Mapping the limits to timber traceability at origin: The case of Para, Brazil

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Article

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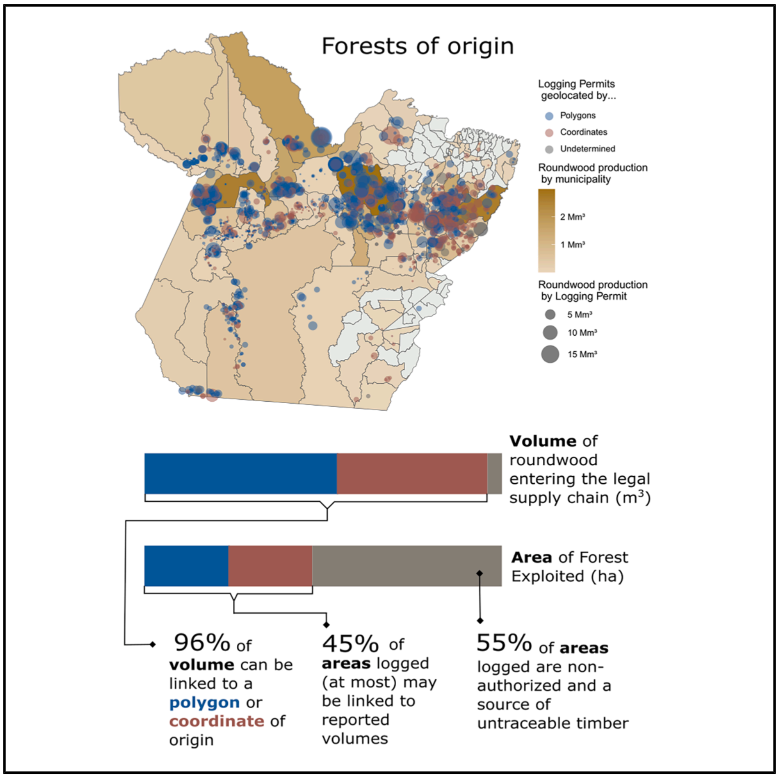
Graphical abstract



Highlights

- We geolocate 96% of officially reported timber volume to polygons or coordinates
- The traceable volume accounts for only 45% of observed forest exploitation
- Our analysis confirms well-documented methods for timber laundering
- Available data can identify accountable actors for most exploited forest areas

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In brief

Building on the backdrop of new EU Deforestation Regulation, demand for information on timber origins and their socioecological impacts is at an all-time high. Analyzing over a decade of data from public digital systems for tracking timber origins requiring geolocation, we highlight key lessons on the limits of determining true origins. Our findings show how timber volumes at origin link (or not) to forest exploitation. Transparency in data is critical for filling gaps in traceability and socioecological risk assessments.

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Mapping the limits to timber traceability at origin: The case of Pará, Brazil

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SCIENCE FOR SOCIETY Forest degradation and loss in the Amazon threatens global biodiversity, climate stability, and local livelihoods—but much of this damage occurs within the canopy and is less visible. Timber products from these forests risk contributing to the damage, making it critical to understand whether sourced products are legal and sustainable. However, we still lack basic understanding of the supply chains linking consumers to timber extraction and impacts. By bridging information gaps, our research shows that while official data from Brazil's timber-control systems can trace timber to origin, matching this to observed forest exploitation reveals widespread unauthorized logging and entry-points for illegally logged timber. As demand for transparency grows, driven by policies like the EU Deforestation Regulation, this research can inform improvements in timber traceability systems, inform law enforcement, and foster collaboration among actors to strengthen shared accountability in managing forests sustainably.

SUMMARY

The decline in integrity of standing forests across the Amazon is an overlooked yet far-reaching threat to biodiversity, livelihoods, and climate stability. With the European Union (EU) Deforestation Regulation driving demand for information on supply chains linked to forest degradation, long-standing timber-control systems provide valuable data for tracing product origins and associated socioecological impacts. However, their ability to reliably link consumption to extraction at source remains uncertain. Here we assess timber traceability in Pará, Brazil—a major timber-producing state and forest degradation frontier—using over a decade of data (2009–2019) from official timber licensing, transport, and commercialization systems. While 96% of roundwood entering the formal supply chain is linked to geolocated logging permits, only 45% of satellite-based logging aligns with legal authorizations. The findings document limits to traceability at origin, underscoring the need for improved data management, transparency, and accountability to address legality and sustainability risks in timber supply chains.

INTRODUCTION

Losses in forest resources continue to outweigh gains throughout land systems globally,[1,2] constituting one of the most significant sustainability challenges of our times.[3] These losses are most evident in the rampant conversion of forests to other land uses, primarily agricultural-driven deforestation in the tropics.[4] The decline in the integrity of standing forests has been far less visible, and hence its effects remain underestimated and less accounted for.[5–7] In particular, for the case of the Brazilian Amazon, recent studies show that forest degradation has climate, biodiversity, and livelihood impacts of equal—if not greater—magnitude to that of deforestation, thus calling for increased attention and research into its drivers and remedies.[5,6,8]

The conservation and sustainable use of tropical forest resources is a collective action problem, requiring concerted efforts from involved parties—Indigenous communities, farmers, ranchers, loggers, commodity traders, and consumers, as well as governmental institutions and civil-society organizations—to build trust, a sense of responsibility, and systems for accountability.[9] A linchpin factor for collective action, crucial for supporting accountability, responsibility, and trust, is greater transparency, monitoring, and traceability in the supply chains for the commodities currently driving tropical forest degradation and loss.[10] Not the least is this evident from the increased transparency in Brazilian cattle and soy supply chains, which has facilitated the emergence of zero-deforestation commitments which—to varying degrees—have contributed to reducing Amazon deforestation.[11,12]

Despite the Brazilian government experience tracking timber products from their place of origin for over three decades—not without significant buy-in and investment from several actors and institutions across the supply chain—current licensing and traceability systems and their parallel versions at the state and federal levels remain not fully integrated.[13] The shared data are scattered piecemeal across several platforms, intermittently available, and not seldomly incomplete, altogether resulting in a fragmented data environment.[13–16] Consequently, we still lack a fundamental understanding of the supply chains that link consumers of Brazilian wood products across the world to authorized timber extraction and its associated socioecological impacts.

However, the availability of such information is in increasing demand as countries importing and consuming tropical timber are seeking to address illegality and sustainability risks, both long-standing challenges associated with Brazilian timber production.[14,17,18] When the EU Deforestation Regulation (EUDR) comes into force in 2025, importers of timber and other forest-risk commodities will be required to trace imports to places of production, proving production was not linked to deforestation or forest degradation.[19] As such, the EUDR raises the bar compared to the 2010 EU Timber Regulation (EUTR) it supersedes,[20] requiring not only legality but also sustainability and full traceability to enable validation of such claims. Central to requirements is the ability to geolocate place of production where, for plots larger than 4 ha, geolocation "shall be provided using polygons with sufficient latitude and longitude points to describe the perimeter of each plot of land" (Art. 2.28).[19]

Improved traceability and transparency for Brazilian timber products is thus crucial for accountability and sustainable management of the country's forest resources. Since 2006, when systems for controlling the production, transport, and processing of products from native forest origins became digital,[21,22] governmental authorities have required timber producers to report, *inter alia*, geolocation of origin for timber logged and entering the supply chain. This implementation of origin control has made available a wealth of data on timber origins.

As shown by Franca et al.[15] and Nonato et al.,[16] information from the existing national- and state-level traceability and timber origin control systems can be leveraged to better understand the supply chain and reveal entry points for illegal timber. Previous work, however, did not match data on timber transport with data on actual logging. Here, we build on this prior work further patching the fragmented data environment. We explore how far publicly available data can be taken to connect timber entering the supply chain to the geographical point of extraction and associated actors, which ultimately can help link downstream supply-chain actors and consumers to forest degradation and related environmental impacts.

To assess the limits to traceability and the extent to which available information can help determine the legality and sustainability risks associated with Brazilian timber, we extend an assembled dataset of logging permits used to substantiate timber production in the state of Pará—a contested forest frontier accounting for over a quarter of Brazil's recent timber production from native forests[23]—for the period 2009–2019, originally documented in Franca et al.[15] We expand this dataset by compiling polygons or coordinates of timber extraction from official sources made available over time, based on the volumes they report entering the supply chain. We then overlay this spatial information with remote-sensing-based data on observed logging for the same time period, from the System for Monitoring Timber Harvest (Simex) initiative,[14,24–27] as well as spatial data on land tenure and governance (see Figure S1 for a method and data overview).

This analysis seeks to answer (1) how much timber entering the supply chain can be linked to a production place (i.e., a polygon or coordinate denoting origin)? (2) How large a share of forest exploitation, as identified by Simex, falls within logging permit polygons or could be associated with logging permit coordinates? And where extraction cannot be linked to logging permits, can land governance and tenure information be used to connect logging to supply-chain actors? Finally, (3) what do the volume officially reported entering the supply chain, the logging permits, and Simex data tell us about the legality and sustainability of logging operations in Pará state? Findings reveal that, although we can geolocate the majority of roundwood production reported entering the formal supply chain, at most 45% of total observed forest exploitation can be linked to these areas authorized. We document limits to establishing such connections, helping shed light on shortcomings in the existing transparency and traceability system as well as evidencing well-documented methods for timber laundering. We also underscore the invaluable nature of the existing control systems already made available, allowing for accountability and further understanding of legality and sustainability risks associated with timber production in these forest frontiers.

RESULTS

Our analysis departs from two different points: one is the roundwood reported logged and entering the supply chain in state- (System for Commercialization and Transport of Forest Product of Pará state [SISFLORA-PA]) and federal-level (National System for Control of Origin of Forest Products [SINAFLOR]) transport records; the other is areas identified as having been logged in the Simex remote-sensing data. The correspondence between the two—or lack thereof—is the object of study, where we quantify and document existing limits in connecting timber flows entering the legal supply chain and the forest exploitation mapped through remote sensing.

Starting with the information contained in transport records, nearly all roundwood (99.1%, 31.08 Mm^3) reported as leaving native forests across Pará state and entering the legal supply chain between 2009 and 2019 can be linked to existing logging permits (Table 1). We were able to connect just over half of the total volume (54%, 16.82 Mm^3) to polygons that delineate the actual area authorized for logging (or Unidade de Produção Anual [UPA]), with an additional 42% (13.17 Mm^3) linked to a coordinate listed in a logging permit. Geolocation data are thus in

Table 1. Overview of roundwood reported entering the supply chain according to associated logging permits and known forest areas exploited

Overall statistics	Roundwood volume	Number of permits	Authorized area[a]	Simex area
Total volume being reported entering the supply chain from forest of origin	100% (31.4 Mm^3)	2,700	N/A	N/A
Total volume being reported entering the supply chain that is traceable to a logging permit	99.1% (31.1 Mm^3)	2,443	5.34–9.37Mha[b]	N/A
Total volume being reported entering the supply chain that is traceable to a logging permit that can be geolocated	95.7% (30.0 Mm^3)	2,168	5.34–9.37Mha[c]	45%
… **by coordinate**	95.7% (30.0 Mm^3)	2,168	5.34–9.37Mha[c]	23%
state-level logging permits	92.8% (29.1 Mm^3)	2,061	1.40–1.52Mha	21.3%
federal-level logging permits	2.73% (0.86 Mm^3)	70	3.84–7.72Mha	1.6%
legal deforestation[d]	0.18% (0.06 Mm^3)	37	0.04–0.07Mha	N/A
… **by polygon, state-level logging permits**	53.7% (16.8 Mm^3)	1,117	0.81Mha	22%

N/A, not applicable.
[a]Lower boundary represents the sum of areas after removing areas of exact duplicates. The upper boundary represents the simple sum of all areas (see also Note S1 for further observations).
[b]Data remained incomplete for 251 logging permits and hence this value is only representative for the permits that displayed the area.
[c]For six permits, coordinates were available but information on authorized area was missing.
[d]Only marginal roundwood production entering the supply chain can be connected to legal deforestation permits (“vegetation suppression”). Unless specified otherwise, production originates from enterprises under SFM premises. See methods for further context.

principle available for most logging permits substantiating the entry of roundwood into the supply chain (Table 1; Figure 1A).

Limits, however, exist across such linkages. First, as can be seen in Figures 1C and 1D, while over half of the volume entering the supply chain can be linked to logging permit polygons delineating the effective area of harvest, this only accounts for about 22% of observed logging (0.18 Mha). The datasets used to bridge the gap between a single coordinate and a well-delineated area help extend this coverage. Polygons available from logging permits that describe wider areas licensed for forest management encompass an additional 15% (0.12 Mha) of forest exploited. Of this, about 1.6% is for enterprises licensed at federal level and 13.5% at state level. Additionally, private-lands and rural-settlements polygons that overlap with logging permit coordinates may further help link 7.8% (0.06 Mha) of actual forest exploited to roundwood entering the supply chain.

Second, compared to the polygons, the data on single coordinates reported in logging permits do not describe the spatial arrangement of the actual area authorized for logging, limiting the connection between areas of forest exploited and the timber entering the supply chain. While nearly all of the timber reported entering the first stage of the supply chain is traceable to a geographical location, if we were to simply overlay single coordinates representing permit locations over Simex data on actual forest exploitation (totaling 0.8 Mha), the overlap would only account for 6.3% of areas identified as logged via remote sensing. This underscores the inherent limitations of a single coordinate to locate authorized area and the need for using different geospatial data to connect such coordinates to areas effectively logged.

Because we are able to connect over half of the total volume to polygons of authorized areas, we can use more than a single coordinate for this share of timber. For the remaining volume that can only be connected to a single coordinate, we found that a substantial share can still be mapped to (1) wider forest management area (state 9.7%, 3.05 Mm^3 and federal 3%, 0.91 Mm^3) and (2) private lands and rural settlements in public lands (21.4%, 6.70 Mm^3); see Figure 1C (and detailed breakdown in Table S1). Thus, most of the reported timber production in Pará is amenable to be traced to a property owner-administrator, who in turn can be accountable for activities within such an area.

The second starting point of the analysis—areas identified as having been logged via Simex—shows that available data can help connect up to 45% of observed forest exploitation to logging permits and volumes entering the supply chain (Figure 1D). The remaining 55% of logging occurring across the state could not be connected to any logging permit, even when assumptions are relaxed and authorized areas are considered more broadly. However, land-tenure data could potentially address approximately 40% of the 55%, with the remaining 15% of logging detected beyond a direct line of accountability from a property's owner-administrator; that is, exploitation occurring in Indigenous territories (TIs), public undesignated lands, and within protected areas without authorization.

While we can patch some traceability gaps using multiple data sources, existing limitations clearly raise challenges for the identification of the true forest of origin, determining the legality of exploitation, as well as post-harvest assessment and the quality of wider sustainable forest management (SFM) enterprises. Below, we further document important limitations for how this timber extraction links to logging permits: first, by taking a closer look at the volume we are able to connect to polygons where logging should effectively take place; second, by assessing the volumes we can connect via coordinates to forests exploited; and, lastly, to the understanding of forest exploitation that occurs across the wider landscape in Pará.

Limits to connecting timber flows to extraction via logging permit polygons

While we can connect 54% (16.82 Mm^3) of the volume entering the supply chain to a perimeter delimiting the area authorized

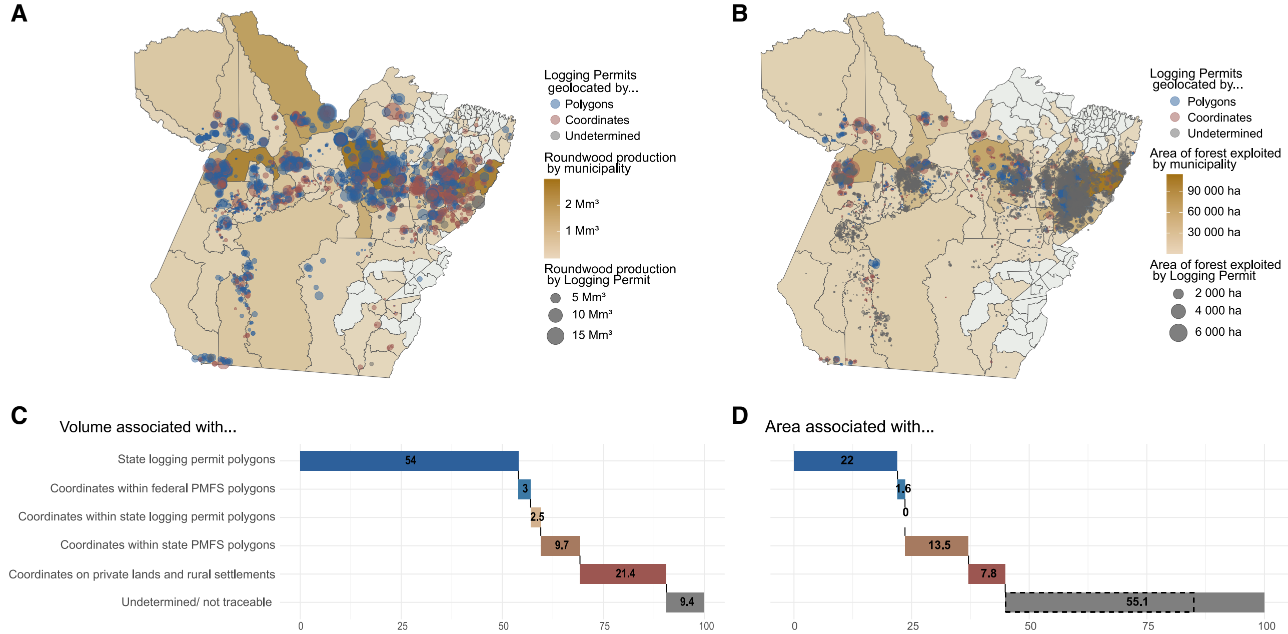

Figure 1. Volume entering the supply chain and its relation to area of forest exploited

Overview of (A and C) volume entering the supply chain and (B and D) area of forest actually exploited that we can trace to logging permits according to geospatial features and different levels of land tenure. (D) The dashed outline corresponds to areas that we have not been able to connect to a logging permit yet exploitation may be accountable through land ownership information. See Figures S2 and S3 for a view of A and B by logging permit category without overlaps. See also Table S2 for a detailed breakdown of numbers presented in (C) and (D).

for logging, this does not necessarily imply that this timber is fully traceable. In assessing patterns of exploitation observed within such areas, we found that a fourth of the volume entering the supply chain and connected to a polygon of extraction (approximately 14%, or 4.4 Mm^3 of total volume entering the supply chain) displayed no sign of exploitation within its perimeter. Three possible reasons for this stand out: first, extraction may not have been detected due the forest management being of very limited impact (e.g., due to reduced-impact logging operations, low harvest intensities, certified forests, and overall best practices). This, however, is at odds with the reported amount of volume entering the supply chain. As evidenced by Figure 2, harvest intensities (reported roundwood volumes harvested per hectare) do not differ substantially between permits associated with polygons with signs of extraction versus those where no extraction has been detected, suggesting this is an unlikely explanation for these authorized areas. Second, exploitation may not have been detected due to the combined effect of the regions' high cloud-cover frequency and the fact manual data checks seek to minimize false positives (that is, mapping logging where this is not present) (see methods). However, considering the scale of logging detected (indeed, substantially beyond what could be linked to logging permit polygons) and the fact the study covers over a decade of data, a third reason should be considered: the permits may have been requested without the intention to fully harvest. This is a well-documented strategy used for the purpose of laundering timber extracted elsewhere.[28,29]

Aside from polygons that simply do not display any sign of exploitation, we also find that about 3% (0.9 Mm^3; see Table S2) of permits with polygons are invalid (i.e., have been canceled or suspended) but were still used to substantiate volumes entering the supply chain. This is a relatively small share compared to the share of invalid logging permits we can only initially geolocate through coordinates (9%) or the amount broadly found for species with high illegality risk, such as *Handroanthus* spp. (16%; see Franca et al.[15]). While various other illegality-risk indicators exist (including those dependent on complete geospatial information[30]), the use of invalid permits can generate an artificial surplus that may be used as an entry point to illegally logged timber.[15] Illegality risks are an intrinsic aspect of—as well as a key hindering factor to—timber traceability and do limit the ability to connect reported timber flows entering the supply chain to logged forests, as evident from the large share of detected logging that cannot be linked to either polygons or coordinates.

While a total of 37% of volumes entering the supply chain on paper seems to be fully legal based on logging permit status and traceable according to official records (i.e., linked to a valid logging permit, with a polygon showing signs of timber extraction), within these we find examples suggesting actual harvests are being overstated; that is, where the volume entering the supply chain is clearly at odds with the identified size of forest area exploited. For instance, when looking at the share of the exploited area mapped within state-level logging permit polygons, we find that a fourth (3.01 Mm^3) of the volume originates from polygons where up to 6% of the area has been exploited, but we find no differences in the harvest intensities between these polygons and those reporting larger shares of exploitation (see Figure S4A). Polygons reporting harvest intensities between 25 and 30 $m^3.ha^{-1}$ of extraction (Figure S4B) but limited exploitation

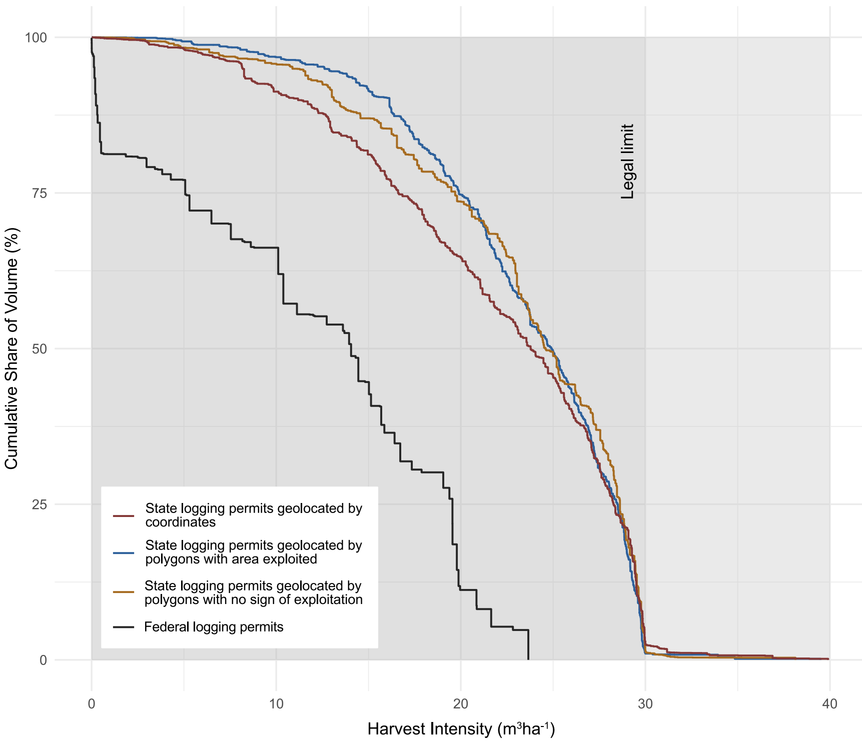

Figure 2. Cumulative sum of volume from each authorized permit where volume has entered the supply chain by the respective harvest intensity

The graph is of roundwood volume entering the supply chain by area reported authorized in logging permits ($m^3.ha^{-1}$).

are clearly at odds with the infrastructure needed to support such high-intensity harvests (i.e., landing sites, secondary roads, storage yards), a parameter assessed by monitoring authorities themselves.[30] Again, this suggests risks that these logging permits may be used for laundering of illegal timber logged elsewhere. Notably, inferred harvest intensities are substantially lower for federally licensed enterprises, which experience a higher level of scrutiny (Figure 2).

Limits to connecting timber flows to extraction via logging permit coordinates

A total of 42% of the volume entering the supply chain (Figures 1A and 1C; see also Table S1 for a detailed breakdown) can be traced solely to a coordinate of origin. However, just as having a polygon does not imply the volume is fully traceable, having only a coordinate does not imply a lack of traceability. Connecting coordinates to actual logging and accountable actors, however, is fraught with challenges and limitations. Standing out among these is the lack of standardization of the geographical coordinate of reference reported in the logging permits, which are the starting point of origin allowing the roundwood entry into the supply chain.

Since the forest management licensing process and timber origin and control systems were brought into the digital space,[21,22] the requests for reporting geospatial features (those related to enterprises' property, compliance with environmental legislation, and the planning of forest management operations, among others) have become increasingly commonplace, a prerequisite for approval in the first place and input for monitoring of related activities.[21,31–33] However, while environmental agencies at different jurisdictional levels may access and produce a wealth of data to allow for the approval of enterprises, these still hold the mandate of determining what is made available. Under the scope of origin control legislation,[22] the responsibility was placed on these agencies to comply with "mak[ing] available to the public, through the internet, the information needed to verify the origin of forest products and by-products" (Art. 3-II, own translation). Here, minimum requirements for reporting revolve around mentions of "geographical coordinates of the place of origin/destination" for the transport licenses and "the indication of the location of the PMFS [Plano de Manejo Florestal Sustentável; i.e., SFM plans] or Authorized Deforestation" (own translation)[22] when the transport relates to roundwood. The normative instruction, which originally put forth the bulk of technical procedures for licensing PMFS,[31] likewise lists as minimum requirement for logging permits the "geographical coordinate of the PMFS that allow for the identification of its location" (Art. 20-VI, own translation).[31] Arguably these instructions still leave space for interpretation of where precisely a coordinate should be placed and, more broadly, on determining (and shaping interpretations on) what information needs to be publicly available.

The ensuing challenge in the case of determining coordinate placement is illustrated in Figure 3. In practice, coordinates of reference as reported may fall anywhere between the centroid of the effective area authorized for harvest and the perimeter of the property (Figure 3A), which is often much larger than the area effectively authorized for harvest. Indeed, it is not uncommon for logging permits to add coordinates close to the property's entrance or any coordinate on the property perimeter (such as a property's corner), implying that coordinates reported in logging permits may be located at the intersection of multiple properties (Figure 3B). Additionally, imprecisions in collecting and reporting coordinates, as well as those related to land-tenure data compilations,[34] may place coordinates over roads adjacent to properties or spaces in between these (Figure 3C). Out of the 9.4% of volume identified as "undetermined" in Figure 1C, 5% (1.6 Mm^3) comes from this latter share (the remainder represents the share of volume we were not able to geolocate [4.3%, or 1.4 Mm^3).

Further, for the connections we were able to establish, it is worth emphasizing that we still lack the precise location of effective areas authorized for harvest within the wider forest management areas or private lands. This clarity would be important for at least three reasons. First, although a PMFS may be approved, not all areas within these are authorized for logging

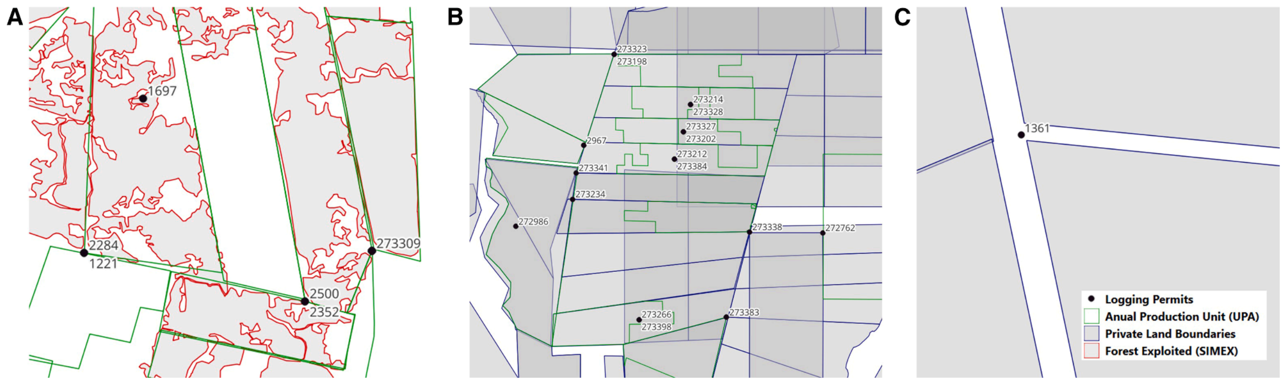

Figure 3. Illustrative overview of limitations to connecting timber flows to extraction via coordinates

(A) Coordinates shared between various areas authorized for logging (UPAs).

(B) Coordinates shared by multiple properties, at times with overlapping claims to property.

(C) Coordinates mapped to spaces between properties.

(A and B) Multiple logging permits geolocated in the same authorized area for logging (UPA) with no clear tracking of the cumulative volume between interrelated logging permits.

within a given year. Hence, extraction occurring outside authorized areas, aside from being illegal, risks influencing the long-term viability of a PMFS enterprise as observed, for example, even in federal concessions with the highest levels of monitoring and scrutiny.[35]

Second, exploitation approved under the PMFS premises should account for the long-term (25–35 years) viability and recovery of the area, implying the expected annual harvest areas (UPAs) will represent only a small share of total forest management area. That is, under optimal conditions, 25–35 UPAs would be set aside, each harvested in turn, until the completion of the harvest cycle. In contrast to this underlying premise, we found that 40% of logging permits used to substantiate volume reported entering the supply chain have UPA areas that are an exact match to that of the total forest management area. While setting aside harvest areas over 25- to 35-year time horizon is a challenge, Costa et al.[36] highlight the predominance of single UPAs in fined PMFSs for the state of Pará. The authors showed that, for those PMFSs with irregularities filed in administrative processes by the Federal Environmental Agency between 2006 and 2021, 82.3% had one single UPA. Only 10 of 158 processes had more than four UPAs. Without clarity on how these add up across the landscape, the practice raises important questions about the actual sustainability of this timber production. Information on the precise delineation of areas authorized allows for cumulative impact assessment beyond a single enterprise.

Third, as observed above, about 2.5% of volume from coordinates comes from overlaps with other authorizations (Figures 3A and 3B) with polygons suggesting more than one authorization may have come from the same effective area being harvested. While this is not necessarily an issue given several factors may prevent a producer from carrying out the complete harvest and subsequently re-issue a permit for the same area, the lack of tracing the areas that have (or not) been logged and subsequently used to move volumes into the supply chain creates a loophole that can be exploited for laundering illegally logged timber. Indeed, illegality risks can also be identified here even if we lack the full knowledge of geospatial features of authorized areas.

Accountability in wider patterns of forest exploitation

The stepwise approach used to connect timber entering the legal supply chain to forest exploitation via logging permits shows we can cover about 45% (0.37 Mha) of the entire logged area identified through remote sensing during the period. When looking at the remaining 55% (0.44 Mha) we were not able to connect to authorized areas, 40% (0.33 Mha) of logging could be allocated to land-tenure classes from private land and rural settlements in public lands (Figure 1D, dashed bar segment). Indeed, although we could cover only 7.8% through the geospatial intersections with logging permits, a direct intersection between observed forests exploited and land tenure shows that (after removing coordinates falling within areas authorized for harvest and wider areas of forest management) we can connect 33% to private lands and 7.2% to coordinates on public lands' agrarian reform settlements. Within different categories of private land, about 14.4% of logging falling within private lands certified by the agrarian reform agency (SIGEF/INCRA), 15.4% to properties in the self-declaratory Rural Environmental Registry (CAR) system, and 3.2% to land titled under the Terra Legal program (see Table S2 for more details). Moreover, the direct intersection between observed forests exploited and land-tenure data showcases that, even if uncertainties exist and volume may not be directly accounted for, exploitation for this share could be connected to an actor. However, because of the missing link to logging permits and transport records, the timber resulting from this logging is not traceable.

Also, land tenure is far from consolidated across this forest frontier's various timber-producing regions. This is particularly evident for the share where exploitation is predatory and traceability impracticable: observed timber exploitation falling completely outside private lands and public forests under concession make up about 15% of total area of identified exploitation. This encompasses logging mapped within conservation areas (3.1%, 0.02 Mha, disregarding legal concessions in conservation areas), TIs (3.7%, 0.03 Mha; see Note S2), or broadly undesignated federal and state forestlands (5.8%, 0.05 Mha). The latter share, however, could be as high as 32% for undesignated forestlands if data from the National Cadaster of Public Forests (CNFP) is used. The unvalidated parcels of the self-declaratory CAR (which, in short, amounts to a land claim), may partly explain the discrepancy in numbers for what can be understood as undesignated forestlands. However, such discrepancies may reflect more the broader and long-standing challenge of coordination in data compilation across governmental institutions.[34,37,38] For TIs, while the limited share described here reinforces this type of land tenure helps safeguard the integrity of standing forests, these territories also face increasing pressure. Silva-Junior et al.,[39] for instance, showed deforestation has increased by 129% inside TIs since 2013, with the top five TIs with significant deforestation trends for the period—the Apyterewa, Cachoeira Seca, Trincheira/Bacajá, Kayapó, and Munduruku territories—all are within Pará state. Such increasing pressures should also be considered over TIs where full recognition and protection is still pending (see Note S2).

DISCUSSION

This study revisits fundamental questions on Brazilian timber origins, going back in time to compile and dissect official public-domain data to assess to what extent we can trace roundwood entering the supply chain to forests being exploited across the landscape. It ultimately paves the way for connecting downstream supply-chain actors and consumers to forest degradation and related environmental impacts and for legal and sustainability risk assessments that will have to be carried out despite existing limits to traceability revealed here.

Results documented here showcase the richness of data available and reflect the collective resources invested in establishing and implementing systems for the control of origin and commercialization of timber products from native forests. Indeed, an overwhelming majority of logging permits substantiating volumes entering the legal supply chain—and accounting for 96% of volume—contain at least a coordinate of geolocation.

However, given the complex land tenure across the region, we find that coordinates of origin alone fall short in supporting full due diligence on legality and sustainability. First, a coordinate does not spell out the effective area where harvest ought to take place. Second, the legislation laying the requirements for geolocation of origin has left space for interpretation, leading to a lack of standard on the placement of coordinates of reference. Combined, these limitations invariably add uncertainty to origin as legal and predatory modes of production coexist across the landscape.

The value of having a well-defined polygon appears to be understood by relevant authorities. Such data have been required in different steps of the licensing process.[31–33,40] They are also available through the various open data and transparency platforms, despite, at times, being incomplete. We found nearly half of the volume entering the supply chain can be connected to polygons that delineate the area authorized for logging, although these encompass only 22% of the total of forest observed being exploited between 2009 and 2019. Shortcomings in transparency are a key determinant for such low figures, shown not the least by the number of additional coordinates with no well-defined polygons to match. However it is clear that, for a licensing process that relies on extensive checks,[41] failing to make data available that conclusively distinguish authorized areas from the rest undermines the potential of SFM from the start.

Several studies over the years have raised alerts about the potentially high rates of illegal logging in Brazil,[14,15,17,28,42–44] and some of the top consumers of Brazilian timber (EU member states) already deemed the risk of illegality "not negligible."[45] Thus, although transparency is key, a reality check on where the latter ends and illegality risk begins is needed. Even if we join logging permits' polygons and coordinates (using the intersection of coordinates with other land-tenure data), we find that up to 45% of observed forest exploitation occurring across the landscape could be connected to logging permits, leaving 55% as broadly unauthorized. Previous estimates for unauthorized logging for Pará do show that, between 2007 and 2019, an average of 68% of exploitation was carried out without authorization from the state's environmental agency (or Secretaria de Estado de Meio Ambiente e Sustentabilidade - Pará [SEMAS-PA]) or federal authorities.[15] Figures presented here are conservative given such estimates include several other illegality indicators (also used by authorities, see Costa et al.[36] and Perazzoni et al.[30]) and the fact that likely not all areas inside land-tenure polygons (leveraged to connect coordinates to exploitation) have been authorized. Indeed, our analyses of both polygon and coordinate data show inconsistencies that warrant further scrutiny, such as invalid logging permits used to substantiate volume entering the supply chain, areas authorized for logging with no extraction observed, and volume transported being incompatible with the area of exploitation. Such factors clearly limit tracing volumes to origin but also suggest loopholes in the current traceability system that can be exploited by actors for the laundering of illegally logged timber.

However, we find that, for a large share of observed exploitation, responsible actors can potentially be identified and held accountable. Only 15% of exploitation occurs completely outside what can be classified as lands where forest management can be authorized to take place in private and public lands, reflecting a history of leniency toward environmental crimes. A comprehensive analysis on administrative processes filed against PMFSs between 2006 and 2021 shows that a significant number of offenders are recidivists, with 59% fined more than three times in the period and 19% with 10 or more fines. While the logic of law enforcement is not to eliminate all illegality,[46] an environment of generalized impunity is counterproductive as it normalizes predatory practices. Indeed, while the level of fines and embargoes have fluctuated over time, evidence points to waves of drastic decline in sanctions having direct influence on the increase in environmental damage.[47–50]

A sense of accountability toward sustainability risks is an even larger challenge. Several studies provide evidence that the current legal framework under which enterprises are licensed for SFM falls short of sustainability.[18,51,52] We found that around 40% of logging permits being used to substantiate timber volume entering the supply chain comes from what is called a "Single Annual Production Unit" or UPA Única, which in practice is an area where the size of the PMFS is equal to that of the effective area authorized for harvest (i.e., UPA). This finding, as discussed elsewhere,[36] contrasts with the promise of what SFM is set to be, which includes enough commercial stocks to allow for a long-term (25–35 years) harvest cycle.[31,40] Moreover, there is a need for evaluating the cumulative impact that forest exploitation imposes across the landscape. In this context, having a clear indication of which polygons delineating areas authorized for logging have been exploited would be fundamental.

Timber traceability systems worldwide are currently undergoing an EUDR shake-up to meet the requirements the regulation sets on due diligence. While there are legitimate questions on the ability to comply with the scrutiny required under this new regulation, those turning a profit on land theft do make full use of the same technological advances that have the potential to support increased traceability and accountability. This is evident from the CAR system, which has become a central tool for environmental monitoring and law enforcement in Brazil,[53] but also for making unsubstantiated claims to land ownership.[34,37,54] Under CAR, polygons delimiting properties' boundaries (alongside legal reserves, area of permanent preservation, and other property features) must be submitted to authorities for compliance analysis.[53] We found, nonetheless, that 60% of CAR polygons that overlapped with coordinates from logging permits were "under analysis" (when considering only the overlap between CAR-only layer and coordinates). It inadvertently raises questions about the legitimacy of land claims and how to address environmental liabilities on these lands. While this may reflect institutional capacity challenges, as well as those related to land-tenure conflicts, it is also important to question who benefits (or is disadvantaged) by the lack of data in this conjecture. Instead, actors operating across timber supply chains and beyond can ensure the new wave of seemingly technocratic requirements do support the land-rights recognition that is long overdue, boost those already doing SFM right, lift front-runners safeguarding forests, support capacity development and transfer in line with technology advances available, and ensure that it reduces burdens of monitoring and law enforcement.

If Brazil's case can offer one lesson to EUDR (and actors adapting to comply), it is that data systems will often not function as designed and yet can still be crucial, above all in providing the basic building blocks for a shared sense of accountability and responsibility toward use of natural resources and even if only to point out to continued overexploitation. It will not be free of loopholes and shortcomings, and hence mechanisms should be built and strengthened to allow for ongoing adjustments. As with main criticisms to the EUTR,[20,55] unclear and non-stringent specifications and vague obligations by parties can severely reduce the effectiveness of a policy. For the case of Brazil, there is an urgent need for attention on what is needed to truly ensure we have "information needed to verify the origin of forest products and by-products" (Art. 3-II, own translation).[19] More transparency is needed from environmental agencies to reduce the uncertainty around whether a certain place of production can be said to be legal to allow for improved traceability as well as support in the evaluation of the cumulative sustainability of both the legal and illegal side of timber exploitation.

METHODS

This analysis builds on four major data sources: (1) the amount of roundwood volumes from native forests entering the legal timber supply chain, as substantiated by timber transport records; (2) the logging permits associated with these flows of timber; (3) the remote-sensing-derived polygons of observed forest exploitation; and (4) the spatial data on land ownership, use, and territorial governance. It covers the period between 2009 and 2019 and focuses on the state of Pará, the second largest timber-producing state in Brazil[23] and prominent forest degradation frontier. We have two different starting points of analysis: the roundwood reported entering the supply chain on one hand, and the areas identified as having been logged (via the System for Monitoring Timber Harvest [Simex]) on the other. The correspondence between both—or lack thereof—is the object of study, where we quantify existing limits in connecting timber flows being credited into the legal supply chain and the forest exploitation mapped by remote sensing.

In the next sections, we provide further background on the timber production systems originating from native forests (that is, primary and naturally regenerating forests[56]) across Pará state and detail the unique aspects of the data leveraged to answer the posed research questions. A methodological overview can be seen in Figure S1. The code for the replication of the analysis can be found in the repository https://github.com/carolsrto/limits-timber-traceability, and the data needed to replicate the study are available via a permanent Zenodo link at https://doi.org/10.5281/zenodo.1567207.

Timber production of Brazilian native species

Most timber production from native species in Brazil originates from areas explored under SFM premises. According to the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA),[23] 87.6% of the roundwood volume entering the Brazilian timber supply chain in the 2012–2017 period came from approved PMFSs, with legal deforestation (7.9%), planted forests (4.3%), and harvest of isolated trees (0.2%) making up the remaining timber production categories. Given its outsized relevance for the state of Pará, we focus on PMFS and the intricacies of this production system throughout the study but include data from all categories in the overall analysis and figures presented.

The resolution setting the technical parameters for PMFS defines 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).[40] Current SFM legal parameters broadly include a 25- to 35-year harvest cycle, an overall upper limit for volume extraction of 30 $m^3.ha^{-1}$ (about three trees per ha), a minimum tree diameter of 50 cm, and a (minimum) retention rate of 10% of trees per species, with special cases applying for certain species (e.g., 15% retention rate for trees of listed vulnerable species,[57] lower exploitation intensities, and smaller areas[40,57]). It is worth noting that a number of studies indicate that these requirements are not enough to safeguard forest ecosystems.[18,52,58,59] Even under reduced logging impact[58] and scenarios of expanded areas through concessions (which lowers pressure over fewer areas),[18] the actual sustainability of these enterprises is a matter of ongoing debate.

Keeping track of timber production in Brazil depends on varying implementations of both licensing and traceability systems. SINAFLOR was instituted in 2014[60] with the objective to integrate the then sprawling diversity in systems. Despite this, state-level systems—which in many ways are precursors to the national system—still coexist along with their national-level counterparts. Broadly, under these systems areas being licensed via PMFS (or Área de Manejo Florestal [AMF]) are optimally split into a group of units based on commercial volume available and the intended harvest cycle within allowable parameters applicable. Larger areas under PMFS, such as those being granted under public forests state and federal concessions, are often further split into "Forest Management Units" (or Unidade de Manejo Florestal [UMFs]). For the purpose of this study, we use "wider areas of SFM" to simplify the varied use of nomenclatures. Logging permits in turn—generically known as Authorization for Forest Exploitation (AUTEX) but also termed AUTEF in Pará state—are issued on the basis of "Annual Production Units" (Unidade de Produção Anual [UPA]), which are the areas authorized to be exploited in the course of a year or two. All such areas can be contiguous or not, part of the same property or not, which should be detailed in the PMFS. While one would optimally have several financially viable UPAs to allow for different aspects of sustainability, the legislation also foresees the exploitation of a single unit known as "single UPA" (UPA Única). Under these terms, the entire AMF area is equal to the authorized area of extraction, a category increasingly questioned whether befitting of SFM premises.[36] Tables S3 and S4 bring a list of acronyms and key relations to simplified mentions across the text.

When the volume authorized is harvested, a license generically known as "Document of Forest Origin" (Documento de Origem Florestal [DOF]) is required for the transport, reception, processing, and stocking of products of native origin.[22,60] Pará still holds its own state-level DOF system or SISFLORA-PA, which issues the DOF-equivalent "Forest Guide" (Guia Florestal [GF]). The integration between licensing and transport would, in principle, allow for a paper trail to follow timber from its origin until the production of a final product. Nonetheless, gaps have precluded full traceability until recently, when the new "DOF+ traceability" has been put in place. Even now, questions remain on whether loopholes known to exist[15,17,30] have been overcome. For instance, a key improvement of DOF+ traceability is a persistent code connecting forest of origin to subsequent processing steps, resulting in the ability of those purchasing the processed timber to directly connect product to reported forest of origin. Nonetheless, underlying loopholes[15,17,30] such as the overestimation of species based on fake tree inventories, the potential use of fraudulent plans and permits issued with the intent of creating surplus credits for laundering illegally harvested timber, misuse of conversion coefficients at sawmill, and the lack of near-real-time integration between state- and federal-level systems (particularly between licensing and transport) that prevent automated check on key inconsistencies remain a risk and will require due diligence.

Quantification of roundwood entering the supply chain

Using the volume reported as entering the supply chain provides a more accurate figure on volume commercialized than figures on what has been simply authorized. Hence, we draw on data reported through the state- (GF) and federal-level (DOF) timber-transport systems to derive numbers on the combined volume of roundwood legally leaving native forests across the state of Pará and entering the formal timber supply chain. The GF data available from the SISFLORA-PA system were accessed via the Timberflow initiative (http://timberflow.org.br/). Since March 2023, they have also been made publicly available by the new SEMAS-PA transparency portal (http://portaldatransparencia.semas.pa.gov.br/), though currently this dataset remains incomplete. The DOF data were accessed via the SINAFLOR "transport" module https://dados.gov.br/dados/conjuntos-dados/dof-transportes-de-produtos-florestais.

All roundwood originating from native forests must (and do) indicate logging permits of origin, as such reporting is a prerequisite for the issuance of the transport licenses.[21] In SISFLORA-PA, all GFs under the GF1—a category used for the first transport of roundwood out of a forest of origin—display an associated logging permit number. In SINAFLOR, a standalone category for roundwood only is not present, and so, for this case, we only use roundwood flows that have logging permit of origin. We ensure the removal of any transaction where actors send volume to themselves (that is, where stated origin equals destination) in order to minimize double counting, as these flows likely also represent some form of logged timber re-transport or duplication between systems.[15] Because we focus on roundwood coming from native forests, we discarded all roundwood coming from plantations (madeira produzida) and any biomass flows being extracted from the area. Here, we notably remove the category toretes (short logs), which has been used by the IBAMA[23] analysis for estimating timber production, but we found it to be mostly transacted through GF2, a category used for biomass. Next, we assess the extent to which we can locate logging permits listed in such transactions and the characteristics associated with these.

Identification of areas authorized for extraction

The authorizations for timber extraction (logging permits) are the main connectors between the legal timber supply chain and the observed forest exploitation. The volume authorized to be exploited through logging permits is the starting point for all timber credits flowing downstream the supply chain and, thus, a key instrument in determining illegality risks as well as assessing sustainability of forest exploitation.

No comprehensive official database currently exists on logging permits for the state of Pará. The lack of a single authoritative database is complicated by the concomitant issuance of permits at different jurisdictional levels and the fact data made available through different official sources have changed over time and have been incomplete. The launch of the latest state's environmental agency (SEMAS-PA) transparency portal (http://portaldatransparencia.semas.pa.gov.br/#/visao-publica) is a current example on challenges with data management and transparency. Replacing the previous Integrated Environmental Monitoring and Licensing System (SIMLAM) webpage (http://monitoramento.semas.pa.gov.br/simlam/index.htm\), logging permits now are easily accessible in digital format, an improvement that contrasts with previous data made available only via PDFs. A single download of the logging permits data, however, will show basic technical issues. The reference number for the permit displayed in the webpage is different from that of the file just downloaded, making those unfamiliar with the data unlikely to connect logging permits and geolocation data made available (a key requirement for origin tracing within the DOF system[22]). Further, while the portal currently makes available polygons of authorized areas per permit listed, these are incomplete: as of January 2025, out of 3,060 downloaded zip-files, 1,611 (53%) remain simply empty and hence a large share of geospatial data are still unavailable. All the while, no data descriptor or dictionary file is made available on variables, nor on information on missing data or potential issues associated with such data gaps.

In order to overcome the lack of integration and gaps in data, we expand the compilation of logging permits from Franca et al.[15] aiming to further build a comprehensive logging permits database. For logging permits issued at state level, we accessed polygons delineating the area authorized for harvest (i.e., UPA polygons) available via shapefile from the previous SIMLAM webpage. To complement these data, we use the information reported in the original logging permit PDFs issued—also accessed via SIMLAM, but currently partially available at the transparency portal. We pooled PDF files from both automated web scraping, as well as manual downloads, totaling 3,068 unique permits between 2007 and 2022. State-level permits formed the bulk of data on authorizations. In addition to state-level logging permits, we have also utilized all permits issued under federal jurisdiction for the period of analysis (2009–2019), accessed via SINAFLOR's "authorization" module https://dados.gov.br/dados/conjuntos-dados/dof-transportes-de-produtos-florestais. These amounted to an additional 193 permits.

Here, it is worth noting that reporting is done differently between state and federal systems, and hence the resulting data structure is also distinct between the two. A relevant difference for this study is that the areas presented in the authorization module of SINAFLOR data do not detail whether this is the total area explored or total area of the enterprise, at times making reference to both (see Note S1 for the example of Extractive Reserve [RESEX] Verde para Sempre). In state-level permits, in turn, several categories are reported, including total area of the forest management, area authorized, area of the property, area of the legal reserve, and area occupied by infrastructure and other activities (area antropizada). Additionally, for the federal-level data, only coordinates of reference are made available in the SINAFLOR's authorization module. We found no geospatial data delineating the effective areas authorized for harvest (UPAs) for these logging permits (although we contend these data exist and are simply a shortcoming in data management and transparency).

After compiling all logging permits through these main sources, we cross-check unique numbers with partial data made available through previous studies,[17,23] as well as the Simex's own permits database compiled over the years.[14,24–27] The next steps of the analysis start with a pool of 3,821 unique permits with varying levels of comprehensiveness on details available. We use this compilation of best available public-domain data to establish the amount of volume entering the supply chain according to reported place of origin. For that, we match logging permits reported substantiating roundwood entry into the supply chain (as described in the previous section) to the compiled data on logging permits, establishing whether we can locate permits used for the transport in the first place and to what extent we can geolocate the origin of this volume. Additionally, we also obtain figures on permits that are invalid (canceled, suspended) for some reason. That is, even after approval, logging permits are subject to analysis by environmental authorities and may be suspended or canceled (due to, e.g., elaboration failure, non-compliance with conditions, or illegality) but may have been used to transport timber. We refer to "undetermined" to communicate the share of roundwood volume entering the supply chain, which we found no permit to back up.

Quantification of exploited forest areas

The detection of forest exploitation on land swathes of continental proportions has been a well-documented technical challenge, particularly when compared to the assessment of land conversion as in the case of deforestation. Several methodologies, however, have been developed and currently present viable alternatives to map extraction and associated loss of biomass even within standing forests.[5,61,62] As Perazzoni et al.[30] highlight, even if hurdles still exist, environmental agencies already make use of such information with relative success when assisting the monitoring of resource use across forest frontiers. The Simex initiative is the longest-standing of its kind, in that it applies a mix of remote-sensing-derived information, cross-referenced with official data, to map and evaluate logging in the Amazon. The initiative, which began in 2008 in the states of Pará and Mato Grosso, now includes four third-sector institutions (Imazon, ICV, Idesam, and Imaflora) and has been operating across the legal Amazon since 2020.

From its beginning, yearly analyses drawn on a semi-automated approach where an Normalized Difference Fraction Index[63] (NDFI) layer produced is visually validated in relation to typical patterns of timber extraction (e.g., tree landing zones, hauling and skidding trails, and roads). The resulting data asset consists of polygons that delineate the area identified as logged, which are subsequently cross-checked and validated against other official information (e.g., to assess legality, quality of management). A few essential features of the dataset are worth pointing out. First, although high-cloud-cover frequency is a limiting factor in remote-sensing products across the Amazon region,[64] Pará is affected to a higher extent particularly around producing regions such as Paragominas where rates of unauthorized logging are among the state's highest.[65] This adds to the fact that the forest areas detected as exploited are limited by cloud coverage in a way deforestation is not, given the canopy can close before a clear image of the region can be assessed.[66] This is particularly relevant if exploitation was carried out early or late in the harvest season as it coincides with higher cloud incidence in different localities.

Second, given the original use for the assessment of areas explored without authorization, the dataset—when compared to a fully automated identification of logging zones—may display more errors of omission than commission. That is, when an area did not display clear signs of logging, it was not classified as logged (omitted) rather than having its exploitation be mistaken with other imagery artifacts (e.g., cloud edges, haze). In that sense, the delineation of logging scars also took into consideration the complex contextual political ecology of the region. For instance, it would be preferable to underestimate logging, particularly in the context of non-authorized logging, than to map it when uncertainty was high. In that sense, while the use of contextual classification algorithm in association with the NDFI has the potential to reach 94% accuracy,[63] when mapping logging for the entirety of the state, a lower accuracy would be expected (also see Shulz et al.[62] when comparing performances on commonly used vegetation indices).

Lastly, it is worth pointing out this data asset—indeed, the equivalent to a training dataset that can be used for the validation of models looking to automate the detection of forest exploitation by logging[67]—was produced by the collective effort of several analysts over the period of a decade and experiencing changes that tools and technology imposed in the period (from time-consuming single-image downloads and processing to the direct access and processing of all available series in Google Earth Engine and latest SimexAI development efforts[68]). Hence, both cloud cover and the contextual features indicate that the overall area detected as exploited should be considered a conservative estimate of ongoing exploitation. At the same time, the application of the methodology minimizes to the largest extent possible any false positives.

With Simex polygons delineating where logging was found to take place, we produce spatial overlays to identify (1) the share of observed forest exploited that can be associated to logging permits UPA polygon; (2) when this association is not possible, whether extraction can still be linked to wider areas of forest management (AMF/UMF); and (3) when no authorized or management area has been identified, whether extraction can still be associated to wider territorial governance. Additionally, for those logging permits with available UPA polygons, we computed the amount of observed forest exploited to report on the share of area exported to authorized and whether any signs of exploitation have been detected within these in the first place. We compare harvest intensities (i.e., amount of volume harvested according per hectare of area authorized) in permits with no sign of exploitation as well as others to discuss legality and sustainability risks implications.

Connecting wider land use and territorial governance

A substantial amount of volume has entered the supply chain through logging permits we can only geolocate through a single coordinate. At the same time, as pointed out by Valdiones et al.,[14] about 44%–68% of logging is carried out illegally and hence more forests are exploited than in fact are authorized. Data on land tenure was thus used to patch the knowledge gap around places authorized for harvest as well as those being logged. The lack of logging permit to substantiate exploitation (or the completeness of this information) does not necessarily mean an actor operating across these geographies is invisible. Nonetheless the question of who owns Brazilian lands is notoriously complex, with overlaps among land-tenure categories summing up to 50% of Brazilian territory.[34]

In order to complement the data on logging permits that could be geolocated by polygons, we first looked at available polygons that could indicate the wider areas licensed under the SFM premises. For the case of enterprises licensed under the state's jurisdiction, we used polygons made available through the previous SIMLAM platform (http://monitoramento.semas.pa.gov.br/simlam/index.htm). The data now are available not in one single shapefile but through the same standalone zip. files described as incomplete for the data on authorizations. For the case of enterprises licensed under the federal jurisdiction, we used the polygons of UMFs available through the latest compilation of the CNFP at https://www.gov.br/florestal/pt-br/assuntos/cadastro-nacional-de-florestas-publicas/cadastro-nacional-de-florestas-publicas-atualizacao-2022/cnfp-2022.

Despite the increase in relative relevance of public land's concessions, most production still originates from private lands.[69] We used the dataset of Sparovek et al.[34] to bridge the remaining data gap, which represents the first integrated map of Brazilian land tenure ever produced. Being periodically updated since,[70] it was accessed through https://atlasagropecuario.imaflora.org/downloads. Sparovek et al.'s integration includes 18 databases and 14 categories and (developed in consultation with several experts) applied a hierarchical approach to prioritize where ambiguities on land tenure exist. This is fundamental as datasets still show substantial overlap despite being produced and maintained by government institutions. To complement the polygons that could potentially connect logging permits to exploitation, we use the categories that refer to private lands, including those certified by the agrarian reform agency (SIGEF/INCRA), registered with the Rural Environmental Registry (CAR) and Terra Legal program as well as Quilombola Territories. We also use the public land's Rural Settlements (RS) category.

For the share of forest exploited, we have not been able to connect to a logging permit either via wider area of SFM or the categories of land tenure just mentioned, so we produce statistics on the direct overlap with remaining categories. Here, it is worth noting we chose to use the categories of public lands, including Indigenous territories (TIs), conservation units (UCs), and broadly undesignated lands, from the latest available compilation of the CNFP, making Sparovek's integration the dataset mostly used for private lands. Additionally, we also use the complete CAR data (https://www.car.gov.br/publico/estados/downloads) to derive additional statistics, which includes overlaps removed and addressed by Sparovek et al.,[34] given the fact that claims to the land that are under "pending analysis" are a key caveat when discussing land tenure and territorial governance.[34,37] Moreover, the analysis consists of identifying where polygons and coordinates related to logging permits are located in this tenure context, as well as to provide figures of how much exploitation we are not able to connect to logging permits but is still located in the broader landscape of land use and tenure.

Quantification of the volume-logging permits-forest exploitation connection

With the amount of volume known to be entering the supply chain per permit, we proceed to establish the extent to which these permits can be geolocated and whether the roundwood volume could be traced to a well-defined perimeter or only to a coordinate. We compute overall values for the volume that is covered by logging permits that have a UPA polygon and, for volume that is associated only with coordinates, we use a tiered approach assigning volume stepwise via the geospatial relation of coordinates to wider land tenure (see Figure S1). In other words, we start by determining all volumes that could be covered by unique permits with a polygon. We then remove these from the next level of analysis and check whether there is still any spatial connection with the coordinates of remaining permits and these initial polygons. Subsequently, we remove these logging permits mapped to initial polygons and seek for any further matches between remaining coordinates and the wider area of forest management (AMFs and UMFs the purpose of simplifying nomenclature refer here to state- and federal-level forest management areas when not further clarified). After removing permits for coordinates that had a spatial overlap with wider area of forest management, we checked whether remaining coordinates had any overlap with private land and rural settlement classes from the Sparovek et al.[34] data (see also Note S3). Any remaining logging permits with geolocation for which we could not find spatial relation to the previous made up the "undetermined" volume coverage. It is worth noting that we have not validated the quality of coordinates reported, following the assumption that, for the logging permit to be issued, such cross-checks have been performed by technical staff during the process of permit issuance. We limited ourselves to fixing small inconsistencies such as switched latitude/longitude and inconsistencies in hemisphere and easting/northing reporting, which are documented in scripts available for the replication of this study. All analyses have been performed in R and Python; see Note S4 for details and references on open-source libraries used.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to Caroline S.S. Franca (caroline.franca@chalmers.se).

Materials availability

The data necessary to replicate the analyses presented in this study are publicly available on Zenodo at https://doi.org/10.5281/zenodo.15672070. All data from official sources used in this study are in the public domain in line with Law 10.650/2003 on SISNAMA public data access, although not in all instances readily accessible. The logging permits data under state jurisdiction were originally accessed through Pará's Environmental Secretariat at SIMLAM at http://monitoramento.semas.pa.gov.br/simlam/index.htm. The webpage underwent a major update in March 2023 and data can now be found in http://portaldatransparencia.semas.pa.gov.br/. The logging permits data under national jurisdiction were accessed through the Brazilian Open Data Portal at https://dados.gov.br/dados/conjuntos-dados/dof-autorizacoes-de-exploracao-florestal. The timber transport data from SISFLORA-PA GFs were accessed via the Timberflow initiative led by Imaflora at http://timberflow.org.br/. Since March 2023, these data can also be found at the new Transparency Portal of Pará's environmental secretariat at http://portaldatransparencia.semas.pa.gov.br/. The timber transport data from national jurisdiction, SINAFLOR DOFs, were accessed through the Brazilian Open Data Portal at https://dados.gov.br/dados/conjuntos-dados/dof-transportes-de-produtos-florestais. Data on the CNFP was accessed via the Brazilian Forest Service at https://www.gov.br/agricultura/pt-br/assuntos/servico-florestal-brasileiro/cadastro-nacional-de-florestas-publicas/cadastro-nacional-de-florestas-publicas-atualizacao-2020. Data from the Rural Environmental Registry (CAR) was accessed via https://www.car.gov.br/publico/. The compiled land-tenure data first published by Sparovek et al.[33] were accessed through the Atlas Agropecuário initiative at https://atlasagropecuario.imaflora.org/downloads, which corresponds to the latest updated version. Data produced through the Simex initiative were accessed directly and can be made available upon request. All other supporting data sources have been referenced. Additionally, the code and instructions necessary to replicate the analyses presented in this study are publicly available at https://github.com/carolsrto/limits-timber-traceability.

Data and code availability

- The data necessary to replicate the analyses presented in this study are publicly available on Zenodo at https://doi.org/10.5281/zenodo.15672070.
- The code and instructions necessary to replicate the analyses presented in this study are publicly available at https://github.com/carolsrto/limits-timber-traceability.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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AUTHOR CONTRIBUTIONS

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

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used AI-assisted technologies minimally. ChatGPT was used in order to improve language and GitHub Copilot was used in order to auto-complete code repetitions. After using these tools, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

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