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Quantifying timber illegality risk in the Brazilian forest frontier

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Illegal logging remains widespread across the tropics, leading to extensive forest degradation and trade in illegal timber products. By adapting environmentally extended input–output modelling to timber originating from Brazilian native forests, we demonstrate how distinct illegality risks can be mapped and quantified at species-level across the supply chain. We focus on high-value *ipê* hardwood from the Amazon state of Pará, a leading producer of timber and contested forest frontier. Data on logging permits and state- and national-level Document of Forest Origin licences are used to estimate illegality risks due to missing or invalid logging permits, overstated *ipê* yields or discrepancies resulting from missing inflows of legal timber. We find that less than a quarter of all *ipê* entering supply chains between 2009 and 2019 is risk-free and highlight diversified strategies for the laundering of illegal timber across geographies. While legality does not ensure sustainability, this information can be leveraged to this end by supporting improved implementation and enforcement of forest regulations.

The Amazon basin contains one of the world's largest remaining areas of undisturbed forest, but is also among the regions experiencing the fastest loss of intact forest landscapes^{1,2}. Forest degradation in the Brazilian Amazon surpasses deforestation in terms of area—amounting to a staggering 34 million hectares (Mha) between 1992 and 2014³—biodiversity impacts⁴ and carbon emissions (estimated to be three times those from deforestation⁵). However, forest degradation has not received the same scientific or political attention as that given to deforestation⁶. Emissions from forest degradation are not included in national reporting to the United Nations Framework Convention on Climate Change nor in Brazil's nationally determined contribution to the Paris Agreement⁷.

Forest degradation in the Brazilian Amazon is caused directly by logging and fires and indirectly through fragmentation and edge effects due to deforestation³. However, while the indirect effects have decreased since the early 2000s—following the reduction in overall deforestation rates—degradation due to logging remains stubbornly high: at about 0.6 Mha yr⁻¹ in 2010–2014, it constituted nearly half of total degradation in that period³. Meanwhile, logging remains a poorly

quantified and understood driver of global change⁶, partly due to much of it being informal and illicit⁸.

In the wake of the 1992 Earth Summit, Brazil took steps to track timber from native forests (that is, primary and naturally regenerating forests⁹) and in 2006 a digital system^{10,11} for controlling the production, transport and processing of products from such origins was established. The system currently consists of partly overlapping, though not fully harmonized, national- (SINAFLO¹²) and state-level systems (SISFLORA-MT in Mato Grosso and SISFLORA-PA in Pará): authorized logging permits detailing areas of extraction (by species) are the source of volume-based credits, which then flow via transport to sawmills, processing industries and traders, all documented through a Forest Guide (*Guia Florestal*, GF) or Document of Forest Origin (*Documento de Origem Florestal*, DOF) under state or federal jurisdiction, respectively.

The digital system creates a paper trail that accompanies the timber and other forest products until final processing and export. However, since individual data entries are not systematically linked, a given timber transaction can seldom be traced back to its origin¹³. The ensuing lack of traceability is exploited by actors introducing illegally

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logged timber into the system. This ‘laundering’ of illegal timber has been documented by Brazil’s public prosecutor’s office^{14,15}, environmental journalists¹⁶, NGOs¹⁷ and scientists^{13,18}. Recent estimates suggest that as much as 44–68% of timber extraction from native forests in the top producing Brazilian states is illegal¹⁹. Despite this, Brazil remains a leading supplier of tropical timber to the European Union, United States and China^{20,21}, notwithstanding efforts to halt trade in illegal timber such as the EU Timber Regulation and the US Lacey Act.

Addressing loopholes in the current traceability system for Brazilian timber is crucial for effectively addressing the environmental, economic and social impacts of logging⁸; while legality does not ensure sustainability^{22,23} nor fairness^{24,25}, the widespread illegal exploitation of Brazilian forest resources precludes effective governance to these ends and has profound consequences, from excessive forest degradation²⁶ to undermining the viability of sustainable forest management²⁷ and fuelling environmental violence^{28,29}.

Here we present an analysis that aims to overcome inadequacies in the current traceability system and improve our understanding of practices for laundering timber in Brazil. We make use of comprehensive logging permit and timber transaction data for the state of Pará for the period of 2009–2019 to identify illegality risks across the supply chain using the case of *ipê* (*Handroanthus* spp.), a group of high-value hardwood species. While accounting for only about 2% of total roundwood production from native forests between 2012 and 2017, *ipê* fetches the highest value among all species per volume, with estimates showing 92% is destined for export—mainly to the United States (35%) and the EU (44%)³⁰.

Ipê, slow-growing and occurring in low densities, has been characterized as the ‘new big-leaf mahogany’^{18,31} and was added to the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Appendix II in November 2022 for its recognized threats³². It is also one of the species with the most prevalent documentation of fraudulence^{18,33}, and a driver of the westward movement of the logging frontier in Brazil, towards the heart of the Amazon³¹. Pará is a contested forest frontier, accounting for 28% of Brazil’s total timber production from native forests (second only to Mato Grosso) and 43% of *ipê* harvests during 2012–2017³⁰.

By compiling data from 1,262 logging permits and 309,198 records on the transport of *ipê*, we quantify different sources of illegality risk and identify at what stage in the supply chain illegally logged timber is potentially laundered (Supplementary Fig. 1). At the point of logging, we assess illegality risks in two ways: first, we match timber transport data to logging permits substantiating volumes credited and quantify the share of timber with missing or invalid logging permits; second, like Brancalion et al.¹⁸, we quantify the practice of overstating *ipê* yields, comparing volumes entering the supply chain per area authorized for logging with *ipê* occurrence estimates from the RADAM forest inventory³⁴, with discrepancies between stated yields and natural occurrences of *ipê* indicating illegality risk. Downstream laundering of timber is quantified by comparing the inflows and outflows of timber, converted to roundwood equivalents, by individual actors; where sales of timber volumes exceed those documented as received by an actor, the discrepancy risks being of illegal origin. Finally, all three quantified sources of illegality risk—missing or invalid logging permits, overstated yields and missing inflows—are traced downstream to apparent consumption through an actor-level physical input–output model. This model uses a mass balance principle and an assumption of proportionality between an actor’s inflows and outflows to overcome the lack of full traceability, allowing us to quantify the upstream embodied illegality risks associated with the consumption of *ipê* originating from Pará.

Results

Our compilation of logging permits (see Methods for details) used to substantiate volume entering the SISFLORA-PA and SINAFLOR timber credit systems shows that most *ipê* in Pará originated from forest

frontiers along the highways BR-163 (running north–south) and the BR-230 (Trans-Amazonian, running east–west), as shown in Fig. 1a. Just three municipalities—Santarém, Juruti and Prainha—in the mid-west of the state together account for nearly 38% of volume logged over the period 2009–2019.

Despite year-to-year variability in production (Fig. 1b), our analysis corroborates the inward movement of the logging frontier towards the heart of the Amazon (Supplementary Fig. 2a,b) reported by other studies^{19,31,35}: in 2009 the mid-state municipalities of Anapu and Pacajá accounted for 38% of total production, but by 2019 these municipalities did not even make the top ten. Meanwhile, seven of the top ten producing municipalities in 2019 were located westward of these, with nearly 49% of *ipê* reportedly coming from the western flank of Altamira (the largest Brazilian municipality, covering a substantial portion of mid-state Pará) and Juruti (bordering the Amazonas state and harbouring the first high-capacity port entering Pará from the west).

Illegality risk from missing or invalid logging permits

Nearly all (98%) of total volume entering the *ipê* supply chain could be linked to an existing logging permit, rendering the illegality risk from missing permits negligible. However, 16% (0.16 Mm³) of *ipê* volume entered the crediting system on the basis of invalid permits; that is, permits that had been suspended, cancelled or that were missing an activation date (Fig. 1b). This substantial share lends quantitative support to the existence of loopholes in current systems, where the issuance and subsequent cancellation of permits is used to generate artificial timber credits that can then be used to launder illegally logged timber, a practice hitherto mainly documented for the case of DOFs^{14,15,17}. This highlights a shortcoming of the licensing system, where multiple permits linked to the same Sustainable Forest Management Plan (PMFS) area may be issued without documentation of their interrelatedness, often leaving environmental agency analysts with the task of manual cross-checks and validation between licensing and crediting systems³⁶.

Three municipalities—Santarém, Juruti and Prainha—together account for 39% of these invalid permits (Supplementary Fig. 2c,d). As shown in Fig. 1b, there is some indication that this risk has decreased over time, potentially as a result of reporting becoming more simplified: until 2014 more detailed information on the reason for permits being invalid (for example, cancelled due to illegality or elaboration failure, among other labels) is displayed, whereas after 2014 permits simply state ‘cancelled’ or ‘suspended’. From 2018 to 2019 only marginal flows were reported coming from invalid permits. Indeed, documented efforts (for example, ref. 37) on technical improvements to the integration of licensing and crediting systems are probably a key driver of this decrease. Nonetheless, uncertainties still exist surrounding the extent and timeline of implementation of these improvements^{36,37}. This therefore implies that we cannot disregard the possibility that the trend is due to a decrease in ability and willingness to pursue suspension and cancellations, in line with the broader downward trend in environmental law enforcement that is evidenced by the reduction of embargoes and infractions issued across the Brazilian Legal Amazon and particularly evident for the later years of analysis³⁸.

Illegality risk from overstated *ipê* yields

While about 76% of *ipê* volume entering the supply chain can be matched to valid state-level logging permits (that is, excluding invalid or missing federal jurisdiction permits and inflows from other states), this timber is not necessarily free from illegality risks. Comparing reported volumes entering the supply chain with the areas licensed for extraction in the corresponding logging permits, we found an average *ipê* yield of 1.8 m³ ha⁻¹ (s.d., 2.2 m³ ha⁻¹). This can be contrasted with field observations from Pará¹⁸, where yields average 0.7 m³ ha⁻¹ (Fig. 2a). While we should expect logging permits to be concentrated in forests with higher than average *ipê* stocking rates (number of trees per hectare), the differences are quite striking: 28% of valid permits display

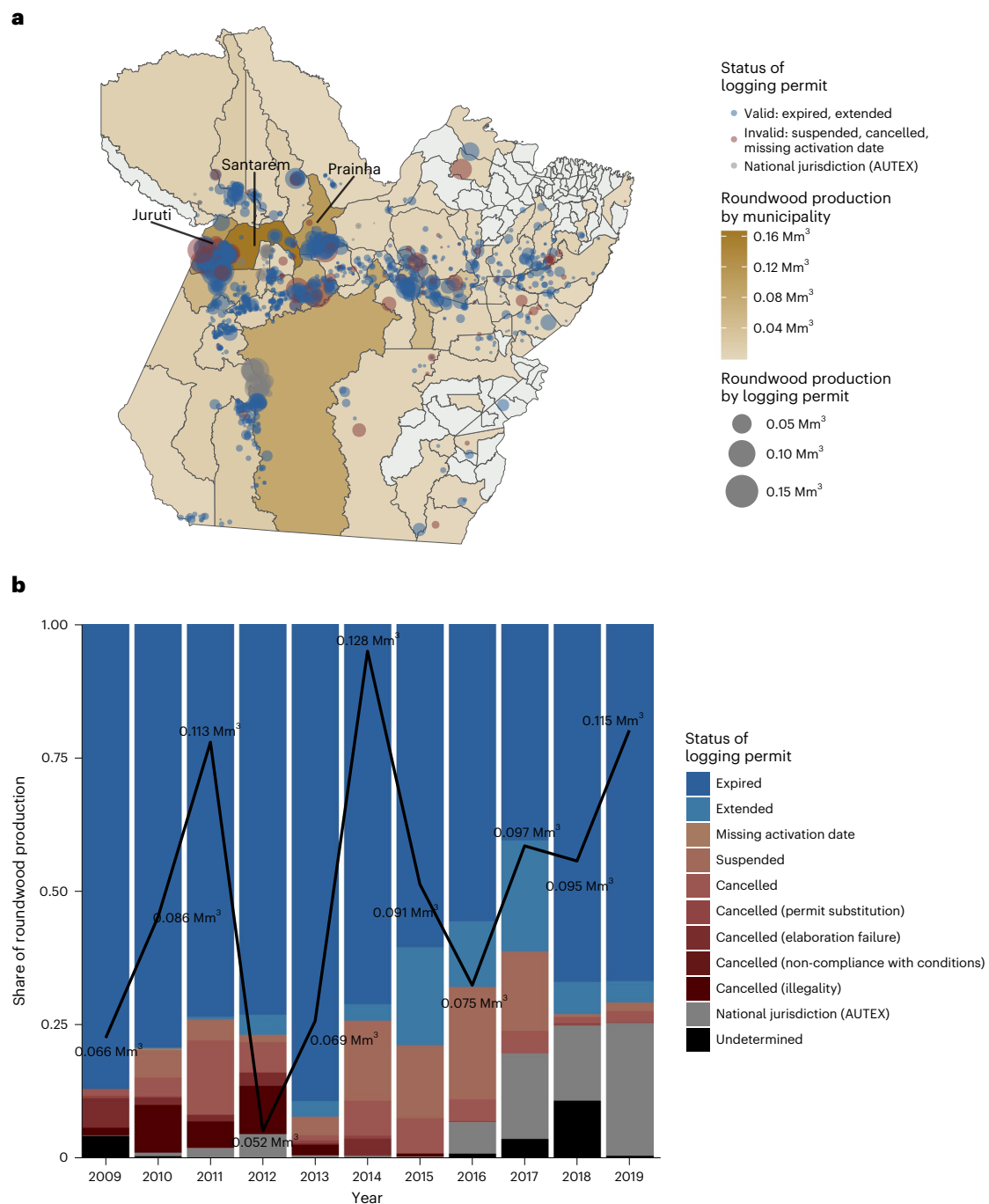


Fig. 1 | Forest of origin. **a**, Spatial distribution of issued logging permits and associated volume entering the supply chain. Unit: million m³ (Mm³). **b**, Status of issued logging permits used to transport roundwood out of forest of origin.

All classes aside from ‘National jurisdiction’ and ‘Undetermined’ come from state-level permits. The black line serves as reference for total annual roundwood production from Pará.

yields that exceed the RADAM plots’ 99th percentile class (2.4 m³ ha⁻¹). More starkly, as shown in Fig. 2b, these permits account for nearly half (48%, 0.36 Mm³) of the volume entering the supply chain under valid permits, but only 14% (0.1 Mha) of the licensed area (Supplementary Fig. 3). In total, valid permits with yields exceeding the 99th percentile make up approximately 36% of all *ipê* entering the supply chain.

Three additional observations strengthen the suspicion that the reportedly high yields reflect an avenue for introducing illegally logged timber: first, we use a conservative threshold for overstated yields, based on simulated yield distributions for the smallest occurring logging plot in our sample (about 19 ha), but 83% of *ipê* volume comes

from authorized areas larger than 370 ha, for which expected stocking rates are more narrowly distributed around the mean (Supplementary Fig. 4). In fact, even if we exclude all timber from the smallest quartile of authorized areas (19–66 ha)—which are most likely to include sites selected for high occurrence of *ipê*—the estimated illegality risk of laundering through inflated yields would only drop marginally (0.02 Mm³) to 45%. Second, as shown in Fig. 2b, areas from federal-licensed enterprises display yields much more aligned with volumes derived from RADAM plots, with an average of 0.68 m³ ha⁻¹ (s.d., 0.87 m³ ha⁻¹). While the SINAFLOR database includes only 29 permits (just 3% of the number from state level), and there is inconsistency in reporting between

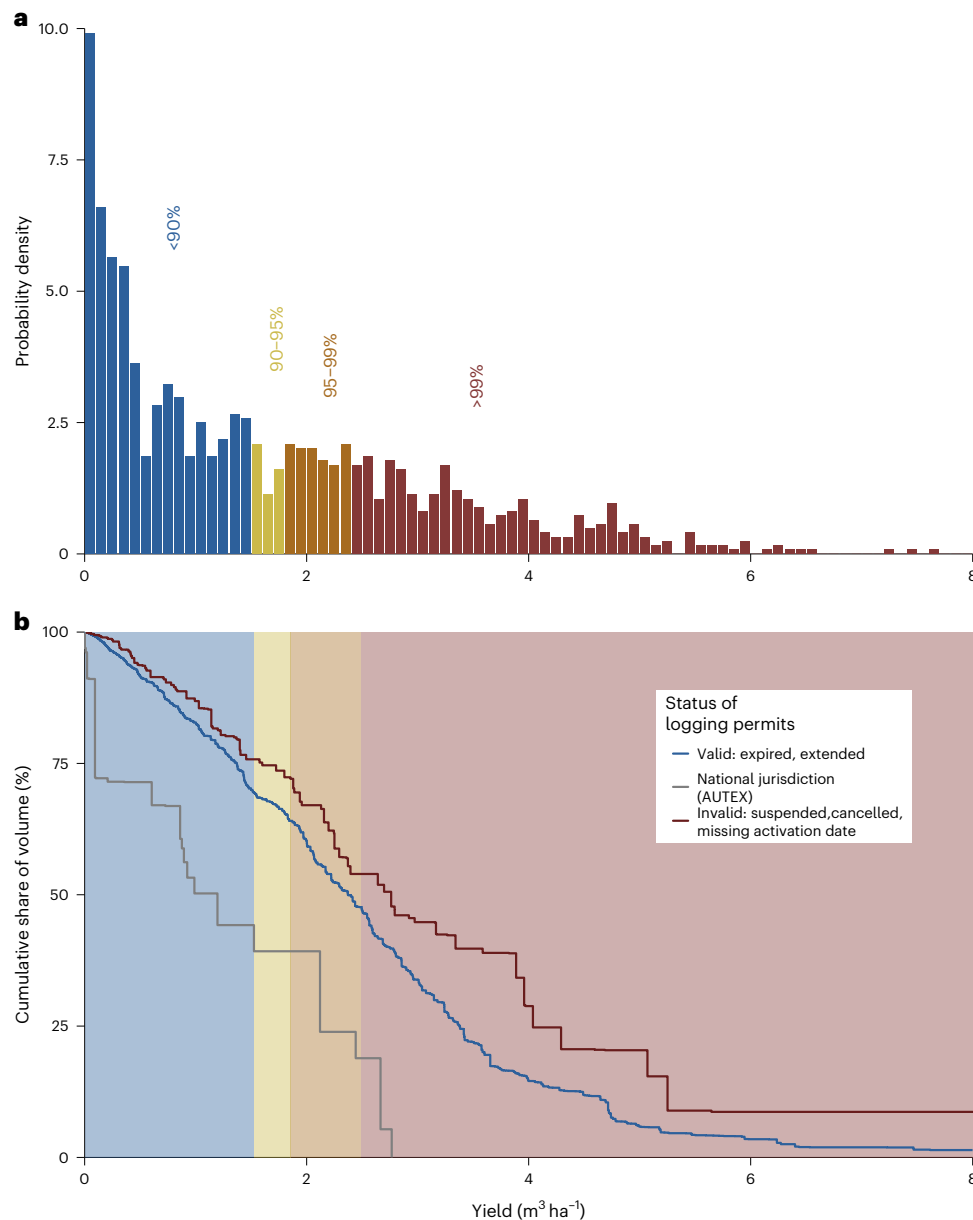


Fig. 2 | Species yield. **a**, *Ipê* yield density when contrasted with the national RADAM forest inventory at <90th, 90–95th, 95–99th and >99th percentiles. **b**, Cumulative share of volume by logging permits status.

state and national level, plus the fact not all volumes may yet have been reported for concessions (given the 2019 cut-off date), this still indicates that national jurisdiction enterprises are less susceptible to this type of illegality risk. Third, the logging permits displaying yields above the 99th percentile class are highly concentrated geographically: the municipalities of Juruti and Santarém together account for 31% of volumes with potentially overstated yields (0.11 Mm³; 11% of the entire roundwood production) (Supplementary Fig. 5).

Illegality risk from production–consumption flows discrepancies

According to the transport records (GF and DOF) analysed, nearly 1.0 Mm³ of *ipê* roundwood was reported as leaving forests across Pará between 2009 and 2019, with an additional 0.17 Mm³ roundwood equivalent (RWE) entering the supply chain from federal units. The figures contrast with the amount of timber originated in the state being consumed nationally and abroad, which, according to the same

data, amounts to nearly twice as much: 2.1 Mm³ RWE (1.8–2.6 Mm³ RWE using a high (53.9%) and low (35%) overall sawmill efficiency in timber processing, respectively; see Methods). Consequently, 37–54% (0.65–1.39 Mm³) of the total *ipê* volume entering the supply chain in Pará cannot be traced to a forest of origin (or to an inflow from other states) (Fig. 3).

Belém, Breu Branco and Itaituba—all key port cities and commercial hubs—together account for 36–38% (0.23–0.53 Mm³) of total discrepancies and this increases to nearly half of all discrepancies—and a fifth of all *ipê* being transported in the Pará supply chain—if also accounting for metropolitan and adjacent cities. The Belém metropolitan region (which includes origin municipalities of Belém, Ananindeua, Benevides, Castanhal and Santa Bárbara do Pará), together with the neighbouring port city of Barcarena—none of which produce any *ipê*, but from where most timber exports leave the state—account for a fifth to a fourth (19–27%; 0.13–0.37 Mm³) of all discrepancies.

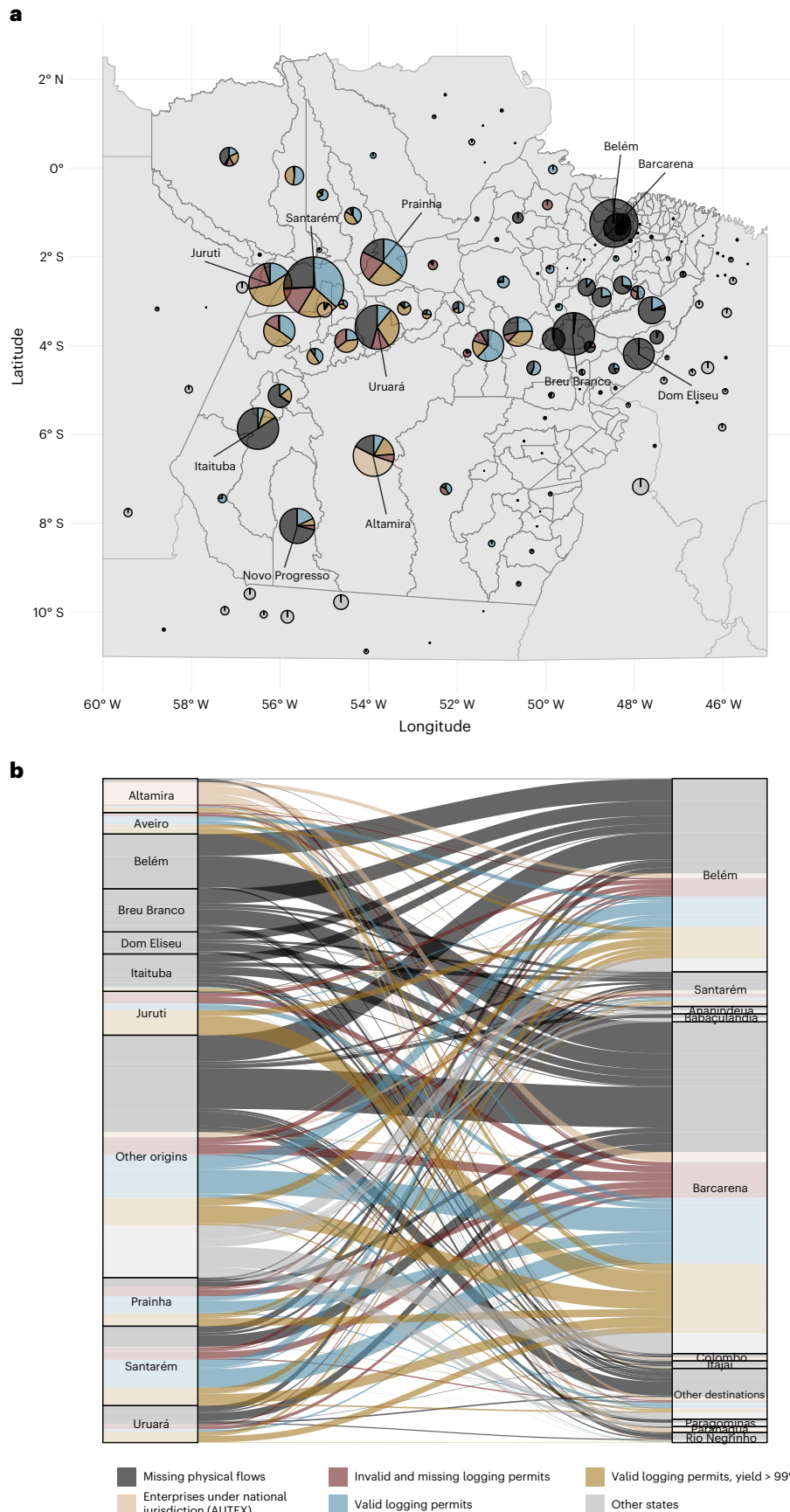


Fig. 3 | *Ipê* origins and destination according to associated illegality risks. a. Municipality of origin according to volume and potential illegality risk associated with timber flows. **b.** Overview of top ten municipalities of origin and destination.

Mapping illegal timber flows through the supply chain

The results above create a picture of diverse strategies for the laundering of illegal timber across the state. Overall, only about 19% of the *ipê* volume transacted as licit in Pará was found to be entirely risk-free. On the eastern and more consolidated frontier (Fig. 3a), the predominant illegality risk comes from flows that cannot be traced to a forest of origin. Relatively low signs of overestimation exist, indicating that here illegal timber entry points are associated with downstream processors and intermediaries, rather than in the first stage of the supply chain. Moving westwards, patterns of illegality risk become more diversified in line with the opportunities offered by larger producing municipalities.

Such diversity can be best exemplified by the contrast between Itaituba and Juruti, both of which are significant points of origin of *ipê* located at the border with the state of Amazonas. Nearly 80% of timber originating from Itaituba cannot be accounted for by own production and inflows, suggesting the more prominent risk here is at the processing and intermediaries level. Meanwhile, more than half of the illegality risk for timber originating in Juruti comes from overstated yields. A significant volume of timber from invalid permits has also entered the supply chain through this municipality, indicating a higher risk for the entry point of illegal timber at the first stage of the supply chain in this municipality.

Despite the diversity of entry points, Belém metropolitan region and neighbouring Barcarena exert a clear consumer pull on supply of *ipê* from across the state (Fig. 3b), largely due to export demand. We found 69–65% (2.59–1.78 Mm³; low–high sawmill efficiency) of the entire *ipê* volume bought and sold along the supply chain is destined for export, while the remaining 31–35% can be interpreted as domestic final consumption or consumption by intermediaries (that may be exported after processing). Only a relatively modest share of *ipê* is destined to other municipalities within Brazil, with two other port cities in the south of the country (Paranaguá and Itajaí) making the top ten municipalities in terms of apparent consumption.

Discussion

Over the past three decades, Brazil has invested significant resources—at federal and state level—in developing legal frameworks, institutional and technical capacity, as well as supply chain actor's buy-in, towards a system for controlling timber extraction from native forests. Our analysis shows that data from these systems—while far from perfect—can be leveraged to identify and quantify illegality risks at the actor level in different stages of the supply chain, from timber harvesting to processing, transport and export. Given previous evidence of the effectiveness of field-based enforcement in controlling deforestation in the Brazilian Amazon³⁹, this points to great potential in using available data from these systems to reduce forest degradation. To date, this potential remains largely untapped: the SISNAMA (National Environmental System) institutions tasked with overseeing environmental enforcement in Brazil have largely ignored the issue of illegal timber harvesting, lacking—as previously highlighted in the case of deforestation⁴⁰—accurate statistics on the magnitude of illegality. This omission is amplified by the recent national downward trend in embargoes and infractions issued by environmental authorities³⁸ and the curtailment in resources availability for SISNAMA institutions⁴¹ under the Bolsonaro regime.

In response to the lack of capacity and political will for environmental monitoring and enforcement^{38,42}, civil society initiatives (for example, SIMEX Network¹⁹ and Imaflora's Timberflow), as well as private sector solutions (for example, BVRio), are currently trying to fill information gaps and support due diligence in the Brazilian timber supply chain. Nonetheless, the lack of transparency, quality and completeness of information made available by SISNAMA institutions makes this a daunting task¹⁹. The most obvious shortcomings of the current traceability system are the lack of systematic connection of processed products with forest of origin, the fact that finished products are captured too broadly (or nor at all) beyond certain categories of

sawnwood and decking, and the inaccessibility of data. Notably, the public-facing SISFLORA-PA (<https://monitoramento.semas.pa.gov.br/sisflora/>) and DOF System (https://servicos.ibama.gov.br/ctf/modulos/dof/consulta_dof.php) search engines, for instance, still only allow for single GF or DOF searches, thus providing limited support for end-to-end due diligence from a buyer's perspective. While the assumption may be that internally such systems operate with lesser constraints, audit documentation from the Federal Court of Accounts³⁶ suggests otherwise: even after a decade of technical cooperation, analysts of the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) still could not access key information from the tax department of the National Registry of Legal Entities (CNPJ) to check if timber transactions of enterprises amounted to a proportionate level of reported economic activity, and had to resort to single-searching platforms and manual cross-checks.

Importantly, poorly integrated state- and national-level systems continue to provide opportunities for the laundering of illegal timber. The lack of integration is evident at two levels: between the licensing (SIMLAM) and the transport (SISFLORA) systems, and between the state and national level of transport systems. In 2014, an agreement on integration across these levels was signed and in 2020 a normative instruction⁴³ again sought to make states comply with SINAFLO. However, full integration remains to be accomplished, with Pará and Mato Grosso data 'still missing for the entirety of the period' in the Brazilian Open Data portal. On the one hand, states have stepped up to devise the first comprehensive timber traceability systems, but lack the national oversight needed for full traceability. On the other hand, national agencies with the mandate have failed to offer a replacement system that incorporates hard-won lessons and improvements made by states (for example, certain features are oversimplified at national level, such as the lack of DOF type, barcode tracing and registrations that may be important for internal monitoring by states).

While the analysis presented above tries to address some of these limitations—through careful compilation and deduplication of data across state- and federal-level systems and constructing an actor-level input–output model to trace timber from origin to consumption—it is no substitute for a full-fledged traceability system. The fragility of the existing licensing and timber crediting systems and the lack of official estimates on illegality, together with the lack of enforcement, currently do little more than add a veneer of legality to a system known to be riddled with loopholes, as our (and other³⁵) results for *ipê* in Pará have clearly shown. Nothing makes the shortfall of the current system more evident than the fact that, while our analysis suggest that over three-quarters of all *ipê* originating from Pará is associated with some degree of illegality risk, most of that timber is still being exported to markets in the United States and EU countries³³ that have legal provisions in place which prohibit the imports of illegally logged timber.

Recent developments, however, give some reasons for hope: as of 5 December 2022, a new 'DOF+ Traceability' (*DOF+ Rastreabilidade*) system has come into force⁴⁴, which automatically generates a persistent traceability code to products being credited into the system, at last allowing for full traceability from timber harvest to consumption or export. While this system—which is meant to replace the current federal- and state-level DOF systems—would constitute a major improvement in traceability for Brazilian timber, our analysis also highlights the need for going beyond just improved reporting. If entered data is not cross-checked for credibility and consistency and used as a basis for monitoring and enforcement, actors are likely to continue to use existing loopholes or find new ones for laundering illegally logged timber.

Methods

We propose three complementary approaches for quantifying sources of illegality risk of Brazilian timber from native forests, reflecting three different stages in the timber supply chain. First, for roundwood being

transported from forests, we match unique identifiers in logging permits and state- and federal-level documents of forest origin (GFs and DOFs) to distinguish timber with valid and invalid logging permits. Second, at the timber-harvesting stage, we quantify the documented practices¹⁸ for inflating the harvest of valuable species to allow illegal timber to enter the supply chain, by contrasting implicit *ipê* yields with stocking rates from the RADAM forest inventory. Third, we assess inconsistencies between downstream actors' input and output volumes to identify the introduction of illegally logged timber, using an adapted environmentally extended input–output model. This model also allows for the connection between localities of production and consumption, supporting an analysis of illegality risks from a consumer perspective. The next sections first introduce the unique data used for the analyses and then detail the three steps outlined above (see Supplementary Fig. 1 for an overview of the methodological approach and the input data used in each step). The analyses have been performed in R and Python and leveraged several open source libraries referenced in Supplementary Note 5.

Timber production and traceability systems in Brazil

Timber originating from Brazilian native forests first enters the supply chain via logging permits generically known as Authorization for Forest Exploitation (*Autorização de Exploração Florestal*, AUTEX). Once the timber is felled, the issuance of a DOF is obligatory for the transport, reception, processing and stocking of products of native origin^{45,46}. The digital DOF System, instituted in 2006^{10,11}, is in practice a forest products credit system based on units of volume: credits are first created in connection with the authorized area, where extracted volumes (by species explored) are credited to the forest owner or administrator. Credits then flow via transport to sawmills, processing industries and traders. The DOF creates a paper trail that accompanies the timber and other forest products until its final domestic processing and export, thus constituting the primary instrument and data source for Brazilian timber traceability and origin accountability.

While this is a simplified national view, implementation of timber origin control has been historically complex and diverse. The National System for Control of Origin of Forest Products (SINAFLO), created in the aftermath of the 2012 Brazilian Forest Code, sought to integrate the varying sub-national control systems for forest product origins, as well as improve and systematize processes related to licensing and monitoring of forest exploitation activities¹². However, Mato Grosso and Pará still maintain their own state-level systems—SISFLORA-MT and SISFLORA-PA, respectively—that are deemed compatible with SINAFLO¹⁰ and in many ways are precursors to the latter. Despite broad compatibility, notorious inconsistencies between these systems still exist and states have been pressured to join the national system⁴³.

A key difference relevant for this study is the use of the Forest Guide (GF), the equivalent of the DOF for internal transport in SISFLORA-PA (and SISFLORA-MT) and used alongside DOF in international due diligence systems (for example, BVRio). Variables in GFs and DOFs are not collected or reported equally (see Supplementary Note 4 and Fig. 6 for further details). Additionally, SISFLORA-PA underwent an upgrade in 2016, resulting in slightly differing data structures for GFs under what is now known as SISFLORA-PA 1.0 (2006–2016) and SISFLORA-PA 2.0 (2016–). The environmental licensing under which logging permits are issued also differs between state and federal level, with the logging permit (AUTEX) having its Pará counterpart called AUTEF. In practice, this implies that the national- and state-level environmental licensing and timber transport systems are only partially overlapping.

Despite varied nomenclature in licensing between states and national systems, the sources of roundwood production can be broadly grouped into four categories: (1) harvest of isolated trees (accounting for 0.2% of Brazilian timber production in 2012–2017); (2) forest plantations (4.3% of volume); (3) Sustainable Forest Management Plans (PMFS) (87.6% of volume); and (4) vegetation suppression

(legal deforestation; 7.9% of volume)³⁰. Each encompasses its own permit issuance requirements and protocols, ultimately constituting different types of logging permits. Requirements for forest management plans were first put forward in 1987, following which exploitation of native forests has been regulated by legal parameters⁴⁷. Current sustainable forest management requirements broadly encompass a 25–35-year harvest cycle, with an overall upper limit of 30 m³ ha⁻¹ (about 3 trees per ha), with special cases applying for lower intensities and smaller areas^{45,48}. A minimum of 10% of trees per species should be retained, ensuring that at least three individuals with diameter at breast height above the minimum harvest diameter (50 cm) are kept in every 100 ha, occurrence below which precludes the exploitation of the species altogether (including differentiated rates for species listed as vulnerable⁴⁹). Legislation underpinning PMFS licensing across jurisdictions include provisions for differentiated harvest intensities according to species. Nonetheless, it is widely recognized that these legal parameters are set at odds with species-specific thresholds for sustainable harvest^{22,50}—particularly for sought-after species such as *ipê*³¹. The PMFS category under which most (96.9%) *ipê* is produced³⁰, therefore, includes everything from actors pursuing best practices (for example, reduced impact logging), to those just fulfilling the legal minimum, or worse.

Illegality risk due to missing or invalid logging permits

In principle, all roundwood being transported from forest of origin should have a valid logging permit that substantiates the volume credited to corresponding GFs and DOFs¹¹. However, fraud schemes starting in this node of the supply chain are well-known^{13,14,17,18,51}. A common practice for laundering illegal timber is the issuance and subsequent cancellation of documentation, which generates illicit credits that are used to enter illegally logged timber into the system¹⁷. This practice has mainly been documented^{14,15} in the case of DOFs¹⁷. In addition, GFs and DOFs may cite logging permits that are either nonexistent or that lack required information. However, the lack of a comprehensive database of logging permits that detail the origins of forest products have precluded an assessment of the extent of these practices.

To overcome this, we compiled a consolidated logging permits database for the state of Pará by combining official data made available publicly or through other publications (see Supplementary Note 1 for details and sources). A total of 1,292 permits have been used by supply chain actors transporting roundwood to report place of *ipê* origin: 1,215 of these were backed up by logging permits issued at state level and 47 at federal level, while the remaining 30 could not be backed up (original permit data could not be downloaded or found).

Logging permit information and timber flows entering the supply chain (as documented through GF and DOF records) were uniquely matched by permit. We used GF data from the SISFLORA-PA system accessed via the Timberflow initiative (<http://timberflow.org.br/>). DOF data were accessed via the SINAFLO 'transport' module (<https://dados.gov.br/dados/conjuntos-dados/dof-transportes-de-produtos-florestais>) (see the 'Production vector' below and Supplementary Note 3 for details). By extracting authorization status and other key information (for example, permit number, activation date, geolocation, area authorized) from logging permits, we identified timber flows with (1) missing logging permits and (2) logging permits that for different reasons had been suspended, cancelled or missed crucial information (for example, activation date). This analysis provides data both on localities of timber production and respective volumes entering the supply chain, as well as indicators of illegality risk (missing or invalid logging permits) that were then fed into the input–output model to trace this risk through the supply chain to downstream consumers.

Illegality risk from overstated *ipê* yields

High-value species are particularly susceptible to yield overestimation, as demonstrated by Brancalion et al.¹⁸ when contrasting volume

authorized for harvest, as listed in logging permits, with volumes estimated from the RADAM national forest inventory. However, actual timber removal as stated in GF and DOF reporting is likely to give a more accurate indication of timber volumes harvested, or being used for laundering of illegally logged timber, than volumes stated in logging permits. Thus, we calculated implicit *ipê* yields as the ratio between volumes entering the supply chain and areas authorized for harvest ($\text{m}^3 \text{ha}^{-1}$) and, following Brancalion et al.¹⁸, contrasted these with stocking rates derived from RADAM.

Figures on exploited volumes were obtained by summarizing roundwood volume entering the supply chain from each listed permit in the GF and DOF records, while figures on area authorized for harvest were obtained from the logging permits dataset, as described in the previous section. We calculated the yield for all logging permits that had a match and where figures on area were available for the logging permit, including for those which had been cancelled and suspended ($n = 1,243$; see Supplementary Note 2 for details).

In determining baseline figures for naturally occurring *ipê* yields, we leveraged the timber volume estimates from RADAM, as well as the code for statistical analyses, from Brancalion et al.⁵². Because the RADAM plots are 1 ha and authorized areas are significantly larger (ranging from 19 ha to 1.3 Mha, with an average of 653.7 ha for valid AUTEFs and 123 kha for AUTEEX, 2009–2019), we performed 10,000 randomizations for plots of larger sizes—starting with the minimum licensed area of about 19 ha—to build a comparable density distribution. Drawing from 394 unique RADAM plots available for the state of Pará, and using only data for trees with diameter at breast height that was ≥ 50 cm, we provide details on obtained yield distributions in Supplementary Fig. 4. While the illegality risk from overstated yields is a gradient, rather than a binary risk, we used the proportion of volume displaying yields above the 99th percentile for the 19 ha distribution (Supplementary Fig. 3b) as threshold for illegality, although we consider this a conservative estimate (see Supplementary Note 2 for further details and for applicable assumptions and limitations).

Illegality risk from production–consumption flows discrepancies

As timber passes through sawmills, traders and other processors and intermediaries, information on forest of origin is no longer systematically reported, making tracing of timber from place of production to consumers cumbersome and, more often than not, impossible. Indeed, the CONAMA Resolution 379 of 2006¹¹ that first put forward minimum national requirements and protocols for reporting under the DOF System, stated that place of origin must be reported “In case of roundwood, the location of PMFS or authorized deforestation must be reported. In the case of transfer, the transfer yard must be reported. ...” (Annex B.6., own translation). This makes traceability beyond the transport of roundwood from forest of origin reliant on actor-to-actor links and associated transfer of timber credits.

To link consumers to timber origin, we therefore used an adaptation of environmentally extended input–output models for physical flows, as proposed by Kastner et al.⁵³. The rationale for this is threefold: (1) to determine where timber consumed is originally produced by systematically accounting for intermediary transactions; (2) to estimate the magnitude of illegality risks associated with consumption of timber product from a given origin; and (3) to assess the risk of illegally harvested timber entering the supply chain, indicated by calculating discrepancies between the magnitude of inflows and outflows of timber for all actors in the supply chain.

The physical input–output model was calculated at actor level using the CNPJ (National Registry of Legal Entities) or anonymized CPF (individual taxpayer identification) numbers to identify distinct actors in the supply chain. When presenting the results, individual flows are aggregated to municipality level. Below we detail how the two components of the input–output model—the production vector

and the bilateral transaction (‘trade’) matrix—were constructed from the GF and DOF datasets.

Production vector. Production figures are derived from roundwood volumes being reported leaving forests within the state of Pará. Inflows from outside Pará are accounted for with the purpose of identification of discrepancies and thus are included in the production vector as a dummy. To avoid double-counting from resale and subsequent retransport, we removed flows where actors sent roundwood to themselves (and as such have no implication on the physical balance of the input–output analysis). These are reported differently between SISFLORA and SINAFLO and thus different logic was needed, as described in detail in Supplementary Note 3. This removed about 11% (75,672 m^3 , 5,970 records) of flows for SISFLORA 1.0 and 6% (19,843 m^3 , 7,531 records) for SISFLORA 2.0. For SINAFLO these removals were substantial; we discarded 66% of roundwood flows (150,610 m^3) alone on the basis of missing logging permits, required at first transfer. Indeed, many of the discarded flows were probably duplicates between systems and further steps to ensure these were minimized have been described in detail in Supplementary Note 3.

Bilateral transaction matrix. Constructing a comprehensive and consistent matrix of all flows of *ipê* between supply chain actors in Pará from the data contained in the SISFLORA-PA and SINAFLO systems required the following data-processing steps: (1) choosing the product categories to include; (2) converting all flows to a common unit; and (3) removing duplicates between the two reporting systems.

Regarding product selection, we included all major timber products relevant for *ipê* as listed in Supplementary Table 1 and detailed in Supplementary Note 3. Given that volumetric conversion factors are used to regulate allowable conversion rates (as well as forming the basis for reporting by actors and monitoring by authorities), we chose to convert all flows into roundwood equivalent. Conversion factors to RWE were drawn from a combination of both legislation and recent research, and estimates aimed to reflect assumptions on both low and high conversion efficiency by processing industry operators. On the lower boundary, CONAMA Resolution 474 of 2016⁵⁴ sets the current baseline for primary breakdown—first processing of logs from which a mix of products is derived⁵⁵—at 35%. The figure is not species-specific and it is understood to assume low sawmill efficiency⁵⁵, as well as incorporate the risk of illegal timber laundering⁵⁶ (since a lower conversion factor implies that less processed product could be sold after processing, for a given input volume). For the upper boundary, operators are still allowed to submit their own technical reports with revised species-specific values to be applied to their own processing (although this is administratively cumbersome). In a recent study, Romero et al.⁵⁷ found *H. serratifolius* to have a primary breakdown conversion factor of 53.9%, probably reflecting the high value of the wood (creating an incentive to reduce waste and loss). Here, we adopt a mid-point estimate (44.5%) when aggregating results across the different illegality risks, also taking into consideration that 45% was the national baseline in the period 2009–2016. Supplementary Table 1 summarizes products and respective conversion factors.

Finally, we looked to minimize instances of double-counting between state and national systems. Given SINAFLO data appears to have CPF/CNPJ of origin set equal to CPF/CNPJ of destination for instances of duplication between systems, and that such records carry no practical implication on the physical input–output balance, we discarded all such flows upfront.

Supply chain discrepancies and environmental extensions. Finally, to estimate the potential introduction of illegal timber in the supply chain for *ipê*, we evaluated the discrepancy between inflows and outflows of timber products (measured in RWE) for each actor. Where outflows exceeded inflows, the missing timber was assigned to dummy

producers, allowing us to track discrepancies by receiving actor and tracing this illegality risk all the way to apparent and known final consumer. Here it is worth underscoring the analysis incorporated transactions for the entire 11-year period and thus it can be expected that the initial lag will cause a possible overestimation of missing origins early in the period (2009–) (although this will to some extent be balanced by missing outflow post-2020). While this is a limitation of the study, we sought to minimize it by incorporating over a decade of data, which allows the magnitude of this legality risk to still be captured. Dummy producers were also added to capture flows with outer-state origins. Given tracing production from forests of origin outside Pará is out of the scope of the current study, we do not make any assessment on the illegality risk associated with such inflows. After proper dummy set-up, we estimated the share of consumption associated with the other two illegality risks as described above: (1) illegality risk coming from invalid and missing permits and (2) illegality risk from overestimation. While we assess the overestimation risk for enterprises under national jurisdiction, the latter is presented separately for the inherent differences between systems discussed.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data necessary to replicate the analyses presented in this study are publicly available on Zenodo at <https://doi.org/10.5281/zenodo.8068431>. All data 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, given the transparency caveats discussed in this paper. 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 with the launch of a new transparency portal and the link redirect users to <http://portal.datransparencia.semas.pa.gov.br/> where this state-level logging permit data can now be found. 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 Imaflo at <http://timberflow.org.br/>. The timber transport data from SINAFLO DOFs were accessed through the Brazilian Open Data Portal at <https://dados.gov.br/dados/conjuntos-dados/dof-transportes-de-produtos-florestais>. The RADAM national inventory data were accessed through the Brancalion et al.⁵² Zenodo repository. All other supporting data sources have been referenced.

Code availability

The code and instructions necessary to replicate the analyses presented in this study are publicly available at <https://github.com/carolsrto/illegality-risk-ns>.

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Author contributions

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.

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Competing interests

The authors declare no competing interests.

Additional information

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The automated download of SINAFLOR data was carried out in R (last replicated in R 4.3.1). Administrative boundaries were obtained via API from geobr R library. The automated download of logging permits and the scraping of logging permit PDFs were carried out in Python (last replicated in Python 3.10 and 3.11 respectively). As of March 2023, the SIMLAM-SEMAS webpage used in the auto-download of logging permit PDFs underwent a major update and logging permits data can now be accessed via <http://portaldatransparencia.semas.pa.gov.br/>.

Data analysis

All steps that pertain to data cleaning, integration, manipulation and analyses as well as output visualization and mapping were performed in R (last replicated in R 4.3.1) and made use of several open source libraries. Data cleaning, wrangling and analyses used particularly the tidyverse, janitor, sf, base R, but also tmap, expm, ggpmisc, reshape2. Graphs displayed throughout the manuscripts were based particularly on ggplot2, scatterpie and ggalluvial, but also on patchwork, scales, paletteer and scico libraries. The code necessary to replicate the analyses presented in this study are publicly available at <https://github.com/carolsrto/illegality-risk-ns>.

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All studies must disclose on these points even when the disclosure is negative.

Study description	We quantify sources of illegality risk and indicate at what stage in the supply-chain illegally logged timber is potentially laundered. First, we quantify the share of timber with missing or invalid logging permits being commercialized by matching timber transactions data to logging permits. Second, building on Brancalion et al. 2018, we quantify the practice of overstating yields, comparing stated harvest volumes per area authorized for logging with stocking rates from the RADAM national forest inventory. Lastly, we compare inflows and outflows of timber by converting all relevant ipê products to volumes of roundwood-equivalent. The three quantified sources of illegality risk are traced downstream to apparent consumption through an actor-level, physical input-output model that overcomes the lack of full traceability, allowing us to quantify the upstream embodied illegality risks associated with the consumption of ipê originating from Pará.
Research sample	We used all data available for logging permits and timber transactions relevant for the scope of the analysis. For the RADAM forest inventory, we used all data from the 1-ha RADAM plots (DBH, ≥50 cm) in line with the replication of Brancalion et al. 2018 study. We used a total of 394 unique RADAM plots.
Sampling strategy	No sampling strategy was applied. We reproduced the results of Brancalion et al. 2018 for ipê yields estimate.
Data collection	We collected and compiled data from different sources and databases, all referenced throughout the study.
Timing and spatial scale	The study covers the period between 2009-2019 and focuses on the Brazilian state of Pará.
Data exclusions	No data were excluded from the analysis. Any data points removed from visualizations are made reference to in captions and text.

Reproducibility	Custom code was developed to allow for the full reproducibility of the current study, including data collection (when applicable), cleaning, integration and analyses as well as output visualization and mapping. To be sensitive in what pertains to data protection laws, not all intermediary code (e.g. cleaning and integration steps) are made available in the public repository, but can be requested directly to authors. The study can also be fully reproduced by obtaining the same datasets and following the methodological steps described in methods and supplementary information.
Randomization	In determining baseline figures for naturally occurring ipê yields, and because the RADAM plots are 1ha and authorized logging areas were significantly larger, we performed 10,000 randomisation's of 19 1-ha plots (minimum authorized area) in order to build a comparable density distribution. This species yields estimation was replicated from Brancalion et al 2018 study approach.
Blinding	Not applicable to our study.
Did the study involve field work?	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involvement in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> Antibodies
<input checked="" type="checkbox"/>	<input type="checkbox"/> Eukaryotic cell lines
<input checked="" type="checkbox"/>	<input type="checkbox"/> Palaeontology and archaeology
<input checked="" type="checkbox"/>	<input type="checkbox"/> Animals and other organisms
<input checked="" type="checkbox"/>	<input type="checkbox"/> Clinical data
<input checked="" type="checkbox"/>	<input type="checkbox"/> Dual use research of concern

Methods

n/a	Involvement in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> ChIP-seq
<input checked="" type="checkbox"/>	<input type="checkbox"/> Flow cytometry
<input checked="" type="checkbox"/>	<input type="checkbox"/> MRI-based neuroimaging