THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

# Timber as a forest-risk commodity: embodied socio-ecological impacts in the Brazilian supply chain


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# Abstract

The continued loss and degradation of forest resources is one of the largest sustainability challenges of our time. The past decades rise in global demand for agricultural and forest commodities have created unparalleled pressure on the natural resources, leading to forest destruction and associated loss in carbon stocks, invaluable biodiversity, ecosystems services, livelihoods. Timber and related wood products have long featured among top forest-risk commodities, yet we still lack elementary understanding of this supply chain and how it links consumers across the world to tropical timber extraction and associated socio-ecological impacts. The overarching goal of this research is to advance the understanding of the socio-ecological impacts embodied in the production to consumption of timber originating from Brazilian native forests. It contributes to answering two foundational questions: To what extent can we connect localities of production to consumption? How are the embodied illegality risks of the supply chain distributed? Paper I provides answers to the latter. By adapting environmentally extended input–output modelling to timber originating from Brazilian native forests, we show how distinct illegality risks can be mapped and quantified at species-level across the supply chain to overcome traceability limitations. We focus on high-value ipê hardwood from the Amazon state of Pará, a leading timber producer and contested forest frontier. We found less than quarter of all ipê entering supply chains between 2009 and 2019 is risk-free, provide insights on the geographical diversification of potential laundering strategies and show how we can use this approach to overcome the lack of traceability. Paper II expands on Paper I in further compiling data on logging permits and timber flows from state- and federal-level transport licenses substantiated by these, and assessing to what extent we can connect forest exploitation to timber flows. We find about 22% of the exploited forests can be associated to authorized areas, whereas the remaining falls within the complex land tenure patchwork of this forest frontier. Next steps include getting closer to answering: How is the embodied forest degradation risk of the supply chain distributed? This thesis may offer important insights toward this end.



**Keywords:** Forest degradation, Timber, Supply chain traceability, Sustainable Forest Management (SFM), Illegal logging, Environmentally-extended input-output model, Transparency, Land use, Forest frontiers

# Appended Publications

This thesis is based on the following papers:

**Paper I** Franca, C.S.S., Persson, U.M., Carvalho, T., Lentini, M., 2023. Quantifying timber illegality risk in the Brazilian forest frontier. *Nat Sustain.* https://doi.org/10.1038/s41893-023-01189-3

C.S.S.F. and U.M.P. conceived the research idea and led the design of the analytical framework and the writing; C.S.S.F. led the data analysis; T.C. and M.L. contributed to the interpretation of results, analysis tools and to the writing of the manuscript.

**Paper II** Franca, C.S.S., Persson, U.M., Cardoso, D., Damasceno, C., Ward, R.S. Souza Jr., C., 2023. Putting numbers on (un)certainties in the timber traceability-illegality-risk nexus: the case of Pará, Brazil. *Manuscript*

C.S.S.F. conceived the research idea and led the design of the analytical framework with support from U.M.P. and D.C.; C.S.S.F. led the data analysis; C.S.S.F. and U.M.P. wrote the manuscript with support from D.C.; D.C., C.D., R.S.W., C.S.J. contributed to the interpretation of results, data and analysis tools and to reviewing the manuscript.

# Other publications

Other publications by the author not included in the thesis:

Lindberg, K., Martvall, A., Bastos Lima, M., Franca, C.S.S., 2023. Herbal Medicine Promotion for a Restorative Bioeconomy in Tropical Forests: A Reality Check on the Brazilian Amazon. Forest Policy and Economics 155. https://doi.org/10.1016/j.forpol.2023.103058

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# Contents

# CHAPTER 1

# Introduction

The upkeep of the forest resources throughout the globe is fundamental in maintaining the stability and resilience of Earth's system [1], [2]. Every year, however, forest resources continue to be degraded and lost at a rate that outpaces recovery efforts and overall gains [3]–[5]. The world's burgeoning appetite for cheap agricultural and forestry commodities over the past decades has been unparalleled in driving this downward trend [6]–[8]. Timber and related wood products have long featured among top forest-risk commodities[1] [7], [9]–[11]. Nonetheless, the ambiguity and multifaceted complexity of its role across regions of major production is notable. On one hand, timber production acts as an ally in helping to maintain standing forests. On the other, it enables forest destruction at its highest level.

The timber production from Brazilian native forests (defined here as primary and naturally regenerating forests [12]) is representative of such ambiguity. Brazil remains one of the largest global producers and exporters of tropical

[1] "Forest-risk commodity" are defined by Rautner et al [9] (p.15) as "globally traded goods and raw materials that originate from tropical forest ecosystems, either directly from within forest areas or from areas under previous forest cover, whose extraction or production contributes significantly to global tropical deforestation and degradation".

timber [2] [13]. The Amazon biome serves as its primary source for roundwood from native species, with the country producing approximately 8 to 11 million cubic meters annually [14]. Under new environmental policy shifts [15]–[18], the operationalization of current instruments relies on the potential of timber production as a strategic mechanism for forest governance and to address the over-exploitation of forest resources [16]. Targets of the reinstated PPCDAm [3] foresee a 5 million hectares increase in the amount of public forests to be placed under logging concession between 2023-2027 [16], which carries a renewed promise of supporting the maintenance of standing forests in the face of forest conversion pressures. At the same time, Matricardi et al [19] highlights forest degradation by logging has remained relatively constant over time at an 4-year average rate of 0.4-0.7 Mha between 1996–2014 across the Brazilian Amazon, even as the most significant drops in deforestation were observed. This degradation encompasses from the application of logging best practices to predatory extraction methods, with estimates indicating that 44-68% of the timber exploitation in top producer states is unauthorized [20]. Yet, much of this illegal timber still makes it into the legal supply chain [21], [22].

Despite the empirically clear differences between timber production that alleviates overall pressure on forests and outright predatory logging, consumers of timber products are still at a loss when minimizing sourcing risks. Brazil has been an early-mover in taking steps to track timber products from native forests [23]. In 2006, a digital system was put in place [24], [25] based on what is known as a "Document of Forest Origin" (DOF) System: a licence needed to transport, send, receive and store timber products which created a paper trail between the production site and any subsequent steps in the timber transport until its final product. However, individual entries were not systematically linked, resulting in consumers seldomly being able to connect a product to its origin. Additionally, the varying implementations at different state and federal levels, the lack of integration between licensing and origin control sys-

[2] Tropical timber, under the ITTO's governing treaty, has been redefined from including "only tropical hardwood saw and veneer logs, sawnwood, veneer and plywood" to encompass "tropical roundwood for industrial uses, which grows or is produced in the tropics situated between the Tropic of Cancer and the Tropic of Capricorn" [13]. Hence, statistics are most useful for broad sectoral comparisons, but should be carefully interpreted at a single-country basis.

[3] The PPCDAm stands for "Action Plan for the Prevention and Control of Deforestation in the Legal Amazon", a policy under which Brazil experienced its sharpest drop in deforestation rates on recorded history (primarily) in the period 2004-2008 [16].

tems and overall issuing data gaps from lack of transparency only exacerbate the lack of traceability [20]. Moreover, several hurdles exist for better comprehending what socio-ecological impacts at production is embodied in final product.

In this context, the overarching goal of the research in this thesis is to advance the understanding of the socio-ecological impacts embodied in the production to consumption patterns of timber originating from Brazilian native forests. The current thesis contributes to answering a set of foundational questions: Where are timber products from different localities consumed? To what extent can we connect localities of production to consumption? How are the embodied illegality risks of the supply chain distributed? Both appended Paper I and II work closely to address these. These questions are foundational because they pave the way for addressing a set of key long-standing yet unresolved questions; the core motivation underlying this research: How much forest degradation is associated with Brazilian timber consumption? Where is forest degradation embodied in the timber products consumed? How is the embodied forest degradation risk of the supply chain distributed? These questions are not answered here, though Chapter 4 offers insights into potential next steps for addressing them.

Both papers presented here build on the painstaking compilation of nearly 4,000 logging permits issued within Pará state between 2009-2019 and the careful analysis and interpretation of the timber transport data they substantiate. Paper I shows that the deployment of an environmentally extended input-output model can be leveraged to overcome some of the traceability shortcomings for Brazilian timber and to connect consumption to localities of production. It exemplifies how socio-ecological impacts could be traced and their distribution across the supply chain understood by putting number to key illegality risks faced by consumers. It underscores illegality risks are species- and geography-specific, which carry important implications for biodiversity conservation. Paper II delves into the nuances of the extent to which roundwood entering the timber supply chain can be connected to observed forest exploitation. It provides insights on what data characteristics may mean in relation to actor's behaviours across the landscape, transparency and wider territorial governance.

The next chapter in this thesis provides further background (Chapter 2) on the dynamics of forest degradation as well as the policies and instruments leveraged in governing Brazilian native forests and the timber production and commercialization originating from these. This background is followed by a discussion on contributions provided by the current work and appended papers (Chapter 3) as well as discussion on what the foreseen groundwork may be needed to start addressing the future questions contended in this research (Chapter 4).

# CHAPTER 2

# Background

## 2.1 Dynamics of forest degradation

### Defining forest degradation

Much like the question on what constitutes "deforestation" or what can be classified as a "forest", the definition of "forest degradation" is a matter of protracted debate [26]–[28]. As put by Wunder [29], a *broad* definition of deforestation, for instance, encompasses characteristics mostly associated with forest degradation; when it includes not only the sole conversion of forests to other land uses, but also the reduction in density and structure, the impoverishment of species biodiversity and genetic pools, the loss of ecosystem services (e.g., loss of biomass, loss of carbon) within standing forests. Arguably, a broad definition of deforestation serves the purpose to account for the overlooked forest degradation, particularly when impacts of forest losses were less known or less of a concern.

A *broad* definition of "forest degradation", in turn, can serve as evidence for why it has been overlooked; if not in the willingness to account for its impact, certainly on its operationalization. When in 2009 the Food and Agriculture

Organization of the United Nations (FAO) put together a Working Group for the purpose of defining forest degradation, the leading problem was the widely varied views beyond what they could identify as an emerging common core: the "reduction of the capacity of a forest to provide goods and services" [30] (p.6). Definitions changed according to the understanding of drivers[1] (whether anthropogenic or not) and, notably, according to the main point of interest of the defining institution: biodiversity conservation, carbon sequestration, wood production, soil conservation, recreation, or cultural aspects [30]. The concept also carries the problem of choosing appropriate reference states, timescales, thresholds, and, ultimately, forest values [31]. Even though several more fora for discussion have been held since then—in particular in the context of REDD+[2]— policy-makers are still unable to agree on a framework for its definition [31], [34]. For instance, FAO still currently leaves degraded forest "To be defined by the country" [12], [34], leading to direct implications on reporting [34]. The EU Deforestation Regulation (EUDR) policy-making process can also be illustrative of the lack of common ground given an operational definition is yet to provided, despite the regulation already having been passed into law [35]. In fact, experts have contended that an agreed upon definition may neither be needed nor desirable [36]. Others see the terms' lack of agreement beyond broad aspects as a hindrance to forest degradation accountability, with not only conceptual, but legal, institutional and operational implications for the establishment of policies and monitoring systems surrounding the loss of forests [26], [28], [31], [37].

*Narrower* definitions of forest degradation take a more pragmatic stance and are directly connected with the ability to measure, compare and account for the impact. For Matricardi et al. [19], [38] "forest degradation occurs within forests and is characterized by a loss of biomass within an intact canopy". Indeed, The Intergovernmental Panel on Climate Change (IPCC), in its own extensive analysis of definitions and operationalization implications finds that "Defining forest degradation based on changes in biomass may be the most straightforward to implement and can be directly related to estimates of all

[1] A distinction is also made between "forest degradation" and "forest disturbance", with the latter being more closely related to causes and so covered in more detail in the drivers section.

[2] The acronym stands for "Reducing emissions from deforestation and forest degradation" and other benefits of forests in relation to climate, as negotiated under the international climate regime[32]. The devise of this mechanism led to substantial advances in the understanding of forest degradation [28], [33].

relevant forest carbon pools" [39] (p.16). Underlying such thinking is the fact that the coupling of remote-sensing techniques and field inventory data is still one of the most affordable methods for wider-scale assessments of forest degradation [33] and has experienced rapid methodological advances over the last decade [40]–[42]. Several recent studies on forest degradation [5], [43]–[45] focus on the area of biomass loss or their associated carbon pools as a way to showcase forest degradation from a practical perspective, and emphasize this is a key impact of the same, if not larger, extent to the carbon losses due to deforestation.

## Socio-ecological impacts of forest degradation

Forest degradation is associated with several consequences. Deforestation and forest degradation are evidently closely intertwined events, the latter naturally seen as a precursor to the former. Vancutsem et al. [5] highlights nearly half of the degradation identified in their study of forests across the humid tropics could be interpreted as a precursor of deforestation (88.6 million ha between 1990–2019). The authors emphasize this is particularly true for Southeast Africa and Southeast Asia. For the Brazilian Amazon, Asner et al. [46] found in an early study that logged forests (a key proximate driver of forest degradation) were 2-4 times more susceptible to be cleared than intact forest and had low survival rates, particularly in the short term. As of late, however, studies [19], [43] have been pointing to the fact that although this sequencing is important to the dynamics of overall forest loss, a substantial share of forests remain degraded, and are not deforested. Matricardi et al. [19] found that about half of the logged-over areas between 1996-2018 remained forest. Although the same authors show other degradation types presented lower survival rates, about a one-fifth to one-forth of degraded forests identified in 1992 remained forest, albeit degraded. This implies forest degradation is frequently not an integral part of deforestation, but an additional impact which should be accounted for separately.

Degraded forests are also intuitively thought of as a better harbour for biodiversity than deforested land. At the same time, research has shown biodiversity losses within degraded forests are not proportional. Barlow et al.[47] show that areas studied that retained a large amount of forest cover (69-80%) lost more conservation value from losses within forests than from straight deforestation. Burivalova et al. [48] also shows logging intensities between 38-63 $m^3.ha^{-1}$ can as much as halve species richness in mammal and amphibian group and increase the influx of more generalist birds, underscoring that impacts on biodiversity have been underestimated, particularly in studies that assume selective logging as one uniform use. In terms of tree species themselves, forest degradation may increase species richness, however at early succession stages [49]. Slow-growing, low-density, non-pioneer populations such as the big-leaf mahogany (*Swietenia macrophylla*), *ipê* (*Handroanthus spp.*), and other high value tree species may become more vulnerable [49]–[52]

Degraded forests retain more forest biomass and carbon than simply deforested land, staving off larger contributions to climate change. However, studies continue to shed light on the extent to which we have underestimated degradation-related emissions and point to the larger role this process has in driving current carbon losses. As Xu et al.[53] emphasizes, terrestrial carbon fluxes continue to be the most uncertain aspect of the global carbon cycle, nonetheless, gross emissions and removals from woody vegetation in the tropics have been found to be four times larger than temperate and boreal ecosystems combined.

Although studies looking at the magnitude of carbon emissions from tropical forests have found these to be at times a carbon source [54], [55] and at others a sink [53], [56], the latest studies agree that for the case of South America [53]—and particularly regarding the Brazilian Amazon [44], [56]—forests ecosystems are becoming increasingly a carbon source. This is exacerbated by carbon stocks' slow recovery in secondary growth due to less favorable conditions connected to where these are situated [57] and the fact woody biomass recovery is far slower than leaf biomass and hence associated canopy closure [46], [58]. Harris et al. [56] estimates that the Brazilian Amazon was a net contributor of 0.06 $PgC.yr^{-1}$ the atmosphere between 2001 and 2019. For forest degradation in particular, Lapola et al. [43] recently estimated up to 0.2 petagrams of carbon are emitted per year ($PgC.yr^{-1}$) across the wider Amazon, which rivals, if not exceeds, impacts of deforestation (0.06 to 0.21 $PgC.yr^{-1}$) between 2001 and 2018. Bullock et al. [45] also highlighted this point, and comparing their work to previous estimates, they found that the area of disturbed forest in the Amazon was 44%–60% more than previously realized for the 1995-2017 period. Additionally, Qin et al. [44] showed for the more recent period of 2010-2019, above-ground biomass losses to degradation were three times more to than deforestation in the Brazilian Amazon: a net contribution of 0.67 PgC to the atmosphere.

Forest degradation is also associated to substantial feedback systems, often teleconnected to wider other processes, that are key for maintaining Earth's stability and resilience [1], [59]–[62]. Most prominently, the loss of forests more broadly (both intertwined deforestation and forest degradation) has been connected to the reduction of evapotranspiration, rainfall and the delayed onset of the rainy season [62]–[65], and increased vulnerability to the spread fire [66]–[69]. All such biophysical impacts also interact at different scales leading to a decrease in the social and economic functions of forests, including of tourism, availability of fruits and medicinal plants, wood, water, tourism, hunting and other ecosystem services [70], [71]. Overexploitation of timber in old frontiers has rendered the continued exploitation of standing forests economically inviable, [72], [73] with evidence showing this may be true even inside of highly monitored federal concession areas where illegal loggers have benefited from new roads and infrastructure [74]. Pressure over frontier forests and disputes over land and access to natural resources also cause substantial social tension and violence across the region [75]–[78]. Clearly, the use of forests have positive gains but particular attention is needed in the wide-ranging, intertwined and cumulative effects of degradation, many which remain understudied.

Box 1. On "Socio-Ecological Systems". The use of "socio-ecological impact" across the thesis stems from the systems thinking roots reflected through the concept of "Socio-Ecological Systems" (SES). At the broadest level, SES's convey the need to go beyond artificial disciplinary boundaries that lead to dismissing fundamental relationships between the social and natural systems (e.g. [79], [80]). Ostrom's [81], [82] body of work particularly stands out. She articulates in depth of why in fact the social and natural systems can be seen as the same and delves into the methodological and policy implication of considering them so in their complexity [81], [82]. Her work formed the basis for further development of SES framework [83], [84]. Even if still challenging to apply in its comprehensiveness [85], when speaking of worldviews, Ostrom certainly captured the struggle of natural resource-dependent peoples through her work of negating the tragedy of the commons and opening the space for furthering the field of political ecology and the varying ramifications we can entertain investigating today [86].

## Drivers of forest degradation

Drivers of forest degradation are the events responsible for the changes in forest characteristics. Two aspects that add nuance to the understanding of drivers are worth clarifying here. First, that 'forest degradation' and 'forest disturbance', refer to different processes; although the concepts may be used interchangeably, particularly within literature aligned with narrower definitions of forest degradation. 'Forest disturbance' has its roots in forest ecology and is often understood as (and interpreted from a mechanistic perspective of) any relatively discrete event that make growing space available within forests [87] (p.90). Because it is associated to events, 'forest disturbance' is often more closely related to the *causes* (e.g. disturbance agents, disturbance vectors) of forest loss, be it deforestation (e.g.[88], [89]) or forest degradation (e.g.[37], [43]). Secondly, that an analysis of the drivers of forest degradation can also benefit from Geist and Lambin's [90] work and be interpreted from (i) a proximate or direct cause perspective (immediate actions at the local level that directly impacts forest cover) as well as from (ii) an underlying forces perspective (or fundamental societal processes of local to global scale) that underpin direct causes.

Both aspects emphasize that drivers are highly context dependent. While myriad proximate drivers have been listed, described and measured at different scales [37], [43], for the case of the Amazon a few stand out. Lapola et al.[43]—informed by several recent lines of research showing feedbacks between forest losses and climate change effects are already being observed [60], [91], [92]—compared four main human-induced proximate drivers: extreme droughts, forest fires, edge effects resulting from deforestation-induced habitat fragmentation, and timber extraction. While it has been known for some time that El Niño-Southern Oscillation (ENSO) events caused peak emissions by their rapid release of carbon stocks above ground and in the soil [44], [66], [93], this study showed that extreme drought events increased the estimate of total degraded area from 5.5% to 38% of the remaining Amazonian forests. Droughts are seen here as overall less severe disturbance events (evaluated as a function of carbon loss in this study). However, when in years of extreme drought events, these can be a catalyst to forest fires, the driver deemed the most severe. Overall the study highlights that, for the remaining of the Amazon forest, about 1.8% have been degraded by forest fires, 1.8% by timber extraction, 2.8% by edge effects, and 41.1% by extreme droughts.

Although edge effects resulting from habitat fragmentation can be seen as a proximate driver [43], these also constitute deforestation-dependent driver [19]. Matricardi et al. [19] in showcasing forest degradation has surpassed deforestation in the Brazilian Amazon, used two broad categories to assess forest degradation dynamics: (i) dependent degradation (DD) and (ii) independent degradation. The first seen as dependent on, or coupled to, deforestation events (i.e., edge effect, fragmentation effects of edges and isolated fragments). The second, those more independent or decoupled from other processes (i.e., deforestation) such as logging and to some extent fire. The study found that forest degradation due to edge effects was by far the largest single driver, associated with a third of the total area degraded for the period between 1992-2014. However, this form of degradation decreased substantially following the decrease in deforestation rates of the early 2000's. Notably, degradation by logging remained relatively stable at around 7-8 $Mm^2.yr^{-1}$ between 1996-2014, with the last four-year average underscoring degradation by logging and edge effect were of quite similar magnitude. Moreover, as we move towards "zero deforestation", the relevance of addressing forest degradation increases if left unchecked. Indeed, "zero forest degradation" already started entering the wider debate as corporate accountability is being hardened of late [94].

Logging, therefore, remains a key proximate driver, with a significant share of independence in relation to others (it is additional and not always codependent) and it is of increasing in relative importance (as its impacts have been of late overlooked). An important differing facet relevant for this research is the role of illegal logging, which can be defined as "all practices related to the harvesting, processing and trading of timber inconsistent with national and sub-national law" ([95], pg.16). Illegal logging and related trade are a complex and multi-dimensional issue [95] and it is one of the most challenging aspects of approaching timber as a forest-risk commodity. Not the least because legality alone does not encompass whether the law is fair or sustainable [96], [97]). But further because legality is plural reflecting national and sub-national context [95]. As discussed by Pacheco et al. [95], in practice there may be no clear distinction between the impacts of legal versus illegal activities given the subtleties of illegality (e.g., [21])

Yet, there are key differences that cannot be ignored when it comes to impacts of illegal and predatory logging. And given context is relevant, this is particularly true for the case of Brazil. In terms of forest disturbances, Tritsch et al. [98] have shown that when comparing sites with known forest management practices (i.e., Conventional and Reduced Impact Logging, RIL) to areas where logging practices were “Undetermined” (indicative of illegal operations), disturbances occurring on latter areas were higher for all indicators being assessed (i.e., disturbance’s maximum intensity, cumulative, average and frequency). Cumulative disturbance over the period of 15 year was found to be 5% for RIL, 12% in Conventional and reaching 35% in plots with “Undetermined” logging practices. Additionally, they found that while plots under RIL and conventional management were logged only once in the period, logging plots with undetermined practices were logged almost three times. Fore the case of Brazil, Valdiones et al. [20] estimates that in the states of most degradation by logging, about 44-68% is done illegally. Illegal activities still lead to a higher risk of deforestation and subsequent forest degradation [19], are a disincentive to the sustainable initiatives [99] and lead to deeply damaging human rights, and land tenure rights abuses [76], [77], [95], [100].

## Timber as a forest-risk commodity

Timber and related wood products have long featured at the top of forest-risk commodities lists [7], [9], [11]. That is, "globally traded goods and raw materials that originate from tropical forest ecosystems, either directly from within forest areas or from areas under previous forest cover, whose extraction or production contributes significantly to global tropical deforestation and degradation" [9] (p.15). Although we are increasingly aware of the unparalleled role of agricultural commodity production in driving deforestation and associated forest degradation [8], Pendrill et al. [7] showed that between 2005-2013, the embodied deforestation associated with forest products (0.8 Mha.yr$^{-1}$, i.e., losses for the establishment of forests plantations) in the tropics was second only to beef (2.2 Mha.yr$^{-1}$), by far the largest driver. Additionally, about 38% of forest loss remained unattributed, likely due to untraced logging as well as what could be considered natural losses, but also as shown by recent studies [19], [43], [45] increasingly understood as compounding human-induced drivers such as edge effect due to forest fragmentation, more severe and extreme droughts events and intensified fire regimes.

Most uncertainties related to the precise role of timber products lie in the dual nature of timber products in relation to forests. In one hand, timber production can be an ally helping maintain forest standing. This is most obvious through forest restoration and rehabilitation initiatives [101], through the uptake of agroforestry systems and the establishment of commercial plantations that use best practices and take advantage of seemingly degraded or unproductive lands. Such forests can act like buffers to other more pressured forests and other ecosystems. On the other hand, forests have at times done just the opposite, putting further pressure on high-conservation habitats for the purpose of producing of pulp and paper [3]. The so called "conversion forests" [102] have provided an rapid yet ephemeral gains from forest clearing but where environmental impacts and social implications appear to be underestimated. Selective logging regimes carried out under the banner of "Sustainable Forest Management" (covered in more detail later) are illustrative of this precise duality as well. This production regime at its best supports the removal of a few individuals and can support the maintenance of all remaining forest resources while supporting livelihoods. At its worse, it supports the systematic forest degradation and its associated cascading effects.

While we have estimates for embodied deforestation associated with forest products, that is not the case for embodied forest degradation. In a key EU-commissioned study carried out when the EU started looking at its impact over forest loss associated to trade the authors were not able to include forest degradation citing the complexity of the issue and lack of data. As Gao et al. [37] points out though, selective logging has been one of the most well-studied forest disturbances relating to degradation in moist tropical forests and it is possible that at this time the knowledge gap was still larger in relation to how we understood impacts associated with agricultural production.

Timber and related wood products, however, continue to be commodities of pivotal relevance. Raising awareness of impacts of climate change and the multi-fold risks it carries has spurred debate on the increased use of timber to reduce carbon footprints from building materials[103] and including to the more contentious use as a renewable energy source [4]. Peng et al. [104] in a recent study concluded that globally, wood harvests are set to increase by 54% between 2010 and 2050, from 3.7 billion m3 in 2010 to 5.7 billion m3 in

[3] https://news.mongabay.com/2022/03/fsc-certified-moorim-paper-linked-to-massive-forest-clearing-in-indonesias-papua/

[4] https://www.nationalgeographic.com/environment/article/europe-burns-controversial-renewable-energy-trees-from-us

2050; a scenario under which it would generate an annualized carbon costs of about 0.95–1.15 $PgC.yr^{-1}$ close to common estimates of annual emissions from land-use change due to agricultural expansion. Moreover, a combination of the need to substituted high-emission materials with timber coupled with the already foreseen increase in demand will likely put more pressure on timber sources across the globe.

## 2.2 Governing Brazilian forests and their timber products

### The roots of timber production, legality and sustainability

Timber production has been of fundamental importance throughout Brazilian history. As put by Miller [105], timber was the steel, oil, coal, and plastic of the early modern period in the Portuguese colony. Timber did not only constitute the commodity of the first economic cycle in Brazil, its extraction supported in many ways Portugal's naval power maintenance and expansion through the 16-18th centuries when maritime traffic routes were highly coveted [106]. Timber production was also the springboard to the subsequent economic cycles all from the construction of sugar boxes and ships with which the commodity was traded globally, to the up-keeping of polities comforts across cities in Brazil and Portugal [106]. While Brazilwood was perhaps the most known timber, certainly playing a role in setting Brazil as the Portuguese crown jewel [107], Maioli et al.[106] highlights that ships sailed off year after year carrying a variety of species. Archival documentation unveiled for year 1784, for example, showed that ships with at least 30 different species described by their vernacular name sailed off that year, with one shipment notably carrying 121 different species, with documents showcasing the growing knowledge on different tropical timbers, the appropriateness of their uses [106], and hence pointing to a growing knowledge base that went beyond the sole use of timber as an homogeneous source of biomass.

Early timber production was most surely an extractive and exploitative endeavour. Brazilwood, copaiba, jatobá, jequitibá, peroba and many others species then traded are still referred today as "madeira-de-lei" or "timbers-under-the-law" [108], which came to be a synonym for good quality timber. As Maioli et al [106] points out, however, the concept has roots in the fact timber resources started to be regulated for the perceived threat exploitation incurred on stocks with several decrees and laws already present by the mid-17th century. Indeed, the Brazilian Forest Law itself has been referred to as "ancient" by environmental law scholars in Brazil [109]. Such regulations, however, can be said to not be motivated by environmental (much less social) concerns, but chiefly for securing the use of such resources by powerful players [106]. The environmentally-concerned timber production, became more prominent much later in the 20th century after the drafting process of the 1965 Forest Code and the movements to lift the right to an ecologically balanced environment to the status of a fundamental right, which was enshrined in the 1988 Brazilian Constitution, something unprecedented at the time particularly in the Global South [109]. Still, forest frontiers continued to be depicted (and broadly perceived) as a bounty of endless resources throughout this period [10] aided by developmentalism dominant views [109]–[111] resulting in a rather extractive mindset still persisting as a legacy in timber production systems from native forests today [112].

Legal frameworks have been a key tool deployed to ensure timber production would take place in a way that prevents over-exploitation, but often not with its intended outcomes. During the colonial period, limiting access of resources by the Crown has led to local communities finding easier to destroy trees altogether and converting forests areas to other land uses rather than seeing timber as a resource to be used and preserved [106]. Unintended consequences such as this still occur in today's implementation of regulations. Richardson and Peres [72] emphasize that there is no evidence that supports the notion that the oldest mechanized logging frontiers have been sustainably exploited as a renewable resource capital. As the authors show, limits placed on legal volume allowable to be removed (broadly 30 $m^3.ha^{-1}$) are used up with the most valuable species looking for profit maximization, where a predictable trend in local extinction of large individuals of high-value species is observed in old logging frontiers. Following a "Hubbert's Curve" pattern—first described for the trajectory of non-renewable natural resource use—the relationship describes a period of increased production which after reaching its peak, continually decreases at the same rate until resource can no longer be extracted. The recent inclusion of *Handroanthus* spp. (*ipê*) and *Dipterix* spp. (*cumaru*) species in the CITES II Appendix in November 2022 [113], shows that in many ways we have already started discussing implications of the post "peak timber" as suggested by Shearman et al [114] and that high value species and individuals are becoming predictably rare.

While not a perfect parallel, Valdiones et al. [20] does point out the fact a substantial decrease can be observed in production of roundwood since we first started understanding the timber market's magnitude in the Amazon. In one of the first comprehensive studies about timber production [115], about 28 $Mm^3$ of roundwood were estimated leaving forests across the region in 1998. The Brazilian Environmental Agency (IBAMA) [14] have estimated that this production is now oscillating between 7-11 $Mm^3$ (2012-2019). This is predictable from a diminishing stocks point of view, but other factors should also be considered such as, although not limited to, (i) the role of product substitution (for example the increased use of planted forests domestically [5] through the expansion of exotics such *pine*, *eucalyptus* and *teca* stands but also use of other materials); (ii) price oscillations in domestic and international markets, including those related to; (iii) unintended consequences and policy leakages of broad scale policy [17] such as those observed during the process of deliberation and establishment of the EU Timber Regulation (EUTR) and Lacey Act amendment [116]–[118]; for instance, leading increase in prices and decrease in traded quantities with North American and European market while increase in trade with less stringent countries [116]–[118]; (iv) lack of incentives for those investing in sustainable forest management [20] or rather the disincentive generated by unsustainable production [99].

## 'Sustainable Forest Management'

When referring to native species most production comes from areas explored under a "Sustainable Forest Management" (SFM) regime. According to IBAMA [14], 87.6% of the roundwood volume produced in Brazil entered the supply chain through approved Sustainable Forest Management Plans (Plano de Manejo Florestal Sustentável, PMFS) between 2012-2017, with the rest coming from legal deforestation (7.9%), planted forests (4.3%) and harvest of isolated trees (0.2%). The Forest Code of 1965 provided the first legal instruments in modern time securing the exploitation of native forests in a way

[5] According to the latest statistics of MapBiomas (https://brasil.mapbiomas.org/), the class "silviculture" has expanded from about 1.5 Mha in 1985 to nearly 8.9 Mha in 2022, with an addition of 3.4 Mha only between 2004-2014. Silviculture encompasses exotic species given that the commercial plantations of native species still very limited [14].

that “can only be utilized in compliance with technical management plans” [119]. The activity has been object of several regulations, including a 1986 ordinance [120] (issued by the then “Brazilian Institute for Forestry Development”, IBDF) where a “Sustainable Management Project” (*Projeto de Manejo Sustentado*) was required for the authorization of timber extraction from native forests; notably prior to key scientific advances in the field of SFM in the tropics. Current legislation setting legal parameters define SFM as “the management of forests to obtain economic, social and environmental benefits while respecting the maintenance mechanisms of the ecosystem object of management considering the, cumulative or alternating, use of multiple species” (own translation, [121]).

SFM legal parameters broadly encompasses [121]–[123] a 25-35 year harvest cycle, with an overall upper limit of $30m^3.ha^{-1}$ ( 3 trees/ha), with special cases applying for lower intensities and smaller areas. A minimum of 10% of trees per specie should be retained, ensuring that at least three individuals with DBH (Diameter at Breast Height) above the minimum harvest diameter (50 cm, DMC) are kept at every 100ha, occurrence below which precludes the exploitation of the species altogether. Such figures can also change according to whether species are listed as vulnerable at in the National "Official List of Brazilian Flora Species Threatened with Extinction” [124] for instance a minimum 15% should be retained and a minimum of four trees/species for 100 ha [123]. It is also clear timber exploitation should happen in accordance to whether use is restricted or prohibited by other national or international norm [123].

Importantly, states and municipalities are entitled to issue complementary norms and resolutions (and they often do), so long as they are more restrictive than national-level regulations. For instance, the state of Amazonas establishes a maximum of 25 $m^3.ha^{-1}$ upper harvest limit [125]. Still, all from conventions on how to submit the SFM plans (known as PMFS) to procedures for post-harvest assessment can differ from one state to another, which can be equal parts positive and excessive. Indeed, overregulation in the forest sector and SFM activities has at times been cited as a factor contributing to predatory forms of exploitation [20] as well as a hindrance to the implementation of concessions [97].

Not only the legal extraction of timber from native forests has extensive regulatory grounds in Brazil, but it is also a strategic element of the country’s current environmental policy and an important income-generating activity in the forest frontier. The PPCDAm (Action Plan for the Prevention and Control of Deforestation in the Legal Amazon)—policy under which Brazil lived the sharpest drop in deforestation rates in recorded history and abandoned under the Bolsonaro 2019-2022 administration—enters its 5th phase maintaining in no small measure the promotion of sustainable forest management as an income generating activity, particularly through a new bioeconomy lenses and as a livelihood diversification opportunity to local communities living within forests and depending in various ways of these resources [16]. As a strategic mechanism in the support forest governance, the PPCDAm foresees the placement of an extra 5 million hectares of public forests under concessions [16]. Expansion to be, amongst others, measured by the amount of timber forest products commercialized ([16], Annex II). The placement of public forests under concession also supports reducing the vulnerability of remaining undesignated public forests—estimated at around 50Mha by 2018, with 11.6Mha illegally registered as "private property" [126]. Although the notion of "log it or lose it" has been now and again challenged [114] (with an ever-growing evidence that what is left only logged is also associated with important impacts), it is still arguably one of several key options to support and buffer remaining forests.

## Timber traceability and the supply chain

The Brazilian government tracks timber production from native origins and their commercialization for over three decades [23]. The then analog system eventually came under growing scrutiny for the widely described frauds it enabled [127]. As a response, in 2006 the “DOF System” was instituted [24]. Ever since digital, it is in practice a crediting system based on units of volume: credits are first generated upon granted authorization for extraction (logging permits) and are transferred to owner-administrator, processors and other intermediaries downstream until its final processing [24], [25]. The new DOF System opened several opportunities for innovation (including by requiring the reporting of coordinates of origin and destination between transactions) but foresaw states being responsible for their own implementation, a consequence of the decentralization process from the new law on public forests also instituted that year [127], [128]. Thus, in addition to the federal system—required for the control of enterprises licensed under national-jurisdiction—, the different approaches taken by states at the early period of DOF System establishment created varying practices that ultimately rendered its purpose of keeping track of products ineffective [22], [127]. For example, items evaluated by the Federal Court of Accounts in 2011 on the control of forest products transport [127], describes the scramble of Federal Highway Police (PRF) agents when confronting several different templates for differences licenses, often displaying different information and with no possibility of information validataion in a centralized database.

The National System for Control of Origin of Forest Products (SINAFLOR) was instituted as a response, with the aim to integrate the varying sub-national systems [129]. The remaining systems today are deemed compatible but only partially overlapping and not fully-integrated. For example, the Brazilian Open Data Portal (October, 2023), points outs "due to lack of integration of state systems, data on internal transportation of the following still missing: [...] Pará for the entire period", evidencing key aspects of integration remain unresolved [6]. As of November 2022, a new “DOF+ Rastreabilidade” (“DOF + traceability”) is established, bringing key improvements to the DOF System (now referred to as "DOF Legado" or "DOF Legacy") [130]. Notably, a permanent code based on issuing agency, authorization type, year, authorization number and number of log will now follow the product from when the harvest if first declared to its final processing facility [7]. For the moment, both "DOF+ Traceability" and "DOF Legado" will continue to co-exist. As pointed out by a recent guide released in support of supply chain operators who are now navigating the changes [131], credits still circulating through DOF Legacy, will continue to do so until its final processing facility and a few procedures are not yet covered by the new system (e.g. importing licenses, niche licenses (AUTESP/DOF special) and the cadaster of transporting units). In fact, several data and knowledge management systems have been undergoing changes over the past few years, both in relation to the institutional dismantling surrounding the environmental agenda [132] and more recently a movement to build back underlying institutional structure (e.g. [16] that allows for the kinds of transparency needed when discussing traceability in this supply chain [133].

[6] https://dadosabertos.ibama.gov.br/dataset/dof-transportes-de-produtos-florestais

[7] https://www.gov.br/ibama/pt-br/assuntos/biodiversidade/flora-e-madeira/documento-de-origem-florestal-dof/dof-rastreabilidadesobre-o-dof–rastreabilidade

# CHAPTER 3

## Advances and Present Work

This research aims to deepen the understanding of socio-ecological impacts that are an integral part of (i.e. embodied in) timber production, and hence consumption of Brazilian timber products. While a variety of methodological approaches can be used that don't link precise geolocation (or perimeter of timber extration) or establish the precise producer-consumer linkages to discuss embodied impacts, this research revisits more foundational questions: Where are timber products from different localities consumed? In fact, which localities produce timber of native forest origins? Can we connect localities of production to consumption in the first place and to what extent? Even after three decades of substantial investment by federal- and state-level governments into instruments for the control of origins of products coming from native forests in Brazil, answers to these questions remain opaque and insufficient from a consumer (or regulator) perspective.

While we can discuss what merits legality [96], [134], illegal logging is often pointed out as a key reason for the lack of proper understanding of logging-associated impacts: at times being singled out as a separate process and in many others shown as inextricably linked with legal logging [20], [95]. It is thus also relevant to explore such questions in the context of quantifiable loopholes that suggest illegality. In other words, how are the embodied illegality risks of the supply chain distributed?

This research contributes on two main fronts. First, by painstakingly compiling data on logging permits and the geolocation of areas authorized for extraction and connecting this to data on timber transport, we show it is possible to connect consumption to production, albeit with limitations [1] for a wider region beyond a case-by-case basis. Second, we show illegality risks do not prevent us from understanding this connection, but rather it can be considered as an integral socio-ecological impact embodied from production to consumption. This impact is quantifiable and its quantification can deliver further actionable information with potential to be leveraged by enforcing agencies (when political willingness is present) as well as a wider set of interested actors [15], [133]. Moreover, the research (Paper I in particular) makes efforts to go beyond the prevalent scientific discourse in what relates to the illegal logging framing for the case of Brazil that concentrates on investigating issues connected to the extraction of wood [136] by also covering gaps and subtleties present when seeing this system from a downstream consumer perspective. All the while, the research (particularly Paper II) emphasizes that key gaps in understanding which also still remain at extraction.

In Paper I, data from 1,262 logging permits and 309,198 records on the transport of *ipê* (the *Handroanthus* spp. species group) were compiled to quantify different sources of illegality risk between 2009-2019 and to pinpoint potential entry-points where such timber was potentially laundered into the legal supply chain for the state of Pará. Across places of timber extraction, two types of illegality risk were assessed: first, whether permits being used to substantiate timber transfers can be identified and whether they are valid; second, like the seminal work by Brancalion et al [21], we estimate whether yields reported entering the supply chain were overstated when comparing with official data from RADAM forest inventory [137] on naturally occurring densities. Across places of processing and consumption downstream, the entry-point of illegal timber is quantified by comparing the inflows and outflows of timber

[1] Limitations here mainly refer to the fact that (i) we assume logging permits and transport data to be the best representation of true legal production, despite evidence other subtle illegality risks have been documented, including cyber crimes [135].;(ii) data quality and transparency have direct implications to figures analysed and (iii) simplifications are needed (e.g. roundwood conversion of products, species groupings, assumptions surrounding the distribution of species across the state among others pointed out in the respective papers)

(after appropriate roundwood-equivalent conversions), where the illegality risk constitutes the actor-based discrepancy between what is been sold and bought. Finally, all three illegality risks assessed were traced downstream to apparent consumption through an actor-level physical input–output model, which was used for the purpose of overcoming the lack of full traceability observed in the Brazilian case. The model is based on an assumption of proportionality between an actor's physical inflows and outflows, allowing the quantification of upstream embodied illegality risks associated ipê products consumption.

Key findings of Paper I suggest that less than a quarter of all *ipê* entering supply chains during the period of analysis is risk-free. We found that a logging permit did, indeed, exist for nearly all volume entering the supply chain, but that about 16% of these were invalid, showing loopholes in the system are visible. Of the valid permits, nearly half of the volume was deemed overstated, showing the validity of a permit may not be enough to ensure legality.

Paper I further emphasizes that illegality risks are species-specific. We use the example of *ipê*, to make this point clear given the high price its timber fetches in domestic and international markets [13] and the role it has in determining the viability of SFM activities [73]. Paper I shows how diversified the risks can be across geographies, from upstream roundwood producers, to downstream processors and intermediaries. This requires different intervention alternatives even amongst localities that may be similar in some ways; for example, when comparing Itaituba and Juruti, which are substantial points of origin but the former is more associated with risks at the processing and intermediaries level whereas, in the latter, more risks are evident at the start of the supply chain (i.e., volume overestimation and use of invalid permits). Paper I shows that we can use the data, even with its limitations, for the very purpose of further understanding what strategies should be deployed in accordance to different risks.

Paper I also corroborates the westward movement of the forest frontier which is well discussed across literature [20], [52], [72], [138]. This pattern is not evident for all species, but rather is a feature of the most valuable timber species as they predictably become extinct in older frontiers, with their distribution even being used as a proxy for frontier age [72]. Thus, this species-specific disaggregation when looking at risks is important to monitor and evaluate biodiversity and frontier dynamics. The species also carry distinct risks for the drivers they relate to. Most exploitation of *ipê* is destined for international markets, whereas other species serve the internal market to a higher extent.

In Paper II, we expand the compiled logging permits dataset used in Paper I to roundwood produced for all species. We combine all spatially explicit official data on logging permits (available through polygons or geographical coordinates) for the volume entering the supply chain and overlay this information with remote sensing-derived data on observed forest exploitation as well as spatial data on wider land tenure and governance. Preliminary findings of this study suggest that, similar to the case of ipê, we can locate nearly all logging permits. Nonetheless, only about half of the volume can be connected to a polygon that delineates an area authorized for logging. An extra 41% of volume can be covered by coordinates. But for both the volume covered by polygons as well as coordinates, uncertainties remain. Notably, only 22% of forest area identified as exploited (through remote sensing) overlaps spatially with authorized areas where a defined perimeter was available, given the very challenge of establishing the spatial arrangement for the logging permits where only single coordinates were available. Although much of the remaining exploitation can be linked to actors given land use and tenure information we can still use—through wider forest management area and the Environmental Rural Cadaster (CAR)—overall traceability is more uncertain and illegality risks are higher. About 16% of observed forest exploitation falls completely outside CAR and authorized areas; likely unauthorized exploitation.

Paper II tests the boundaries of data transparency and quality in the context of rapid technological development. First, among many noteworthy reasons for focusing on Pará, transparency in timber production and traceability is higher here [20]. Despite the state being a relative front-runner, the study still dealt with the reality that Pará's Environmental Licensing and Monitoring System's (SIMLAM) key original dataset (i.e., logging permits) was still only available through PDFs, leading to data inconsistencies and cleaning needs not consistent with data quality and knowledge management (e.g. metadata maintenance) standards increasingly required. While certain aspects of traceability can be simply impractical or infeasible depending on context [139], it is also true we are living through an "explosion in accessible information about how supply chains operate, and the environmental and social risks and opportunities they pose" [133]. Barriers have been increasingly lowered by technological advances and the demand is increasing for such information (the EU Deforestation Regulation perhaps is the leading example). As put by Arts et al. [139], aside from the specific interest of producers, authorities and consumers, the public at large also has the right to be informed about what occurs across supply chains and by extension what the producers, traders and authorities allow to happen across value chains globally.

Additionally, in what relates to the object of study, Paper II moves beyond the initial question of whether can we geolocate production to exploring the extent to which we know the perimeter delimitation of where extraction was authorized to take place. The question is key for ensuring legality, but also going beyond it to understand what type of quality of management is being carried out across these localities. This is something that currently appears to show more promise for agricultural commodities than forest ones (particularly timber) [35] despite the longstanding body of research on the effects of logging [37], [46]. Scrutinizing the boundaries of authorized areas is important because, within Environmental Impact Assessment literature [140], the concept of cumulative effect assessment is very well-developed, but not applied to the overall logging enterprise in the case of the co-evolving fronts of forest degradation that currently push the frontier. This is particularly true when considering that legal and illegal logging are inextricably connected, with similar trends of parallel increase/decrease [2]. We explore the boundaries of data availability that are in the public domain (despite often not being readily accessible) to establish to what extent we can connect impacts more directly or rather explore methodologies that support filling in data gaps while these remain.

Several limitations also apply for both Papers I and II. These have been expanded in the appended; nonetheless, a few broader aspects unaddressed in these may stand out. First, several other illegality risks exist. These are of a different nature (e.g., tax avoidance, cyber frauds, labor law violations) [21], [22], [95], [135] and can be systematically checked. BVRio's proprietary solution, for instance, can make over 150 legality and consistency checks by leveraging big data approaches, pending continued and up-to-date access to data [141]. With Paper I, we focused on showcasing how the approach could be used to trace embodied socio-environmental impacts of similar nature for the timber supply chain, while also prioritized detailing illegality risks deemed

[2] The pattern is evident in the Mato Grosso's historical trend in timber exploitation https://imazon.org.br/wp-content/uploads/2022/09/Simex-Mato-Grosso-Agosto-2021-a-Julho-2021-PDF.pdf

critical [21], [22] and yet not quantified from a downstream perspective. This paper also suggests that illegality risks' relevance should also be assessed in relation to where their incidence is the highest, because they may differ across geographies.

Additionally, our figures lack field validation, which could potentially show an unknown overall share of permits are simply fake [22]. Likewise other issues (such as cyber-frauds and "imaginary" data [22]) could warp how we view the data being used here. Nonetheless, the analyses presented with this thesis carry the assumption the data is official and to some extent the best representation of what can be captured from "legality-in-practice" [139]. This being said, Perazzoni et al. [135] shows, even for the authorities whose work is to primarily monitor forest exploitation activities, detailed field checks are often simply unfeasible and so this type of research does contribute actionable insights in this space.

# CHAPTER 4

# Outlook and Future Work

While the work presented in this thesis makes its own contributions, it also lays the foundations for connecting the consumption of timber products to the potential forest degradation it embodies, as well as its associated environmental impacts. Thus, the upcoming work seeks to come closer to addressing: How much forest degradation is associated with Brazilian timber consumption? Where is forest degradation embodied in the timber products consumed? How is the embodied forest degradation risk of the supply chain distributed? Several studies make clear forest degradation advances at a steady pace, while the environmental policy framework remains unclear on how it accounts for this impact or addresses it (even if signs of a downward trend in forest loss are evident under the new political administration[1]). Despite recent announcements that Brazil will restore commitments under the Paris Agreements[2], Amazonian forest degradation still must be properly incorporated into the climate agenda given its relevance [142]. Additionally, aside from the legality aspects already expected to be addressed through different policies in place

[1] https://news.mongabay.com/2023/09/deforestation-in-the-amazon-rainforest-continues-to-plunge/

[2] https://institutotalanoa.org/wp-content/uploads/2023/09/Brazils-NDC-2023-analysis-September-20th.pdf

(e.g EUTR, Lacey Act amongst others), the recent establishment of the EUDR brings renewed demand for better understanding the sustainability of timber production from native forest origins beyond their legality [15], [94].

The work foreseen in the next steps, however, are of similar nature to previous papers. It focuses on bringing together underexplored datasets to derive new insights—underexplored either because they have been around for a long time but lack accessibility (e.g., lack of transparency, not machine-readable) or because these are new and the caveats of their limitations may still preclude their full use. First, we continue to explore data on timber transactions and in particular their connections to the licensing of enterprises (i.e., logging permits and wider PMFS data), the consequences of their operations (i.e., illegality risk, forest degradation) and the wider territorial governance within the landscapes production takes place. For the case of the timber transport dataset, which only recently started being made available[3], it is clear the lack of full integration between state and national-level licensing and traceability systems is still a bottleneck. The recent transition to the new "DOF+ Traceability" represents a key improvement in adding a persistent identification from forest of exploitation to final product. Yet, arguably "DOF Legacy" and its intricacies remain underexplored beyond overall reporting of broader trends [14] despite the many lessons it offers (e.g., Paper I).

Second, while we were able to indicate in Paper I how much timber was reported as "exported" at destination, the extension of the analysis to incorporate detailed trade data can provide yet another layer of insight. The extensive work done through the Trase initiative[4] for other forest-risk commodities highlights a wealth of unknowns regarding the timber that can still be explored (e.g., location of sawmills and processing facilities, major jurisdictions and actors are involved in the trade and their respective exposure to risks). Norman and Zunino [143] have detailed the trade in *ipê*, highlighting exports how from Brazil have doubled form 2010-2016 to 2017-2021. Combining the analysis presented in this thesis with data on trade would allow us to analyze what international demand is more associated with illegality risks or potentially other socio-ecological impacts embodied in this trade.

Third, connecting the risk of a product being linked to forest degradation has not been previously done and hence attempting to get closer to address

[3] https://timberflow.org.br/

[4] https://www.trase.earth/

such question can serve for better understanding and accounting of socio-ecological impacts (e.g., embodied carbon losses and biodiversity impacts). As preliminary findings of Paper II shows—even when only simply referring to the area exploited and not the quality of management—new insights in this field can serve to showcase what could be useful in directing all from law enforcement to a wider set of actors to whom geointelligence [135] of this supply chain is also relevant. As Arts et al.[139] puts it also, the public at large have the right to be informed about what occurs and what actors in this supply chain (producers, traders and authorities) allow to happen across the value chain. In turn, more transparency (when properly harnessed) can support the uplifting of several place-based sustainability initiatives which do count on timber as well as a set of other forest products for their maintenance [112].

Core to answering the posed questions is the ability to connect what happens within the confines of the authorized areas of timber extraction and the characteristics products embody. Paper II delves into the immediate challenges, which constitute a blend of incomplete knowledge about the features of the PMFS (for instance, effective area explored within these) with the complexity of a contested frontier, where land tenure can be uncertain or the outcome of illicit schemes. Yet, challenges are not fully overcome. Discussions under the umbrella of the new EU Deforestation Regulation (EUDR) have cautioned placing the burden on producers to come up with detailed information (geolocation, supply chain tracking systems) risking excluding smallholders [144]. Indeed, it is worth noting that the complete and precise delineation of extracted areas and their connection from producer to consumer may be in certain contexts infeasible, leading to adaptations of what can be achieved in practice [139].

The body of regulations guiding the exploitation and commercialization of forest resources in Brazil, however, have long required places of activity (extraction, storage, processing) to be geolocated and/or perimeters to be described [24], [121], [128], [129], [145]. We also found these requirements appear to be followed (at least on paper, for the coordinate geolocation and not considering field validation). In addition, those making the most profit from environmental destruction already take advantage of technological advances [75]. Take the example of the Environmental Rural Cadaster (CAR), which has been at times co-opted for the purpose of land-grabbing [126]. Here the potential owners submit the perimeter of their properties to undergo analysis and in Pará alone, nearly 270.000 polygons have been submitted, most still under analysis. Although traceability and understanding the impacts of management have their challenges, it is likely that closing the technological gaps for producers and other supply chain actors merits more attention. We can come up with methodological approaches to connect forest degradation to consumption, but the question remains around which approaches limit damaging activities and support sustainable initiatives that have shown to effective at protecting forests.

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