, 1997; LENGLET; COURTONNE; CAURLA, 2017; MANTAU, 2015; PAROBEEK et al., 2014; SUTER; STEUBING; HELLWEG, 2017). However, only few studies (CAMPOS, 2012; JOHNS; BARRETO; UHL, 1996; SASAKI et al., 2016) were based on material flow analysis of commercial timber logged in the Amazon forest.

In this paper, we quantified the generation of logging residues during three different forest management operations using material flow analysis, focusing on resource efficiency between Brazilian Amazon timber and residue production and their origins within the logging practice.

4.2 Materials and Methods

Primary data on harvested logs and residues generated by selective logging activities were collected between 2002-2009 from forests located in the Paragominas (F1),

Portel (F2) and Baião (F3) regions in Pará State, Brazil, comprising a logging area (TA) of 13,078 ha. These forests are classified as equatorial, and the climate data shows regional average temperatures and regional average precipitation from 1980-2010 of 27.36 °C and 2,233 mm, 27.24 °C and 2,565 mm, 27.30 °C and 2,669 mm for F1, F2 and F3 respectively (INMET, 2017; AgMERRA database).

Forest exploitation was licensed and monitored by the Pará State environmental authorities. The logging intensity (LI) was established by property owners based on site-specific surveys of the amount of commercial species per hectare and in accordance with Brazilian regulation for sustainable forest management (current law during these management operations: Federal Law nº 4,771 Article 5, December 11th, 2006) with a maximum LI of 30 m³ ha⁻¹ each 30 years. All LI values were close to the maximum: F1 30 m³ ha⁻¹; F2 29 m³ ha⁻¹ and F3 27 m³ ha⁻¹. The total logged timber volume was 371,594 m³ of stems, out of which 110,400 m³ in F1, 107,996 m³ in F2 and 153,198 m³ in F3.

Figure 4.1 shows the complete material flow of wooden building products. However, the system boundary of this study was limited to wood fluxes related the logging operations (felling, extraction and processing by delimbing and topping the tree) in the first cutting cycle (dark blue dashed line). Re-entry logging, residue generated by cutting of vines, lumber manufacturing, industrial processing, the use phase and end-of-life were not considered.

Figure 4.1: Schematic of material flow of wooden building products from the Brazilian Amazon forest under selective logging. The System Boundary is presented by the area delimited by the dark blue dashed line

Source: adapted by author from ISO 14040 (2018)

Values for all residues generated with a diameter equal or greater than 10 cm during the forest management were obtained from primary data reports. These data were gathered by forest engineers on demand of foresting companies as part of the exploration authorization report required by Para's Environmental and Sustainability Secretariat (SEMAS) to explore the possibility of using residues to produce charcoal.

In the reports from the study areas, the residual stem ratio found for each cubic meter of commercial log was found to be between 1.6 m³ to 1.8 m³. The ratio was based on the logging residues geometric volume per timber geometric volume. Statistics results for each forest with the mean, standard deviation and coefficient of variation are described in the Appendix A.

From these forests an extracted sample from the forestry inventories composed of 107 (F1), 102 (F2) and 115 (F3) tree stems were appraised. All trees had their logged commercial timber volume and dbh measured in the forest inventory. In total, there were 46 commercial tree species identified in these samples, so these species represented at least 80% of the total of 56 commercial tree species identified in each

plot. After logging, the amount of residue volume was assessed based on their origins. For each residue (≥ 10 cm) produced in each logged stem were measured individually to obtain its geometric volume.

Commercial timber logs dry biomass (in metric tonne per hectare) were found using the factor between basic mean density of logged trees (metric tonne per cubic meter) and the its logged volume (cubic meter from primary data obtained by the Sustainable Forest Management Plan) corresponding to the tree stem from the base and the first branch of the crown. Then, it was possible to obtain the canopy biomass by Higuchi's allometric equation and, therefore, the distribution of the tree crown waste.

Total logging residues include residues from logged trees (logged tree crown + buttress roots and hollow logs) and the collateral damage. The collateral damage consists of i.e. broken or fallen trees during logging, residues generated by the opening of roads (primary and secondary), skid trails, etc.

Aboveground dry biomass (AGDB) values were 226.1 t ha^{-1} (F1), 165.8 t ha^{-1} (F2), and 167.2 t ha^{-1} (F3), with AGDB values based on aboveground standing biomass as given by Saatchi (SAATCHI et al., 2007) minus water content of live biomass estimated as 39.72% of total aboveground standing biomass (HIGUCHI et al., 1998).

The total mass of logged timber at each site was calculated multiplying the LI ($\text{m}^3 \text{ ha}^{-1}$) by the mean basic density (t m^{-3}) of the commercial biomass, with values for each classified species obtained from literature (ARAÚJO, 2007; BRAZILIAN FOREST SERVICE, 2018; IPT, 2018; NOGUEIRA et al., 2007) and multiplied by the volume fraction estimated for each tree species.

Figure 4.2: Illustration of the nomenclature adopted in this research. Harvested Tree Residues (HTR) comprising the tree Crown, Buttress Roots (BR) and Hollow Logs (HL). The commercial timber Logs (LOG) is the stem wood that was commercialized. The Collateral Damage (CD) is the biomass of other trees which were damaged around the logged stem during LOGs Felling or during transportation, including the residues from the Log Deck areas (LD), Primary Road (PRoad), Secondary Road (SRoad) constructions and Skid trails (Strails).

Source: by author (2018)

Logging residues (**LR**) are defined as all residues or damaged biomass from the logging operations. Thus, it results not only from harvested tree residue (**HTR**) biomass, but also from the biomass of damaged surroundings caused by the felling and transportation of the commercial timber log (**LOG**). We termed this collateral damage (**CD**), consisting of all residues that are not from the commercial tree (Figure 4.2). It's worth pointing out that we didn't consider tree roots in the LR biomass for the reason that during forest management belowground assessment turned out to be too costly.

Total logging residues from each managed forest with a diameter equal or superior to 10 cm (**TLR_{≥10}**) were directly collected, measured and piled on site, providing a ratio of residue stere volume to their geometric volume (statistic results in Appendix A). The residues were separated by origin: biomass damage due to **LOGs felling**, such as destroyed trees, branches, broken trunks, etc. and the harvesting residues (**HR**) which includes residues from the biomass of the harvested tree; primary road opening

(**PRoad**); secondary road construction (**SRoad**); passage of skid trails for carrying the logs (**STrails**); and the Log Deck areas (**LD**). The $TLR_{\geq 10}$ volume from each of these sources was then measured. Their mass was calculated by multiplying the volume (m^3) by the mean of basic densities ($t\ m^{-3}$) of the typical values for the entire forest per total logged area (ha).

Residue volumes from hollow logs (**HL**) and buttress roots (**BR**) (e.g. from *Dinizia excelsa*, Ducke) that belong to the harvested commercial timber trees were also quantified based on in situ measurements. Dry mass per hectare from these residues were found by multiplying the volume with the mean basic density and dividing by the total managed area.

The total dry mass ratio between log and residues for tree species with commercial interest was defined by an allometry equation (HIGUCHI et al., 1998) where the dry mass percentage is 17.8 (%) for the $LR \geq 10\ cm$, 16.6 (%) for the $LR < 10\ cm$, combining to 34.4% tree crown dry mass and 65.6% log dry mass. The total harvested tree residue mass is considered to be the sum of the dry mass from commercial timber log residues and the residues due to hollow logs and buttress roots.

The amount of logging residues with a diameter equal or superior to 10 cm from collateral damage (**LR_{CD≥10}**) was calculated by the difference between the TLR and $LR \geq 10\ cm$ from the HTR (LR_{HTR}).

Logging residues with a diameter under 10 cm from collateral damage (**LR_{CD<10}**) were not collected and measured as $TLR_{\geq 10}$. For that reason, we decided to estimate its value by using the same ratios as for the commercial tree between log (0.656), $LR \geq 10\ cm$ (0.178) and $LR < 10\ cm$ (0.166) (HIGUCHI et al., 1998). With the logs in this case also belonging to $LR \geq 10\ cm$. Equation 4.1 calculates **LR_{CD<10}**:

$$LR_{CD<10} = \frac{LR_{CD\geq 10}}{1-0.166} \times [1 - (0.656 + 0.178)] \quad (4.1)$$

This might lead to a small underestimation of the value of **LR_{CD<10}** as small trees, especially ones with a log diameter $< 10\ cm$, would contribute a larger part of their relative weight to **LR_{CD<10}** compared to **LR_{CD≥10}**. That being said, because of their low biomass in comparison to the bigger trees, these smaller trees make only a modest

contribution to the total amount of LR and as there is no other estimation available this calculation is believed to be the best approximation.

Residues related to the transportation of commercial logs (**Rtransp**) were calculated by the sum of the dry mass of the residues related to transporting the harvested logs, which includes residues from the primary road opening, residues from secondary road construction, and residues from skid trails.

Results for total residue dry mass from collateral damage (**CD**) were determined by the difference between the total residues caused by the LOG felling and the residues belonging to the harvested tree itself, added to the sum of residues related to the transportation of commercial logs and those due to the log deck area.

The resource efficiency (**RE**) for each forest is measured by the ratio between the total product dry mass and the total biomass withdrawn. The amount of dry mass from the commercial timber log is divided by total amount of dry mass withdrawn, residues and commercial timber. This gives a relative score between 0 and 1, where a higher value is better and a value of 1 represents no residue generation.

4.3 Results

In Table 4.1, we present an overall summary of original data from each forest as well as the aboveground dry biomass and mean basic density of commercial trees needed for the calculations. The largest managed forest area is in F3, however it has the lowest mean basic density and LI. We found that STRails areas are larger than the sum of all the other areas which are necessary to transport or to store the logs. Moreover, the high quantity of residue volume originating from BR shows a significant presence of commercialized tree species with buttress roots in these forests, but also significant differences between forests.

Table 4.1: Raw data from each logging plots.

Forest		F1	F2	F3
Aboveground dry Biomass (AGDB) ^a	t ha ⁻¹	226.1	165.8	167.2
Total Area Managed (TA) ^b	ha	3,680	3,724	5,674
Logging intensity (LI) ^b	m ³ ha ⁻¹	30	29	27
Mean Basic Density (MBD) ^{b c}	t m ³	0.65	0.67	0.63
Ratio between commercial timber logs and total logging residues ≥10 cm ^b	m ³ m ⁻³	1.71	1.78	1.78
Total logging residues ≥ 10 cm (LR ≥ 10) ^b	t ha ⁻¹	43.6	46.4	40.4
Total logging residues < 10 cm (LR < 10) ^d	t ha ⁻¹	12.56	13.09	11.43
Primary Road Area (PRoad) ^b	ha	15	15.75	20
Secondary Road Area (SRoad) ^b	ha	37.5	31.95	46
Skid Trails Area (STrails) ^b	ha	193.36	193.05	294.14
Log Deck Area (LD) ^b	ha	30	28.20	37
Hollow Logs (HL) ^b	m ³	1,257	1,255	1,913
Buttress Roots (BR) ^b	m ³	11,776.90	23,179.96	29,827.13

^a From literature review (ASNER et al., 2005; FEARNside, 1997; GERWING; JOHNS; VIDAL, 1996; KINDERMANN et al., 2008; NOGUEIRA et al., 2008; PALACE et al., 2007)

^b Primary Data

^c Mass weighted average

^d From Higuchi et al. (1998)

Source: by author (2018)

A simplified flow on a dry mass basis and its percentage of main biomass flow is expressed in Table 4.2. The total commercial timber log quantity ranges from 17 t ha⁻¹ to 19.5 t ha⁻¹. Total biomass withdrawn (LOG mass and the LR mass) varied from 68.8 t ha⁻¹ to 78.8 t ha⁻¹, which implies residues generation of 51.8 t ha⁻¹ to 59.4 t ha⁻¹.

Table 4.2 Simplified biomass flow (dry basis) summary results expressed as a percentage of total AGDB and resource efficiency for F1, F2 and F3.

Forest	Units	Initial Forest AGDB	Commercial Logs LOG	Logging Residues LR	Remaining Forest RF	RE %
F1	t ha ⁻¹	226.1	19.5	56.1	150.5	25.8
	%	100	8.6	24.8	66.5	
F2	t ha ⁻¹	165.8	19.4	62.1	84.3	24.6
	%	100	11.7	35.9	52.4	
F3	t ha ⁻¹	167.2	17.0	53.5	96.7	24.7
	%	100	10.2	31	58.8	

Source: by author (2018)

Figure 4.3 (a, b, c) shows the main results of material flow analysis in which, for each studied site, Sankey diagrams reveal the biomass flows in tonnes on dry mass basis and its percentage based on the initial aboveground dry biomass. The width of lines is proportional to the quantity in the flow.

Figure 4.3: Sankey diagrams of biomass flow in F1, F2, and F3 before and after logging.

Source: by author (2018)

On a dry mass basis, the most relevant biomass flow width is made up by wood flows related to logging residues. LR represent ≈ 3 times the relative amount of the commercial log biomass. Quantities of collateral damage are shown to be the greatest mass flow and correspond to 19% to 26% of the Initial Biomass, meanwhile harvested tree residue flows were between 6.1% and 10.2% of the Initial Biomass.

When comparing LR origins in the flow diagram, residues originating from the logged tree felling are highlighted as the largest flow, comprised of damage to the surrounding trees and the harvested tree's crown. Secondly, we found that for transport flow predictions the total biomass in Skid Trails residues was typically a stronger predictor than the biomass in the Primary and Secondary Road residues. Hence, yield information on actual material flows provides insight into the extent of transport needs for the biomass harvesting. In the figures, buttress roots represented the third largest flow, which support the view that commercialized tree species having buttress roots in the tropical forest is a common feature.

Graphic 4.1 presents a more detailed description for the allocation of total LR. In a planted forest, all trees are commercial, and all residues are from the logged trees. Under selective logging practice, dead biomass from logged trees is only about one quarter of the total residues.

Graphic 4.1 – Total residue biomass distribution following its origins in each forest

Source: by author (2018)

Material flow analysis of the total biomass withdrawn shows that harvested tree residue amounts varied mostly due the buttress roots percentage. F1 has the lowest relative value showing there was a lower occurrence of trees with buttress roots in that area, combined with a large average diameter ($\text{dbh} \geq 70 \text{ cm}$) of the commercial timber log. Also, in forests F2 and F3 more of harvested commercial timber log belonged to large individual tree species with flat log buttresses such as *Piptadenia suaveolens*, Miq., *Carapa guianensis*, Aubl. and *Couratari oblongifolia*, Ducke et R. Knuth. In our study, the occurring frequency of buttressed commercial logs is a representative sample at 24% to 37% of the total logged trees.

Hollow log residue fractions did not vary significantly between the 3 logging intensities. Trees of commercial interest for timber logging will not be cut if detected as hollow. However even after the verification using chainsaws from trunk to chest height, some

of the logs presented small hidden hollows, reflected in the low percentage of 0.4% of the LR.

The tree crown percentage represents results from 74% to 85% over the harvested tree residues. The variation of these percentages is also attributed to the tree density and the volume of individual commercial timber logs due the tree crown shapes, when its diameter size is defined as medium and larger (≥ 20 m), as in *Hymenaea courbaril* L. and *Couratari oblongifolia*, Ducke et R. Knuth.

The relative amount of CD residues ranged from 72% to 76% of the LR. We calculated the percentage of CD results for felled trees in the selective logging process. It was found that the LR percentage for other tree residues due to the logged tree's felling had the largest flow average of 60% in the logging plots. We also estimated residues related to transport and on-site storage during the opening of roads and log yards. The total sum represents $\approx 1/4$ of the CD in the forests, with Skid Trails as the major contributing factor to the CD percentage ranging from 8.6% to 10.2%.

In terms of resource efficiency, we evaluated the study sites based on the amount of log as product and the total logging residues as waste by the sum of harvest tree residues and the collateral damage (Graphic 4.2).

Graphic 4.2 – Resource efficiency results from the case studies in percentage of commercial timber logs, harvest tree residues and collateral damage

Source: by author (2018)

4.4 Discussion

The high tree diversity in the Amazon forest with just a small number of tree species of commercial interest results in a selective logging technique, and thus collateral damage is inevitable. However, LR are defined as a hidden flow in material flow analysis meaning that they are not commonly shown in economic accounts or in trade and production statistics (OECD, 2015). As it has been shown that LR make up the largest material flow in forest management this has a large negative impact on CO₂ emissions and needs to be taken into account.

Standard allometry equations (HIGUCHI et al., 1998) don't identify residues due to buttress roots and hollow logs from the commercial tree. However, this research shows that mainly buttress roots represent a significant source of residues making up 3.7% in F1, 7.1% in F2 and 6.4% in F3 of the LR biomass. Moreover, in standard allometry equations this is mass attributed to the commercially desired stem, but in reality, it has no economic interest and will become residue. Buttress roots should therefore be taken into account when performing material flow analysis.

In this paper, we have found that even under forest management plans the large amount of LR affect the relative resource efficiency directly. The results presented around 25% resource efficiency in the studied forests, a very low value in comparison to coniferous or planted forest's values of 60% to 77% (ANTTILA et al., 2013; HANSSEN et al., 2018; SMITH et al., 2002; STOKES, 1998). This difference is partly due to the tree species having more homogeneous shapes (i.e. without buttresses roots) thus less residues, but mostly because there is very little to no CD in these homogenous forests.

F1 had the highest amount of AGDB (226.1 t ha⁻¹) and LI (30 m³ ha⁻¹), which could be expected to lead to higher CD because of this additional biomass. But F1 actually presented the highest resource efficiency, as it had the lowest percentage of harvested tree residues mostly due to a lower buttress root percentage. Buttress roots are cut away from the stem, thereby doubly influencing the resource efficiency by reducing the amount of product and increasing LR values. This shows that buttress roots cannot be neglected in resource efficiency estimations and not only the collateral damage needs to be considered as an important source of LR and CD in wood flow.

To increase the efficiency, the LR values must decrease. However, logging residue flow related to HTR (between 18% to 21% of TBW) cannot be significantly reduced considering the heterogeneity of the commercially demanded tree species (as *Buchenavia huberi* Ducke, *Piptadenia suaveolens* Miq, *Hymenolobium excelsum* Ducke, *Dinizia excelsa* Ducke, *Ceiba pentandra* (L.) Gaertn.) and the availability of commercial tree species in the area (limited by dbh $\geq$ 50 cm and the minimum number of remaining species) where normally only dominant or codominant trees are cut per hectare.

The key to reduce LR flow is reducing collateral damage. Residues related to transport already have a lower impact and will not influence LR variation greatly. Even if in some cases the primary road residue flow could be excluded in following cutting cycles when roads would still be used to access other areas, usually they will be left to regrow. Also, this flow made up just 1.2% to 1.3% of the total LR flow. Though secondary road construction results in a larger LR flow ranging between 2.7% and 3.0%, these are even less likely to remain useful after a harvesting cycle than primary roads and therefore significant reductions are not likely.

Another alternative to decrease the LR flow is to find a use for LR $\geq$ 10 cm as product biomass instead of remaining a hidden flow. The commercialization of logging residues is already common practice in timber producing countries like Sweden, Finland, Canada and Japan, used to produce bioenergy and or biochar (BÖRJESSON et al., 1997; MALINEN et al., 2001; MATOVIC, 2011; SILVA et al., 2007; YOSHIOKA et al., 2000).

It is estimated that the transformation of wood residues to charcoal could reach over 75% of the residue volume (NUMAZAWA et al., 2007, 2009, 2014), which would help to increase economical gains, produce bioenergy and effectively use the residue's embedded CO₂ instead of letting it decompose in the forest.

Another hypothetical technique to increase the effectiveness by decreasing CD flow is standing log harvesting. Currently, it is a selective logging method using helicopters to remove cut trees from the forest by lifting them using cables. This is mostly performed in inaccessible areas and is limited by the carrying capacity of the helicopter (AKAY; ACAR; SESSIONS, 2008; AKAY; BILICI, 2016; CLEAVER, 2001; PARTHIBAN et al.,

2014). As the major source of LR in the Amazon forest is the damage to the logged tree's surrounding during the felling, the logging procedure should include keeping the tree upright during the final cutting and lift it out of the forest with minimal disturbance to its surroundings. With this process, CD would be greatly reduced.

4.5 Reference

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5 MATERIAL FLOW ANALYSIS FROM AMAZON MANAGED LUMBER: RESIDUES AND CO₂ FOOTPRINT

Abstract

Wooden building products can be considered as the most important construction material that stores carbon, as trees grow by sequestering carbon dioxide (CO₂) from the atmosphere. In order to evaluate the sustainability of managed Amazon lumber incorporated into construction, three approaches using material flow analysis were calculated: the amount of biomass residues, the net committed CO₂ emissions and the carbon storage in final products. Primary data on 6 commercial tree species harvested in managed plots in the Western Amazon was used to combine forest and sawmill results for a cradle-to-grave analysis. The logging residue flow combined with the sawmill residue flow was found to be 5.5 to 6.6 times greater than the lumber mass flow. The results showed that the average sawmill yield was 54% for lumber production. Considering the forest regrowth over a 30 year period after logging, the CO₂ footprint of the lumber ranged between -6.06 tCO₂ t_{lumber}⁻¹ as carbon stock (reduced impact logging) to +6.64 tCO₂ t_{lumber}⁻¹ emissions from cradle-to-gate, and 0 tCO₂ t_{lumber}⁻¹ (reduced impact logging) to +7.47 tCO₂ t_{lumber}⁻¹ from cradle-to-grave, excluding the energy consumption.

Keywords: Material flow analysis; Amazon managed lumber; Biomass residues; CO₂; Carbon.

5.1 Introduction

It is a common view that intact old-growth forests such as the Amazon forest can be seen as a global carbon dioxide sink (ESPÍRITO-SANTO et al., 2014; LE QUÉRÉ, 2009; PAN et al., 2011), but generally there is scientific consensus that ageing forests cease to uptake carbon as they reach a balance between growth and decay and maintain a steady state of biomass (ODUM, 1969; CHAMBERS et al., 2013). Because of this phenomenon, wood products from sustainably managed forests in the Amazon can help with climate change mitigation by functioning as carbon stock as forest regrowth removes atmospheric CO₂, while generating jobs and revenues (HOLMES et al., 2002; REID et al., 2004; SASAKI et al., 2016).

From a perspective of the carbon dioxide balance of wood, forest regrowth starts once again the process of carbon dioxide uptake after logging. While wood products continue to keep carbon out of the atmosphere during their service life, which can be extended if the wood is reclaimed and used to manufacture other products. The potential benefit is therefore dependent on the turnover time of carbon in construction wood and on the recovery of the carbon sinks lost in the forest after management operations (LEHMANN, 2013; IPCC, 2016; LIPPKE et al., 2010; VALSTA et al., 2017).

Based on temperate forest exploitation data, green building certification systems recommend the use of timber in construction (ESPINOZA; BUEHLMANN; SMITH, 2012; GUSTAVSSON; SATHRE, 2010; RITTER; SKOG; BERGMAN, 2011; WANG; TOPPINEN; JUSLIN, 2014) due to the fact that wood from managed coniferous species is recognized as renewable and their CO₂ footprint from the total product life cycle (cradle-to-grave), including the use of energy sources, can range from CO₂ negative (-3.11 tCO_{2eq} t⁻¹) to almost neutral (0.09 tCO_{2eq} t⁻¹) depending on the post-use scenario (WEIGHT, 2011).

However, sawn wood produced in a conventional unplanned Amazon forest and including the stages of logging, lumber production and transportation of products until the consumer market (cradle-to-gate) has emissions ranging from 7.5 tCO₂ t⁻¹ to 28.6 tCO₂ t⁻¹. These emissions are much higher than those from coniferous forests, a result of the large amount of logging residues generated and because forests do not fully recover within cutting cycles, leading to deforestation (CAMPOS, 2012).

The CO₂ footprint balance in lumber is comprised of four main phases: timber harvesting (raw log extraction and forest regrowth), lumber manufacturing, use phase and end-of-life (JUNGMEIER et al., 2002) as you can see in the Sankey diagram bellow. However, there is no data in the literature available on lumber from managed forests in the Brazilian Amazon.

Figure 5.1: Simplified overview of the wood flow on lumber from managed forest in the Amazon forest and system boundaries from cradle-to-grave (dark blue dashed line) and cradle-to-gate (cyan dot line)

Source: author (2018)

Unlike the managed temperate forests, the great biodiversity and the lower frequency of commercial tree distribution requires selective logging, implying a higher generation of residues (NUMAZAWA et al., 2017). Also the great biomass losses due to lumber manufacturing increase the CO₂ footprint embodied in lumber which needs to be quantified. Hence, the aim of this study is to present for the first time a biomass flow including residue generation, product mass and CO₂ footprint for selectively managed Amazon lumber (cradle-to-grave), based on material flow analysis using original data.

5.2 Materials and Methods

As the CO₂ footprint of the Amazonian wood is negatively influenced by the generation of residues throughout its life cycle (CAMPOS, 2012), this study uses the material flow tool (CHENG et al., 2010; LINDNER et al., 2010, 2011) to estimate the biomass flow and the CO₂ footprint of Amazon lumber, excluding energy related emissions .

Primary forest data on the initial aboveground dry biomass, forest residues, commercial logs and remaining biomass were obtained in case studies (Chapter 3 and Chapter 4) (NUMAZAWA et al., 2017) of 4 typical exploitations of managed forests in the Amazon. Logging intensity ranged from 15 m³ ha⁻¹ (as reduced impact logging, RIL) up to 30 m³ ha⁻¹ with a 30-year cutting cycle, following the Brazilian Forest Code by the Normative Instruction from the National Environmental Council (12,651/12). Forest aboveground biomass ranged from 165.6 t ha⁻¹ to 226.1 t ha⁻¹.

Data on sawn wood were collected at two sawmills in the State of Pará for six species commonly processed in the industry. The flow and CO₂ footprint of the sawn wood was based on 10 log units for each tree species. It is noteworthy that the species included in this study cover 70% of the wood volume processed by the sawmill in its industrial park:

- angelim vermelho (*P*) with basic density (bd) of 0.83 t m⁻³;
- cumarú (*Dipteryx odorata*, (Aubl.) Willd) with bd = 0.91 t m⁻³;
- ipe (*Handroanthus serratifolia*, (Vahl) Nichols) with bd = 0.87 t m⁻³;
- jatobá (*Hymenaea courbaril*, L) with bd = 0.76 t m⁻³;
- maçaranduba (*Manilkara huberi*, Ducke A. Chevaier) with bd = 0.83 t m⁻³; and
- tauari (*Couratari guianensis*,Aubl) bd = 0.52 t m⁻³.

For each log, the geometric volume of the log (GV) was determined based on the Smalian Formula (5.1).

$$GV = 0.7854 \times (\text{mean } d^2 + \text{mean } D^2) / 2 \times L \quad (5.1)$$

where:

d and D = are the mean cross-diameters of the opposite extremities of the log;

L = Log's length (m).

The dry wood biomass of the logs is GV per bd.

Lumber Volume (V_{LUM}) was calculated by the geometric volume of the log. The coefficient lumber yield (C_{LY}) is calculated (Equation 5.2).

$$C_{LY} = V_{LUM} / GV \times 100 \quad (5.2)$$

The total withdrawn dry biomass will be degraded by fire or microorganisms, transforming mainly in CO_2 of which the quantity is estimated by Equation 5.3.

$$P_{CO2} = t \times 0.49 \times 3.67 \quad (5.3)$$

where:

t = dry biomass in metric tonne;

0.49 is the carbon fraction in the dry wood (IPCC, 2013);

3.67 = ratio between the atomic mass of carbon (12) and carbon dioxide (44).

We applied descriptive statistics on sawmill data to analyze the sample of LOGs and their performance under 10% admitted error (Appendix-B).

Resource efficiency (RE) was also calculated as a performance indicator in the lumber supply chain, to focus on the resource productivity (OECD, 2015), and it is a result of the ratio of dry product biomass to the total withdrawn dry biomass (TWB).

The wastage rate (WR) was estimated based on the cumulative residue biomass generated from the final wood product (as log or lumber). It was calculated by the ratio between residue biomass and the biomass of the final product. A lower rate is better.

5.3 Results

5.3.1 Forestry operation

The following table shows the basic data of material flow mass from 3 conventionally managed forest scenarios (results from Chapter 4) and from one reduced impact logging scenario (result from Chapter 3).

Table 5.1: Basic data from material flow mass in 4 different forests

Forest	Data	Mass (t ha ⁻¹)	%
F1 LI 30 m ³ ha ⁻¹	Aboveground dry biomass	226	100
	LOG	20	8.62
	Logging residues	56	24.84
	Remaining Forest (after logging)	150	66.54
	Aboveground dry biomass after 30 years	197	87.2
F2 LI 29 m ³ ha ⁻¹	Aboveground dry biomass	166	100
	LOG	19	11.70
	Logging residues	59	35.85
	Remaining Forest (after logging)	88	52.45
	Aboveground dry biomass after 30 years	121	73
F3 LI 27 m ³ ha ⁻¹	Aboveground dry biomass	167	100
	LOG	17	10.17
	Logging residues	52	31.00
	Remaining Forest (after logging)	98	58.73
	Aboveground dry biomass after 30 years	132	78.9
F4 LI 15 m ³ ha ⁻¹	Aboveground dry biomass	226	100
	LOG	10	4.4
	Logging residues	26	11.5
	Remaining Forest (after logging)	190	84.1
	Aboveground dry biomass after 30 years	226	100

Source: by author (2018)

Logging residues resulted in values from 72% to 76% of the total biomass withdrawn from the forest, while commercial timber logs made up between 25% to 28% of the withdrawn biomass. After 30 years, only F4 recovered 100% of the initial forest biomass. A permanent loss of living biomass was noticed in F1, F2 and F3 as shown in the forest balance (Table 5.2). Under these last conditions managed Amazonian wood cannot be considered fully renewable.

Table 5.2: Biomass balance and CO₂ emissions from forest management in the Amazon forest after 30 years

Forest	Data	Initial dry biomass	TWB*	Regrowth biomass (after 30 years)	Forest Balance
F1	Initial Biomass (t ha ⁻¹)	226	- 76	+ 47	- 29
	%	100	- 34	+ 21	- 13
	CO ₂ in the forest (tCO ₂ ha ⁻¹)	- 406	+ 137	-84	+ 53
F2	Initial Biomass (t ha ⁻¹)	166	- 76	+ 32	- 46
	%	100	- 47	+ 19	- 28
	CO ₂ in the forest (tCO ₂ ha ⁻¹)	- 298	+ 140	- 58	+ 82
F3	Initial Biomass (t ha ⁻¹)	167	- 69	+ 33	- 36
	%	100	- 41	+ 20	- 21
	CO ₂ in the forest (tCO ₂ ha ⁻¹)	- 300	+ 124	- 59	+ 65
F4	Initial Biomass (t ha ⁻¹)	226	- 36	+ 36	0
	%	100	- 16	- 16	0
	CO ₂ in the forest (tCO ₂ ha ⁻¹)	- 406	+ 65	- 65	0
*Total withdrawn biomass = LOG + Logging Residues					

Source: by author (2018)

In Table 5.3 the resource efficiency, wastage rate between the commercial timber log and logging residues and the CO₂ footprint results are shown.

Table 5.3: RE, WR and CO₂ footprint per logs mass and volume in forestry operation

Forest	RE (%)	WR (t t ⁻¹)	WR (t m ⁻³)	tCO ₂ t _{log} ⁻¹	tCO ₂ m _{log} ⁻³
F1	26	2.9	1.9	0.85	0.55
F2	25	3.1	2.1	2.45	1.64
F3	25	3.1	1.9	1.93	1.21
F4	28	2.6	1.8	-4.41	-3.00

Source: by author (2018)

5.3.2 Processing in sawmill

Processing in the sawmill generates more sources of residue, which includes bark, sawdust, trims, sander dust, etc. Hence, measurements were performed to obtain primary data on 10 logs belonging to six different commercial species that were processed to generate 10,150 lumber products. The descriptive statistics of the sample logs' results are presented in Table 5.4, it shows the individual logs' geometric volume, lumber volume and the mean values per species.

Table 5.4: Geometric volume of logs (V_{LOG}), lumber (V_{LUM}), residues (V_{RESIDUES}) and its mean (m^3)

LOG	Angelim Vermelho			Cumarú			Jatobá			Maçaranduba			Tauari			Ipe		
	V_{LOG}	V_{LUM}	V_{RESIDUES}	V_{LOG}	V_{LUM}	V_{RESIDUES}	V_{LOG}	V_{LUM}	V_{RESIDUES}	V_{LOG}	V_{LUM}	V_{RESIDUES}	V_{LOG}	V_{LUM}	V_{RESIDUES}	V_{LOG}	V_{LUM}	V_{RESIDUES}
1	5.8	3.9	1.9	4.8	2.6	2.2	3.6	1.7	1.9	7	3.4	3.6	3.6	1.7	1.9	1.8	0.8	1
2	5	2.8	2.2	1.5	0.8	0.7	2.6	1.4	1.2	2.8	1.3	1.5	2.9	1.4	1.5	4.8	2.5	2.3
3	5.1	3.3	1.8	2.8	1.5	1.3	3.9	2	1.9	2.4	1	1.4	2.4	1.3	1.1	2.1	1.3	0.8
4	5.6	4.1	1.5	3.4	1.9	1.5	3.1	1.5	1.6	5.5	2.6	2.9	6.6	3.4	3.2	3.2	1.6	1.6
5	6	3.9	2.1	2.5	1.4	1.1	3.1	1.8	1.3	5.1	2	3.1	5.6	2.5	3.1	2.3	1.4	0.9
6	6.3	4	2.3	2.2	1.3	0.9	4	2.2	1.8	2.6	1.3	1.3	2.9	1.8	1.1	1	0.6	0.4
7	7.9	4.5	3.4	2.2	1	1.2	6.1	3.2	2.9	2.3	1.2	1.1	2.1	1.1	1	0.7	0.4	0.3
8	5.9	3.5	2.4	2	1.2	0.8	2.3	1.1	1.2	2.5	1.1	1.4	4.2	2.2	2	2	1.2	0.8
9	4.8	3.4	1.4	3.8	2	1.8	3.7	2.2	1.5	3.4	1.6	1.8	2	1	1	1.9	0.8	1.1
10	2.5	1.6	0.9	1.2	0.7	0.5	3.7	2	1.7	3.2	1.5	1.7	2.7	1.4	1.3	1.8	0.9	0.9
Mean	5.5	3.5	2	2.6	1.4	1.2	3.6	1.9	1.7	3.7	1.7	2	3.5	1.8	1.7	2.2	1.2	1

Source: by author (2018)

Figure 5.2 presents the mean percentages of residues and products per tree species in the sawmill (coefficient lumber yield). On average, 46% of the logs turned into residues. The total volume logged was 210.8 m^3 which generated 114.8 m^3 of lumber and 96.0 m^3 of residues, with a RE ratio in the sawmill of $0.54 \text{ m}^3_{\text{lumber}} \text{ m}^{-3}_{\text{TWB}}$.

Figure 5.2: Sankey diagrams from wood material flow in sawmill

Source: by author (2018)

5.3.3 Mass balance and CO₂ footprint: from cradle-to-gate

From cradle-to-gate, including forest and sawmill residues, the average amount of residues generated ranged from 5.7 t t⁻¹ to 6.6 t t⁻¹ of lumber (Table 5.5). Residues will eventually degrade mainly in CO₂, releasing between 55.0 and 121.7 tCO₂ ha⁻¹. The carbon dioxide in the lumber ranges from 10.18 to 11.86 tCO₂ ha⁻¹ and the forest regrowth after 30 years, captures between 59.5 tCO₂ ha⁻¹ to 90.8 tCO₂ ha⁻¹. The resulting carbon balance was between -35.86 tCO₂ ha⁻¹ and 62.21 tCO₂ ha⁻¹. Hence, from cradle-to-gate, CO₂ emissions results for conventional logging ranged from 2.63 tCO₂ t⁻¹ (F3) to 4.56 tCO₂ t⁻¹ (F2) of lumber, excluding the energetics. Meanwhile in F4,

using the reduced impact logging technique the lumber has a CO₂ footprint of negative of 6.64 tCO₂ t⁻¹ from cradle-to-gate.

Table 5.5: Forest and sawmill biomass balance in metric tonne from cradle-to-gate

Source of LOGs	LOG	Logging Residues	Sawmill Residues	Total Residues	Lumber Products*	Residues (t t ⁻¹ lumber)	Residues (m ³ t ⁻¹ lumber)
F1	20	56.2	9.2	65.4	10.8	6.2	4.0
F2	19	59.4	8.7	67.8	10.3	6.6	4.4
F3	17	51.8	7.8	59.9	9.2	6.5	4.1
F4	10	25.5	4.7	28.6	5.5	5.7	3.9

*Based on sawmill yield average of 54%

Source: by author (2018)

Table 5.6: Forest and sawmill CO₂ balance in metric tonne of CO₂ from cradle-to-gate

Source of LOGs	Forest regrowth uptake	Uptake of lumber	Emissions from total residues*	Balance	Emissions (tCO ₂ t ⁻¹ lumber)*	Emissions (tCO ₂ m ⁻³ lumber)*
F1	- 84.0	- 11.09	+ 116.7	+ 32.75	+ 3.11	+2.02
F2	- 59.5	- 11.86	+ 121.7	+ 62.21	+ 6.06	+ 4.06
F3	- 60.7	- 11.71	+ 107.5	+ 46.80	+ 5.10	+ 3.21
F4	- 90.8	- 10.18	+ 55.0	-35.86	- 6.64	- 4.52

*Considering lumber as a carbon stock

Source: by author (2018)

5.3.4 Cradle-to-grave

Due to the large quantities of carbon stored in wood as a building material, it is important to facilitate a long service life, which requires good design with moisture protection during the construction and use phases and proper building maintenance. In Brazil, considering climate related factors, the largest potential for long-term wood-based carbon storage in building materials can be achieved by application in flooring, ceiling or roof structures (NUMAZAWA, 2009), providing an opportunity to reduce the carbon footprint of the building.

That being said, lumber products will still have some additional losses and will generate more residues during installation, use and maintenance (i.e. to cut some parts for fitting as floor components on site, to replace a part of the product affected by termites etc.), until the end of its life when the product will inevitably be degraded to CO₂. Meaning, the temporary carbon stock of the wood used for construction products will oxidize and be released into the atmosphere. This results in total emissions from cradle-to-grave

between 0 tCO₂ t⁻¹ for RIL and 7.47 tCO₂ t⁻¹ for conventional logging as described in the following table.

Table 5.7: Forest and sawmill results of resource efficiency and total CO₂ emissions from cradle-to-grave

Source of LOGs	Total Emissions (tCO ₂ t ⁻¹ lumber)	Total Emissions (tCO ₂ m ⁻³ lumber)
F1	+ 4.78	+ 3.11
F2	+ 7.47	+ 5.00
F3	+ 5.86	+ 3.21
F4	0	0

Source: by author (2018)

5.4 Discussion

From the cradle to the gate of the sawmill, assuming that (partial) recovery of the forest occurs between cutting cycles and disregarding the use of energy consumption, the footprint of the managed Amazonian wood varied in a range between -6.64 tCO₂ t_{lumber}⁻¹ (RIL) to 6.06 tCO₂ t_{lumber}⁻¹ (F2) from cradle-to-gate, and between 0 tCO₂ t_{lumber}⁻¹ to +7.47 tCO₂ t_{lumber}⁻¹ from cradle-to-grave. These results show higher values than found for the total lifespan of European wood products (0.09 tCO₂ t⁻¹), which includes consumption of fossil fuels, but much lower values than those found for the footprint of unmanaged Amazonian wood (18.1 tCO₂ t⁻¹).

As the total biomass withdrawn during logging will not be fully recovered in 30 years by forest regrowth in F1, F2 and F3, a reduction of CO₂ footprint can be obtained by reducing the maximum logging intensity allowed by the Forest Code to values close to RIL (15 m³ ha⁻¹). With less biomass destroyed, the forests would recover in a shorter amount of time. Also, increasing the time between cutting cycles to allow full recovery can be a solution.

Another option it is to extend the lifespan of the lumber to a time equal or longer than is required for the complete recovery of the wood biomass, since wood products are considered carbon stock and therefore a positive influence on the CO₂ balance.

Besides that, after multiple iterations of recycling, sustainable wood material from managed forests can be used for bioenergy production, in this way replacing fossil fuels (BÖRJESSON et al., 1997; ERIKSSON; GUSTAVSSON, 2008; HOLTSMARK,

2012) and reducing their footprint by offering a source of energy, instead of decomposing without added benefits. Afterwards, wood ash could be used as fertilization of the forest floor to increase the amount of nutrients in the soil (ERNFORS et al., 2010).

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CONCLUSION

The thesis describes the material flow, products and residues of managed Amazonian lumber and estimates its CO₂ footprint, the resource efficiency of the production process and its wastage rate. This method allowed for assessment and comparison of the potential impacts of residue generation on climate change and uncovering opportunities for climate change mitigation. The research was based on a combination of primary data from 5 managed forests and data obtained from literature.

Forest management strategies in the Brazilian Amazon aim for preservation of the forest carbon stock and biodiversity between sequential loggings, as is considered key for climate change mitigation, while assuring sustainable economic exploitation by ensuring a sustained yield of timber and non-timber products. However, the study has shown that the New Forest Code regulations, which allows a logging intensity up to 30 m³ ha⁻¹, limited to trees with diameter at breast height ≥ 50 cm in a 30-yr logging rotation cycle, do not necessarily allow full forest recovery.

Logging intensity equal or close to 30 m³ ha⁻¹ in a 30 years cycle will most probably result in a progressive decrease of aboveground biomass, carbon stock and biodiversity while also eroding the economic interests in preserving the forests. Therefore, the current rules of the Forest Code do not ensure sustainable forest exploitation and policy change is required. This could be achieved by increasing the rotation period, decreasing the logging intensity or adopting new harvesting techniques to increase the resource efficiency.

Forest regrowth equations applied in our analyses have some limitations and are likely to represent a best-case scenario of regeneration considering that studied plots were located in well-managed areas and disregarded variables such as fire, illegal logging, climate change and the specific recovery of commercial timber species.

However, the results showed correlation between logging intensity and the recovery capacity in a data-driven comparison, estimating a recovery time of 22 years for a logging intensity of 15 m³ ha⁻¹ and 43 years for 30 m³ ha⁻¹. Further research is required to provide evidence of regrowth biomass variables and consequently more effective logging methods.

From all the forests in the studied cases, only the case applying the reduced impact logging method ($15 \text{ m}^3 \text{ ha}^{-1}$), which is required for certification by the Forest Stewardship Council, was able to fully recover the original aboveground biomass within the 30-year cutting cycle, thereby sustaining the biodiversity and the carbon stock of mature tropical forests. This way, the study has shown that the current Forest Code does include guidelines allowing for sustainable forest exploitation on which further tightening of the law can be based.

The small number of commercially interesting tree species in the Amazon forest makes selective logging necessary, greatly increasing the residue generation and CO_2 footprint during exploitation in comparison with monoculture Northern hemisphere temperate coniferous forests. However, these logging residues are usually considered a hidden flow and are often ignored in economic accounts or in trade and production statistics. But from an environmental perspective, logging residues affect the relative resource efficiency directly, making up a share ranging from 71% to 76% of the total forest biomass withdrawn.

The resource efficiency of the logging operation was between 25% and 28% of commercial product from the total biomass withdrawn, which is a considerably lower percentage than found for planted monoculture forests at $\approx 60\%$. The logging residue masses found in this study were between 2.5 to 3.1 times greater than the commercial log mass. Left on the ground, these will decompose mostly into CO_2 , resulting in a CO_2 footprint varying from $-4.41 \text{ tCO}_2 \text{ t}_{\text{log}}^{-1}$ (for reduced impact logging) up to $2.45 \text{ tCO}_2 \text{ t}_{\text{log}}^{-1}$, ($-3 \text{ tCO}_2 \text{ m}_{\text{log}}^{-3}$ to $1.64 \text{ tCO}_2 \text{ m}_{\text{log}}^{-3}$ respectively) from cradle-to-gate when discounting the CO_2 uptake by the forest regrowth between cutting cycles.

Furthermore, logging residue flows related to the logged tree (between 24% to 28% of the total logging residues or 6.1% to 10.2% of the initial dry aboveground forest biomass) cannot be significantly reduced considering the anatomy of the trees, as typically a percentage of around 66% of the tree mass is commercial stem wood, with the other 34% resulting in residues.

To decrease the negative impact of Amazon forest logging on biodiversity and climate change it is key to reduce collateral damage, as it represents the largest source of

logging residue flow (between 72% to 76% of the total logging residues or between 18.8% to 25.7% of the initial dry aboveground forest biomass).

Hypothetically, the standing stem logging technique can avoid collateral damage. Although this technique has not been applied in the Amazon, it is already practiced in North America and Canada. With less biomass destroyed due to on ground logging operations, the forests would recover in a shorter amount of time, positively influencing remaining forest carbon stock.

The easiest way to raise profits of forest exploitation is by increasing the logging intensity, which implies larger CO₂ emissions, forest destruction and biodiversity extinction. However, as described in the discussion of Chapter 4, it is also possible to increase economic gains by effectively using the residues' embedded carbon content. Instead of letting residues decompose in the forest as a hidden flow, logging residues with a diameter equal or greater than 10 cm could be given economic value through coproduct conversion (i.e. charcoal).

It's estimated that the transformation of wood residues to a useful product could reach an amount of over 75% of the residue volume ordinarily left in the forest to decompose. This way, a substantial amount of dead wood could be used for ecosystem functions or for biofuels.

That being said, this strategy should focus on maximizing the economic gain to ensure logging viability while implementing the reduction of logging intensity necessary for full forest recovery within cutting cycles. The created biofuels should therefore be used to reduce firing of fossil fuels. Perspectives focused only on economic gain encourage deforestation similarly to illegal logging practices if the law does not ensure sustainable practice.

During sawmill processing on average 46% of the log was converted into residues, even while using state-of-art sawmill machinery and employing sawmill simulation models to optimize lumber cutting to increase operation efficiency. The resulting resource efficiency for lumber production after sawmill processing was between 13% and 15%. A part of the residues generated in product-processing mills are also suitable for coproduct conversion.

At the end of the production process (from cradle-to-gate), including extraction from the forest and sawmill processing, disregarding energy consumption and including the forest regrowth, the total wastage rate ranged between $5.7 \text{ t t}_{\text{lumber}}^{-1}$ to $6.7 \text{ t t}_{\text{lumber}}^{-1}$ and the CO₂ footprint of the managed Amazonian wood ranges from $-6.64 \text{ tCO}_2 \text{ t}_{\text{lumber}}^{-1}$ (RIL) up to $6.06 \text{ tCO}_2 \text{ t}_{\text{lumber}}^{-1}$ or $-4.52 \text{ tCO}_2 \text{ m}_{\text{lumber}}^{-3}$ to $4.06 \text{ tCO}_2 \text{ m}_{\text{lumber}}^{-3}$.

By extending the lifespan of lumber products to a time equal to or longer than required for the complete recovery of the wood biomass in the forest (≈ 43 years, Chapter 3), long-lived wood products from managed Amazon forests can increase the overall carbon stock and may offset carbon stock loss by the decay of wood residues after logging and lumber production. If these criteria are met, lumber production as a whole can have a positive influence on the CO₂ balance.

The CO₂ footprint across all life phases from cradle-to-grave, based on the material flow analysis and depending of post-logging uses, for lumber from reduced impact logging has remained neutral while the CO₂ footprint for lumber from the other forests varied from $4.78 \text{ tCO}_2 \text{ t}_{\text{log}}^{-1}$ to $7.47 \text{ tCO}_2 \text{ t}_{\text{log}}^{-1}$ disregarding energy consumption. A high value in comparison to the total CO₂ footprint of European wood products (from cradle-to-grave: $0.09 \text{ tCO}_2 \text{ t}_{\text{lumber}}^{-1}$), but a considerably lower value than found for the CO₂ footprint of unmanaged Amazonian wood of $18.1 \text{ tCO}_2 \text{ t}^{-1}$ from cradle-to-gate. Moreover, the research showed the possibility for an overall negative or neutral footprint (in reduced impact logging method), if strict forest management is applied generally.

All things considered, this research is a start in creating databases and analysis tools that can help architects, engineers, and other professionals to evaluate environmental impacts of whole buildings using wood products.

Highlights of chapters

Chapter 4: LOGGING RESIDUES AND CO₂ OF BRAZILIAN AMAZON TIMBER: TWO CASE STUDIES OF FOREST HARVESTING

- L30 and L15 produced a notable logging damage, however only L15 recovered the initial biomass.
- Without considering the fossil fuel consumption, on cradle-to gate, both CO₂ balance was negative for 120-year time horizon.
- Growth model describes that it takes 42.3 years to recover total biomass under L30 while under L15 it takes 21.2 years.
- L15 is best for environmental purposes.
- L30 yields twice as much revenues.

Chapter 5: BRAZILIAN AMAZON LOGGING RESIDUES: MATERIAL FLOW ANALYSIS FROM 3 DIFFERENT FORESTS MANAGEMENT OPERATIONS

- MFA approach was applied to identify and quantify logging residues.
- Results were based upon original data from 3 managed forests in the Amazon.
- Resource efficiency average results 25% of commercial timber log of the total dry mass of biomass withdrawn.
- Collateral damage has the largest hidden flow of the logging residues ($\approx 73\%$ of TWB).
- Alternatives to decrease the forest residues were discussed.

Chapter 6: RESIDUES AND CO₂ FOOTPRINT FROM AMAZON FOREST LUMBER

- Material flow and CO₂ footprint from managed Amazonian lumber on 6 tree species.
- Sawmill yield average was 54%.
- Ratio between products and residues was in average 6.2 t t^{-1} .
- CO₂ emissions related to the Amazon lumber (cradle to gate) considering the forest regrowth varied in the range between $-6.1 \text{ tCO}_2 \text{ t}_{\text{products}}^{-1}$ (F4) and $4.6 \text{ tCO}_2 \text{ t}_{\text{products}}^{-1}$ (F2).
- Without considering the fossil fuel consumption, from cradle to gate CO₂ emissions from Amazon lumber are estimated $\approx 3 \text{ tCO}_2 \text{ t}_{\text{products}}^{-1}$.

FUTURE WORK AND RESEARCH NEEDS

These are further research suggestions arising from the thesis limitations.

1. Analyze social and economic impacts in life cycle assessment from Amazon managed lumber;
2. Contributions to economic and environmental gain of new products from recycling;
3. Compare regulations in the New Forest Code with research based on primary data to determine the efficiency of forest productivity and its biodiversity protection;
4. Inclusion of fuel consumption of typical logging equipment and emissions from transportation and industrial operations in life cycle assessment from managed Amazon forest lumber products;
5. Comparative effectiveness research of residue generation due to collateral damages to biomass through tree extraction by helicopter;
6. Access to long term studies on biomass recovery of commercial tree species;
7. Discuss strategies that maximizes revenues and allow for the full recovery of the forest, supporting biodiversity;
8. Comparing the difference between short and long-lived wood products over their full lifespan in affecting their carbon stock in life cycle assessment;
9. Identify wood treatments and building design alternatives which provides quantifiable measures of lifespan performance-improvement; and
10. Create databases that help architects, engineers, and customers evaluate the environmental impacts of wooden buildings products.

APPENDIX A – STATISTICS RESULTS OF LOGS VOLUME CONVERSION IN LOGGING RESIDUES ≥ 10 CM

Forest Plot 1 (L30) in Chapter 3

Forest 1	Units	Results
Mean ratio	$\text{m}^3 \text{ m}^{-3}$ (residues ≥ 10 cm per stems logged)	1.78
Standard deviation	$\text{m}^3 \text{ ha}^{-1}$	1.033
Coefficient of variation	%	57.8
Representativity of number of populations up to the total	%	80

Forest Plot 2 (L15) in Chapter 3

Forest L15	Units	Results
Average ratio	$\text{m}^3 \text{ m}^{-3}$ (residues ≥ 10 cm per stems logged)	1.71
Standard deviation	$\text{m}^3 \text{ ha}^{-1}$	0.289
Coefficient of variation	%	16.9
Representativity of number of populations up to the total	%	80.4

Forest Plots in Chapter 4

Forest	Units	Results
Average ratio	$\text{m}^3 \text{ m}^{-3}$ (residues ≥ 10 cm per stems logged)	1.78
Standard deviation	$\text{m}^3 \text{ ha}^{-1}$	1.03255
Coefficient of variation	%	57.8
Representativity of number of populations up to the total	%	80

APPENDIX B – DESCRIPTIVE STATISTICS EQUATIONS AND RESULTS OF LOGS SAMPLE ON SAWMILL DATA

Statistics Equations

Arithmetic mean:

$$\bar{X} = \frac{\sum_{i=1}^n X_i}{n} \quad (5.4)$$

Standard deviation:

$$s_x = \sqrt{s_x^2} \quad (5.5)$$

Coefficient of Variation:

$$CV = \frac{s_x}{\bar{X}} \times 100 \quad (5.6)$$

Average Variance:

$$s_{\bar{X}}^2 = \frac{s_x^2}{n} \quad (5.7)$$

Standard Error:

$$s_{\bar{X}} = \pm \frac{s_x}{\sqrt{n}} \quad (5.8)$$

Absolute Error:

$$E_a = \pm t \times s_{\bar{X}} \quad (5.9)$$

Relative Error:

$$E_r = \pm \frac{t \times s_{\bar{X}}}{\bar{X}} \times 100 \quad (5.10)$$

Confidence Interval for the arithmetic mean:

$$CI = \bar{X} \pm SE_{xt} \quad (5.11)$$

Where

i = initial number of sample; n = sample size (LOGs) = 60; s = Standard deviation of a sample data; s^2 = The variance sample data; SE = Standard error; t = 2.001 (Degrees of freedom with a confidence level of 95% = n-1); x = an individual value upon which other subgroup statistics are based; $\bar{X}$ = Population Mean.

Results from statistics in Chapter 5

Descriptive statistics results of logs sample from sawmill

Arithmetic mean (%)	53.8
Coefficient of Variation (%)	33.0
Standard deviation	17.8
Mean Standard Error	2.3
Lower Confidence limit	49.2
Upper Confidence limit	58.3
Absolute Error	4.6
Relative Error	8.5
n (calculated)	43.7
n (needed)	44.0

Source: by author (2018)