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Characterization of technical and legal irregularities in management plans in the Brazilian Amazon

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ABSTRACT

A Sustainable Forest Management Plan (SFMP) is essential for promoting the appropriate use of forest resources in the Brazilian Amazon. However, in contrast to technical and legal precepts, some plans can be used to hide environmental crimes. Therefore, based on 184 administrative processes, this study aimed to analyze the main technical and legal irregularities found in the SFMP filed by the Federal Environmental Agency between 2006 and 2021. These plans are located in eight states of the Brazilian Legal Amazon, covering an area of 746 thousand hectares of forest management and involving the authorization of 4.1 million cubic meters of round wood. It was found that 82.3 % of these SFMPs were authorized by single annual production units (APU), which contradicted the precepts of forest management and tended to facilitate the commission of illegal acts. The analysis identified 27 variables, resulting in 1,003 technical and legal nonconformities identified by the Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA), a federal agency responsible for environmental protection. Multivariate cluster analysis demonstrated the relevance of the main factors throughout the analyzed period, highlighting problems in the chain of custody, irregular forestry transport, unauthorized forestry exploitation, and fraudulent movement of credits; the latter was present in 72.8 % of the SFMP analyzed. The factor analysis grouped ten factors that explained 74.3 % of the total variance. The importance of forest management and the sustainable use of forests in the Amazon is irrefutable; however, the results suggest that SFMPs, when misused, can act as vectors for environmental crimes, mainly by incorporating and hiding wood without legal origin. Addressing these deficiencies may contribute to improvements in forest control mechanisms to curb unfair competition and ensure the sustainability of this activity.

1. Introduction

One of the most significant biomes on Earth is tropical forests, which are responsible for one-third of land surface productivity and evapotranspiration (Crowe et al., 2023; Malhi, 2012, 2014). Furthermore, according to estimates, this biome is home to more than half of the global terrestrial biodiversity (Malhi, 2014; Pillay *et al.*, 2022; Pimm and Raven, 2000).

Sustainable forest management is one way to achieve sustainable use of tropical forests is through sustainable forest management (Braz *et al.*, 2021), where timber production requires the preservation of forest functions and the regeneration of commercial species stocks during each harvesting cycle, allowing for a continuous supply of ecosystem services and sustainable yields of the managed species (Avila *et al.*, 2017; Oliveira, 2005).

Brazil, home to the largest portion of the Amazon, has approximately 12 % of the world's forests, with approximately 4.8 million km^2 representing 56 % of its territory (Veríssimo and Pereira, 2014). Brazilian forests, especially those in the Amazon, have the highest diversity of timber species worldwide. Therefore, Brazil's native wood market is economically important (Gontijo *et al.*, 2017).

Despite its global importance, the Amazon suffers from deforestation and illegal logging. The deforestation arc encompasses municipalities with the highest rates of vegetation suppression in the Amazon and is associated with the advancement of the agricultural frontier over the forest (Brazil, 2023). The municipalities comprising the arc of deforestation are categorized into two levels: municipalities for actions to combat deforestation and municipalities with deforestation monitored and under control (MMA, 2023).

In general, the most deforested municipalities in the Amazon have a

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very low Social Progress Index (SPI) compared with other regions of Brazil. The index was developed by evaluating health, sanitation, housing, security, education, communication, gender equity, and environmental quality. In other words, deforestation and illegal logging have generated poverty and significantly slowed social progress in the Amazon (Santos *et al.*, 2021).

According to Lentini *et al.* (2021) and Valdiones *et al.* (2022), Mato Grosso was the leading wood producer in the Amazon between 2008 and 2020, followed by Pará and Rondônia. It is essential to highlight the increased importance of the state of Amazonas, which represents 9 % of Amazon log production in recent years, demonstrating progress on the timber front.

Although the remaining Amazon rainforest has a significant stock of timber species, it would be irresponsible for the actors involved in forestry exploitation to consider this sufficient to guarantee continuous timber production (Ferreira, 2012; Higuchi, 1994). Despite recent efforts to reduce deforestation by 2023, logging in the Amazon rainforest continues unabated. However, it is a preferred alternative to deforestation, as the forest ecosystem is significantly impacted by logging activity (DeArmond *et al.*, 2022, 2023).

According to Brancalion *et al.* (2018), in the Amazon, illegal logging is a problem on a scale comparable to deforestation, and the implementation of stricter environmental legislation has improved the detection of some forms of illegal logging. However, there are vulnerabilities in forest control, especially in more subtle methods that mask the origin of illegal timber. Wood without a legal origin is a high-value commodity that is easily mixed with legitimate forest products to avoid detection (Bisschop, 2012), and its origin is directly linked to deforestation and forest degradation. Between 44 % and 68 % of the timber from the Amazon rainforest in the main Brazilian-producing states is illegal (Valdiones et al., 2022). New European law prohibits the consumption of products originating from deforested or illegally exploited forests (New European Parliament, 2023).

According to UNEP and INTERPOL, environmental crime, which includes illegal logging, is the fourth most profitable illegal activity in the world, behind only drug trafficking, forgery, and human trafficking. In the last decade, illicit environmental impacts have grown two to three times faster than global GDP (Nellemann *et al.*, 2016). While environmental crime can be as profitable as illegal drug trafficking, the penalties are much lower, and such illicit acts are more difficult to detect, making them highly attractive for organized crime (EUROPOL, 2022; Kleinschmit *et al.*, 2021).

Command-and-control actions and policies that include incentive instruments must be implemented to address illegal logging (Börner *et al.*, 2015; Lima *et al.*, 2018). Otherwise, illegal logging is more advantageous than legal logging for several reasons, including broad access to timber stock and lower exploration costs (Azevedo-Ramos *et al.*, 2015; Lima *et al.*, 2018).

1.1. Forest management in the Brazilian Amazon and the responsibility of IBAMA

Brazilian legislation establishes that one of the alternatives for the appropriate use of natural forests is through Sustainable Forest Management Plans (SFMP), which are defined by the selective logging of commercial species with a maximum logging intensity of 30 m^3 ha^{-1} in cycles of 25 to 35 years, allowing the cutting of trees with a minimum diameter at breast height (DBH) of 50 cm, while maintaining at least 10 % of the number of trees per species suitable for logging, respecting the minimum maintenance limit of 3 trees per species per 100 ha. Trees with a DBH between 40 and 50 cm were considered remnants and were preserved for the next cycle. The logging parameters of the SFMP, considering local specificities, may be altered upon the presentation of technical studies, which must be approved by the relevant environmental agency (Brazil, 2006).

SFMPs are authorized by competent environmental agencies, whether at the federal or state level. To approve an SFMP, the landowner must initially conduct a forest inventory of the respective area, which includes the exact location of each tree, its species, and volume, and identify protected specimens, such as those located in non-exploitable zones or prohibited from logging (Perazzoni et al., 2020).

Once the SFMP is approved, the designated trees can be logged and commercialized. Thus, an SFMP account is created in the forest control system, which operates virtually, and the volume authorized for logging is converted into timber log credits. A forest transportation document was issued for each transported load, accompanied by an invoice detailing the exact volume present in the transporting vehicle. Upon arrival at the destination, after inspection and receipt, the credit is transferred within the system between the SFMP and the receiving timber company, debiting this credit from the SFMP "account" and crediting it to the company's "account."

At the beginning of the Amazonian timber production chain were the SFMPs, which were targeted by illicit activities aimed at the illegal logging of forest products and/or the generation of virtual credits (without physical backing) that would be used to conceal illegally sourced timber, often logged from protected areas such as Indigenous lands and conservation units, constituting the fraudulent movement of timber credits.

In Brazil, IBAMA aims to exercise the power of the environmental police and carry out actions under national environmental policies related to federal attributions, relating to environmental licensing, quality control of the environment, authorization for the use of natural resources, and environmental inspection, monitoring, and control (IBAMA, 2022).

Brazilian law stipulates the need for control over native forest products and establishes a national system for controlling the origin of wood, which is coordinated, supervised, and regulated by the IBAMA. This system includes inserting and trading virtual wood credits; hence, IBAMA is legally responsible for inspecting Sustainable Forest Management Plans (SFMPs) and ensuring the legal origin of wood logged within the national territory (Brazil, 2012).

In cases where SFMPs are suspected of irregularities, IBAMA analyzes the information within the control system and conducts on-site inspections to verify the activities in the forest, comparing them with those stipulated in environmental legislation. Upon identification of technical and legal irregularities, administrative penalties such as fines, seizures, and embargoes are imposed. The initiation of the administrative process to investigate environmental infractions with IBAMA occurs with the issuance of the Infraction Notice by the federal environmental agent, exercising their police power, following the identification of behaviors and activities harmful to the environment, as outlined in Brazilian legislation. However, owing to the weaknesses of Brazilian environmental legislation, the punishment of offenders, especially those with greater purchasing power, is scarcely effective.

Considering the importance of forest management for sustainability and the need to strengthen measures to combat illegal logging (Sen, 2020), this study aimed to identify and analyze the main legal and technical irregularities committed in sustainable forest management plans (SFMP) in the Brazilian Amazon, which compromise the sustainability of the activity and increase unfair competition.

2. Materials and methods

2.1. Selection of administrative processes and data collection

The study was conducted based on the IBAMA's administrative processes relating to SFMP penalties in the Amazon states between 2006 and 2021. Initially, to filter the processes of interest, penalties were selected that were classified in Articles 51-A (execute management plan in disagreement) and 82 of Federal Decree No. 6,514/2008 (present or prepare false or misleading information) and had a direct relationship with the SFMP (Brazil, 2008). This review identified 184 processes

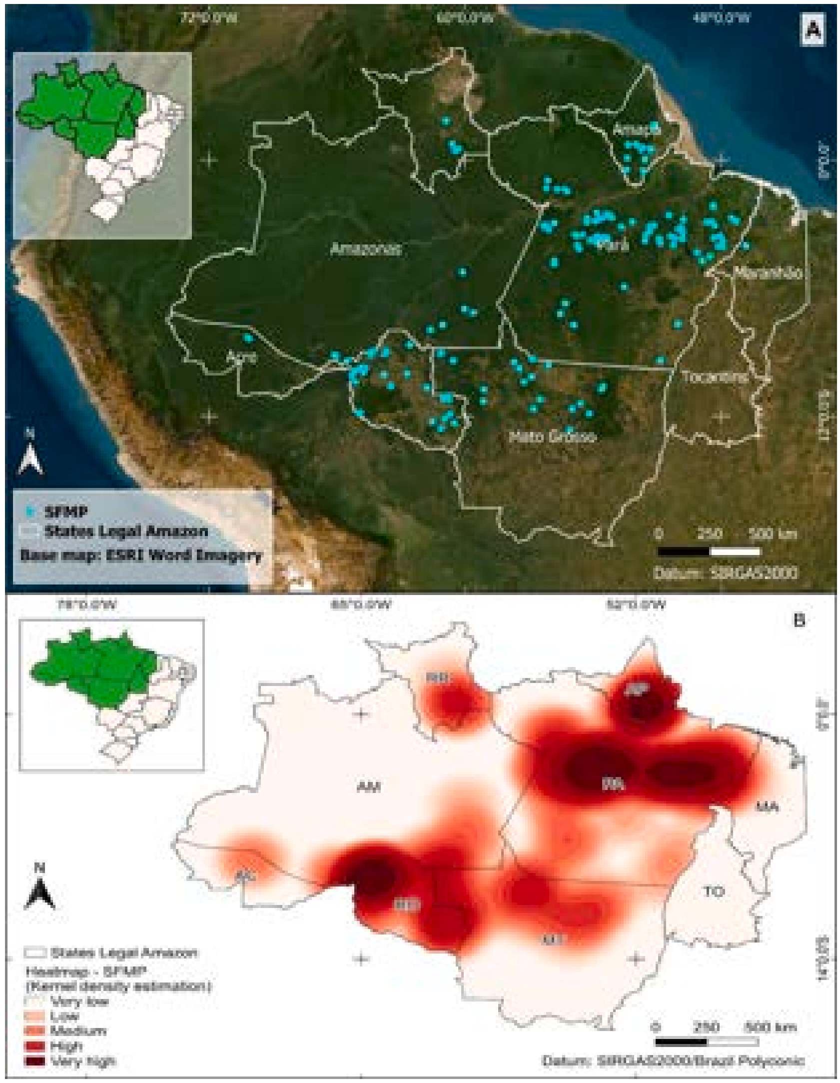

Fig. 1. A- Location map of SFMP fined by IBAMA. B - Heatmap of the geographic distribution of SFMP (kernel density estimate).

involving different SFMPs with an access level classified as public.

The procedural analysis aimed to obtain quantitative and qualitative information on two main topics: (I) general aspects of the management plans and (II) data on the technical and legal irregularities detected in the SFMP using complementary analyses of official control systems. The Brazilian government, such as the Electronic Information System (SEI-IBAMA), Registration, Collection and Inspection System (SICAFI), the National System for Controlling the Origin of Forest Products (SINAFLOR), and other official systems. Technical and legal irregularities were identified and described by IBAMA and reported in the respective inspection reports within the administrative process under review.

Forest management activities are divided into six main stages: plan development, measures to ensure safe and efficient work in forest management operations, pre-exploratory activities, exploratory activities, post-exploratory activities, and monitoring and control (Sabogal *et al.*, 2009). During the procedural analysis, 27 technical and legal irregularities were identified in connection with 13 forest management activities encompassing both the pre-exploratory and exploratory phases. For this study, the pre-exploratory phase was defined as all activities that precede actual forest exploitation. In contrast, the exploratory phase includes activities that begin with the felling of trees, representing an adaptation of Sabogal *et al.* (2009).

2.2. Location and geographic distribution

Based on forestry exploitation authorizations from the SFMP and maps prepared by IBAMA, the geographic reference coordinates of each management plan were collected; only two plans did not contain this information. QGIS 3.16 software generated shapefile point layers of the Forest Management Plans (SFMP) to examine their spatial distribution and create a heat map (kernel density estimate). The federal limits of the Legal Amazon and protected areas were obtained from the Terrabrasilis Geographic Data Platform of the National Institute for Space Research (INPE).

Regarding the geographical distribution obtained, the 184 SFMP analyzed are located in eight states of the Legal Amazon, being distributed as follows: Acre (2), Amazonas (8), Amapá (21), Maranhão (1), Mato Grosso (21), Pará (88), Rondônia (37) and Roraima (6) (Fig. 1A).

The heat map (kernel density estimate) demonstrates the distribution of the SFMP, through which it is possible to note the concentration of inspected plans in four main regions, located in the west and southeast mesoregions of Pará, in the northwest of Rondônia bordering Amazonas, and in the southern portion of the state of Amapá. The SFMP in Mato Grosso was distributed throughout the northern region of the state (Fig. 1B).

Among the SFMP analyzed, 48.4 % were located in priority

Table 1
Frequency distribution of environmental impact severity.

Severity of environmental impact	Scale	Class interval (scores)
No damage	1	0.00 – 3.01
Little damaged	2	3.02 – 4.59
Damaged	3	4.60 – 6.16
Moderately damaged	4	6.17 – 7.74
Very damaged	5	≥7.75

municipalities for actions to combat deforestation, 8.7 % were located in municipalities with monitoring and control over deforestation, and 42.9 % were located in municipalities without significant deforestation rates, according to the Brazilian government's classification. This may suggest that some SFMPs may have been used to cover up wood originating in illegally deforested areas via the movement of fraudulent credits.

2.3. Statistical methodology

Multivariate statistics were applied with Cluster Analysis and Exploratory Factor Analysis to understand the main technical and legal irregularities in SFMP in Amazon detected by IBAMA.

In the cluster analysis using the hierarchical method, a simple correspondence coefficient was applied, and binary variables (0 and 1) were used: zero for the absence of a particular event and one for the presence of a problem indicated by the environmental agency. This technique aims to identify natural groupings among all the variables detected by IBAMA and described in the analysis of 184 enforcement proceedings. Similarity measures are used to determine the resemblance between objects in a multivariate sample characterized by qualitative variables, particularly binary variables.

In the case of exploratory factor analysis (EFA), to obtain the latent variables (factors), environmental impact severity scores were applied to the original data of each SFMP, defined based on the characteristics of the management plans (area and authorized volume), environmental infractions found, and history of environmental crimes carried out by the offender, following legislation. The scores were divided into five levels based on environmental impact severity scales with 5 levels, namely:

1. No damage;
2. Little damaged;
3. Damaged;
4. Moderately damaged;
5. Very damaged.

The environmental impact severity scores applied to each management plan were obtained using the expression shown in Eq. (2):

$$Score = \log 10 \frac{(Ema \times Av \times Ep \times (Compl \times 0,1))}{4} \quad (2)$$

where: Ema: effective management area (ha); *Av*: authorized volume (m^3); Ep: number of environmental penalties with IBAMA; and Compl: total number of irregularities detected by SFMP. The variation in scores results from the influence of the number of detected irregularities, an additional factor in the formula variables related to area, volume, and environmental violation history. For instance, an SFMP with a large

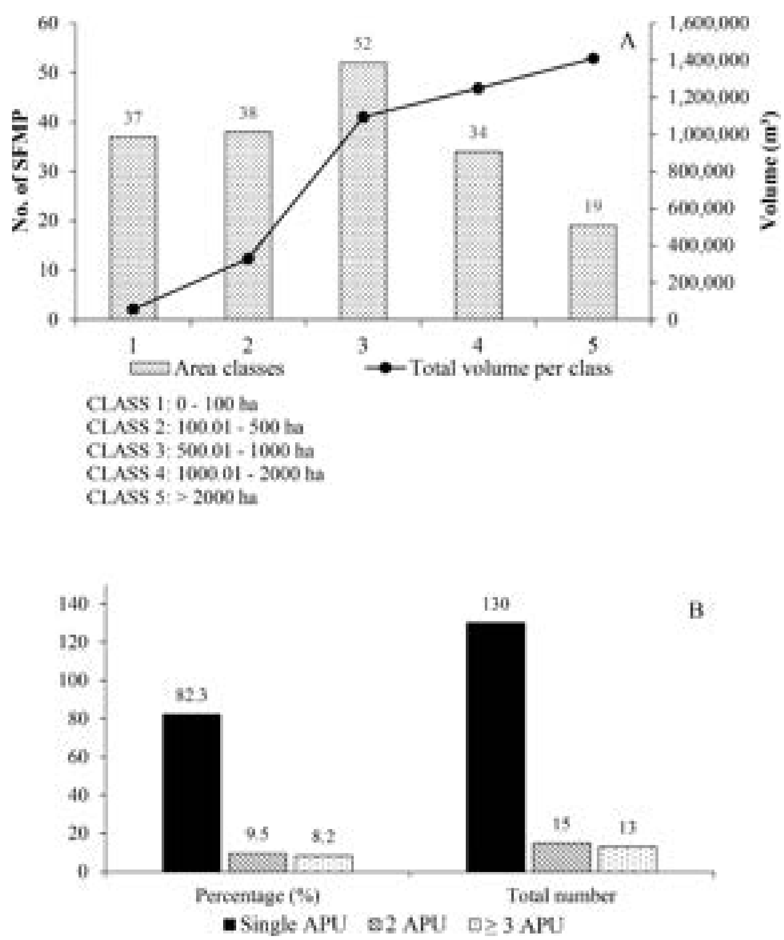

Fig. 2. A - Quantity of SFMP and average volume authorized by the class of effective management area. B - Absolute number and percentage of annual production units.

area, significant authorized volume, and adverse history of infractions with the IBAMA have a more substantial environmental impact than a management plan with a smaller area, reduced authorized volume, and no evidence of environmental infractions. Therefore, although the absolute number of irregularities is higher in the latter case, its relevance is lower. In contrast, in the former case, a low number of detected irregularities still maintains the significance of environmental damage.

After obtaining the score for each management plan, the values were classified according to an environmental impact severity scale ranging from 1 to 5 (Table 1).

EFA began with the application of the *Bartlett* sphericity test and the *Kaiser-Meyer-Olkin* (KMO) sample adequacy test (Hair et al., 2009; Santos et al., 2019). Principal component analysis was then applied, and the correlation matrix was analyzed (Novak, 2016). In the extraction process, based on the criterion of the number of factors that explain a specified proportion of the total variance (Matos and Rodrigues, 2019), a fixed number of factors was selected, that is, 10. Varimax rotation was used for the orthogonal rotational method (Fávero et al., 2009). Finally, factor loadings or estimated weights (below 0.5) were suppressed. In addition, a loading or component graph is generated in the rotated space (Hair *et al.*, 2009).

3. Results and discussion

3.1. Characteristics of management plans

The vast majority of SFMPs fined by the IBAMA were authorized by state environmental agencies, mainly due to the decentralization of forest management enacted by Federal Law No. 11,284/2006 (Brazil, 2006). Concerning personality, plans were authorized for 137 individuals (74.5%), and 47 were legal entities (25.5%). Of the total, only 2 plans located in the state of Pará refer to forest concessions; the rest are, in theory, "private" areas.

According to Toni (2006), given the land problems and constant practices of grabbing public lands, information on the ownership of private lands in the Amazon region is unreliable. However, most private land belongs to large- and medium-sized loggers and ranchers, responsible for most deforestation in the Amazon.

The history of environmental penalties for offenders with IBAMA was evaluated together. The 184 defendants have 1074 infraction notices (IN), generating an average of 5.8 INs per defendant, demonstrating that a significant part of those involved are habitual offenders and continue to carry out illicit activities, even after environmental sanctions. Of those fined, 58.7 % were fined more than three times, and 18.5 % had 10 or more fines with IBAMA. Some individuals, including legal entities, have more than 20 infraction notices, and two companies have been fined more than 30 times. According to Brazilian legislation, the commission of a new environmental infraction by the same offender within a five-year period results in the aggravation of pecuniary sanctions following administrative decisions (Brazil, 2008). In the criminal sphere, recidivism in environmental crimes is an aggravating circumstance (Brazil, 1998).

These data suggest the permissiveness of the Brazilian state regarding the recurrence of environmental violations, especially concerning native Amazonian timber. This is because companies and individuals with significant environmental fines have limited access to Brazilian forest resources. The history of these fines should be considered when issuing environmental authorizations and licenses, particularly in the case of SFMP.

Only four SFMPs did not have information on the forest management area (FMA); thus, the 180 plans comprised 746,050.29 ha, generating an average of 4,144.72 ha per SFMP. When analyzing only the effective management area (EMA) of the assessed plans, a total value of 164,361.37 ha was obtained, with an average of 913.12 ha per SFMP. We identified 19 SFMPs with areas greater than 2,000 ha, representing 10.6 % of the plans. Approximately 20.6 % of the SFMP had EMA equal to or less than 100 ha, and 68.8 % had areas greater than 100 ha and less than or equal to 2,000 ha (Fig. 2A).

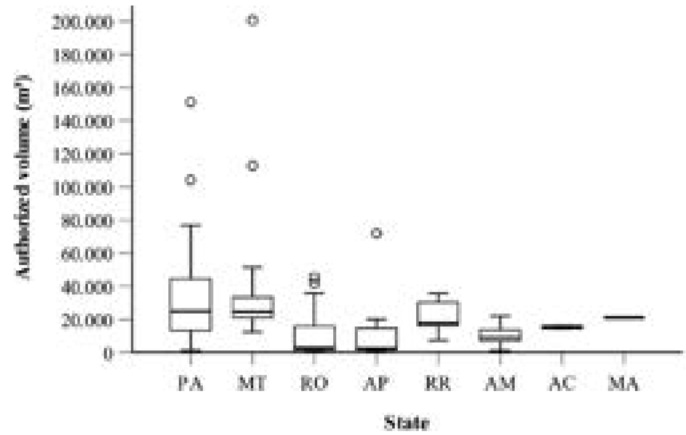

Fig. 3. Boxplot of the distribution and variation of log volumes authorized for exploitation in the SFMP by state.

Only 32 SFMP (18.7 %), with an average EMA of 2,306.93 ha, had an authorized volume above 40 thousand cubic meters, totaling more than 2 million cubic meters, representing 51 % of the total volume analyzed. At the opposite end, 53 SFMP (31 %), with an average EMA of 170.19 ha, were authorized to explore 172,768.53 m^3, in other words, 4.2 % of the analyzed volume.

Regarding the total number of annual production units (APU) for the 158 processes that presented this information, 130 SFMP had unique APUs. Only ten SFMPs were planned for more than four units of annual production. The results demonstrated that 82.3 % of the SFMP were authorized as a single APU; the forest would be exploited once in 1 year and could only be returned after 35 years (cutting cycle) (Fig. 2B).

An SFMP with a single APU contradicts the precepts of forest management, which provide procedures that allow the establishment of a balance between the intensity of cutting and the time necessary to restore the volume extracted from the forest to guarantee continuous forest production. Considering that these forested areas will remain without economic use for more than three decades, it is probable that, during this period, the forests will be illegally replaced by other land uses. Pereira (2020) reported that in the Brazilian Amazon, more than 90 % of the wood produced comes from private forests, and SFMP with a single APU, or at most five APUs, are still common. Consequently, timber companies are searching for new forest areas to guarantee the supply of raw materials. According to Sist *et al.* (2021), it is necessary to reevaluate forest management because the current model of timber production does not achieve effective sustainability.

From the analyzed set of plans, 171 processes contained descriptions of the authorized volume, amounting to 4,136,367.07 m^3 of logs. This generated an average volume per Forest Management Plan (SFMP) of 24,189.28 m^3 and a median of 17,303.95 m^3 (Fig. 3). The SFMP in the state of Pará (PA) was authorized to harvest approximately 2.5 million cubic meters of logs. In contrast, Mato Grosso (MT) had approximately 759 thousand cubic meters of authorizations. The authorizations in Rondônia (RO) amounted to 361 thousand cubic meters, and the remaining states accounted for 439 thousand cubic meters.

Brazilian legislation allows a maximum logging intensity (LI) of 30 m^3 ha^{-1} (Capanema et al., 2022). The average IC for the 171 SFMP analyzed that contained such information is 26.96 m^3 ha^{-1}. In general, 53.8 % of SFMP have a logging intensity (LI) close to the maximum allowed above 28 m^3 ha^{-1}.

In tropical forests, such as the Amazon, polycyclic forest management systems with current cutting cycles of approximately 30 years may not allow complete recovery of the forest, as they are insufficiently long (Avila *et al.*, 2017; DeArmond et al., 2022; Hawthorne *et al.*, 2012; Sist

Table 2
Irregularities highlighted by the federal environmental agency in SFMP found in the Amazon in the pre-exploratory and exploratory phases.

Phase	Forest management activity	Irregularities	Variable	N° of irregularities detected
Pre-exploratory	Authorized documents	Irregularity in documents	V_1	41
	Delimitation of the management area	Failures in macro and micro planning	V_2	38
	Forest Inventory 100 %	Irregular botanical identification	V_3	44
		Errors in dendrometric data and volume estimates	V_4	34
		Non-existent or non-commercial trees suitable for cutting	V_5	17
	Selection and marking of trees for cutting	Problems in marking and locating trees	V_6	45
	Cutting lianas	Failure to cut lianas	V_7	25
	Definition of the successional stage	Forest with signs of exploitation before SFMP	V_8	14
Exploratory	Presentation of information about activities	Fraudulent movement of credits	V_9	134
		False declaration presented in the packing slip and/or system	V_{10}	29
	Cut	Preservation areas damage	V_{11}	24
		Stump height	V_{12}	16
		Absence of hollow test	V_{13}	27
		Directional cutting failures	V_{14}	36
		Overexploitation of the forest	V_{15}	33
		Abandoned logs inside the FMA	V_{16}	40
		Unauthorized tree cutting	V_{17}	39
	Drag	Unplanned drag roads and extensions	V_{18}	46
		Drag roads and extensions in the preservation areas	V_{19}	15
	Storage yard	Storage yards with excessive dimensions or allocated in prohibited areas	V_{20}	24
	Transport	Transport irregularities	V_{21}	76
	Chain of custody	Problems in the chain of custody	V_{22}	81
		Presence of logs without origin in the vicinity of the SFMP	V_{23}	27
	Forest interventions	Unauthorized forestry exploitation	V_{24}	58
		Storage of SFMP logs in unauthorized external yards	V_{25}	12
		Unauthorized deforestation	V_{26}	19
		Intentional forest fire	V_{27}	9
Total	13	27		1003

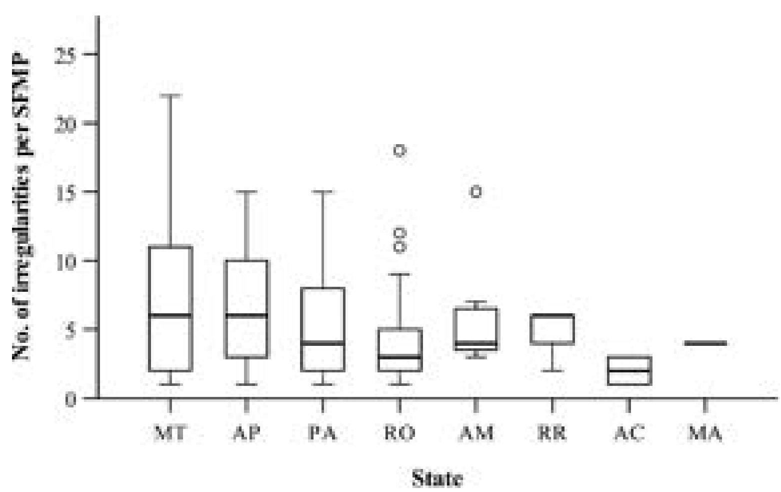

Fig. 4. Boxplot of the number of irregularities identified by the federal environmental agency in the SFMP distributed by the state.

and Ferreira, 2007). The logging intensities in the SFMP made it impossible to exploit the same species in the next cycle, especially those with slow growth and high economic value.

According to DeArmond et al. (2023), the forest heterogeneity in the Amazon biome likely prevents a one-size-fits-all exploitation system. To achieve sustainability and reduce the impacts of exploratory activity, a lower intensity of exploration must be implemented, around 10 to 15 m^3 ha^{-1}, and a longer cutting cycle, between 40 and 60 years.

To optimize the results in the fight against illicit activities in SFMP, control bodies, whenever possible, must prioritize the selection of targets with the highest EMA and authorized volume, considering their representativeness in the general context and the possibility of misuse of significant quantities of virtual credits.

3.2. Technical and legal irregularities in SFMP

The procedural analysis revealed 27 technical and legal irregularities related to 13 forest management activities in the pre-exploratory and exploratory phases. The total number of irregularities observed in the universe of the 184 processes was 1003 irregularities (Table 2).

On average, each SFMP presented 5.5 irregularities for a confidence interval ranging from 4.81 to 6.09, with a standard error of 0.33. The median corresponded to four irregularities. The measures of dispersion, variance, and standard deviation obtained were 19.42 and 4.41, respectively. The coefficient of variation was 80.84 % for a range of 1 to 22 irregularities. MT, AP, and RR states presented the highest medians, and MT, AP, and PA successively demonstrated the largest interquartile ranges and upper limits. Only two states, RO and AM, exhibited outliers (Fig. 4).

The pre-exploratory phase presented six forest management

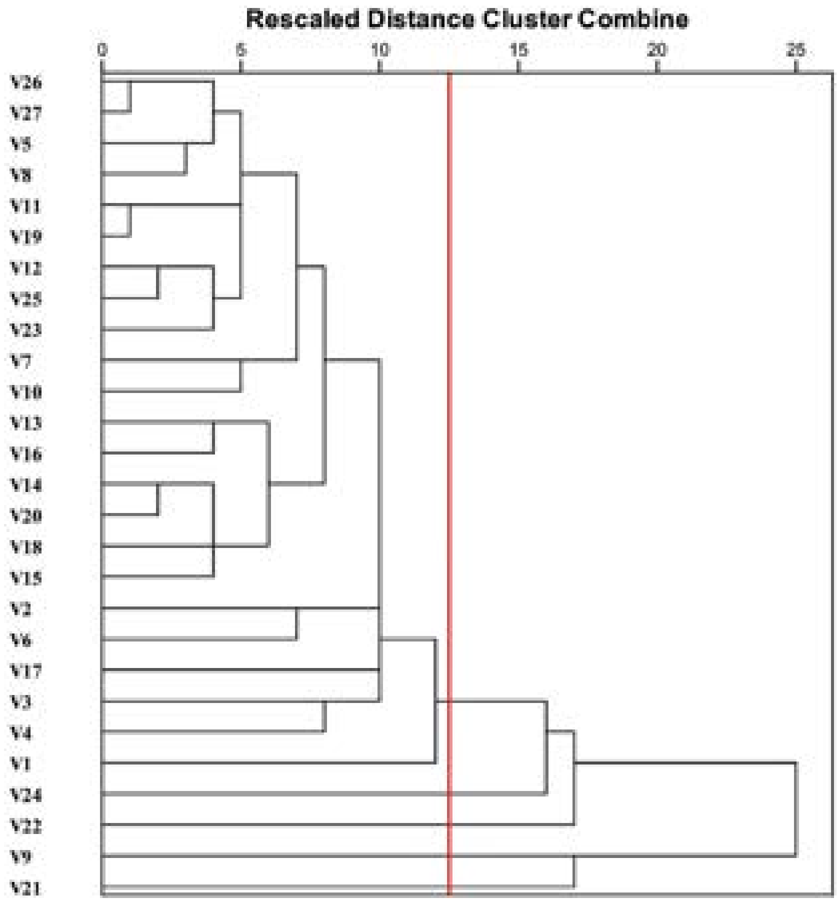

Fig. 5. Dendrogram using average linkage (between groups) and applying simple correspondence coefficient for the variables of interest (V).

activities and eight types of related irregularities, totaling 258 problems identified by IBAMA. In summary, the three irregularities that occurred most frequently in the pre-exploratory phase were *problems in marking and locating trees, irregular botanical identification, and irregularities in documents*, representing 45, 44, and 41 observations, respectively. This phase accounted for 25.7 % of the total number of irregularities and was mainly related to activities prior to the issuance of authorization for forestry exploration. The information presented by the administrator is in the analysis stage, and undue situations are remedied with detailed documentary analyses and technical inspections before issuing forest exploitation authorization, eliminating intentional and non-intentional errors.

The exploratory phase presented seven forest management activities and 19 types of related irregularities, totaling 745 identified problems. The four most representative incidents were the *fraudulent movement of credits* with 134 observations, *problems in the chain of custody* (81), *transport irregularities* (76), and *unauthorized forestry exploitation* (58). The exploratory phase contained 74.3 % of the irregularities observed in the SFMP analyzed, demonstrating that the majority of the non-compliances detected occurred after obtaining authorization for forest exploitation.

3.3. Cluster analysis

A dendrogram is a graphical summary of the cluster solution obtained using the hierarchical method. The number of groups was obtained based on the cutoff adopted through a straight vertical line applied to the dendrogram, equivalent to 50 % of the resized distance between points 0 and 25, 12.5 (red vertical line shown in Fig. 5). Five main groups were identified at this cutoff point, one for each point on the vertical line that intersected the cluster branch (horizontal lines).

In this case, the position of the vertical cut line (red line) is exactly where there is a "gap" between the similarity coefficients (0.724 and 0.647), demonstrating that the generated grouping was representative and differentiated the groups of existing variables.

Group 1 consisted of 23 variables, starting with "*unauthorized deforestation*" and ending with "*document irregularities*." The other groups were formed using a single variable. Group 2 is formed by "*unauthorized forestry exploitation*," Group 3 is described by the variable called "*problems in the chain of custody*," "*fraudulent movement of credits*" represents Group 4, and the last group (5) is composed of the variable "*transport irregularities*."

Group 1 contained the majority of the variables analyzed, around 85.2 %, both in the pre-exploratory and exploratory phases, totaling 654 irregularities out of a total of 1003 observed; however, these irregularities, on average, were present in 15.5 % of the SFMP analyzed. The applied algorithm brought together variables in Group 1 that were defined both by events of significant importance (*unauthorized deforestation*) and less relevant events (*stump height*).

The four groups (2, 3, 4, and 5) formed, respectively, by the unique variables of *unauthorized forestry exploitation, problems in the chain of custody, fraudulent movement of credits*, and *transport irregularities*, all of which add up to 349 incidents, representing 34.8 % of the total irregularities observed.

The *fraudulent movement of credits, problems in the chain of custody, transport irregularities*, and *unauthorized forestry exploitation* were detected in 72.8 %, 44 %, 41.3 %, and 31.5 % of the SFMP analyzed, respectively. On average, irregularities from Groups 2, 3, 4, and 5 were present in 47.4 % of the analyzed SFMPs. The results demonstrate the importance of these irregularities in the absolute number of detected irregularities.

Groups with unique variables are composed of significant

Table 3
Total variance explained for the extracted factors.

Component	Initial autovalues			Extraction sums of squared loads			Rotation sums of squared loads		
	Total	% of variance	% cumulative	Total	% of variance	% cumulative	Total	% of variance	% cumulative
1	7.357	27.248	27.248	7.357	27.248	27.248	4.051	15.004	15.004
2	2.270	8.408	35.656	2.270	8.408	35.656	2.578	9.548	24.552
3	1.922	7.119	42.776	1.922	7.119	42.776	2.181	8.076	32.628
4	1.796	6.652	49.428	1.796	6.652	49.428	1.882	6.970	39.598
5	1.497	5.545	54.973	1.497	5.545	54.973	1.881	6.966	46.564
6	1.314	4.867	59.840	1.314	4.867	59.840	1.787	6.619	53.183
7	1.203	4.457	64.297	1.203	4.457	64.297	1.701	6.299	59.482
8	0.951	3.521	67.818	0.951	3.521	67.818	1.610	5.962	65.444
9	0.904	3.348	71.166	0.904	3.348	71.166	1.296	4.799	70.243
10	0.837	3.101	**74.268**	0.837	3.101	74.268	1.087	4.025	**74.268**

Extraction Method: Principal Component Analysis.

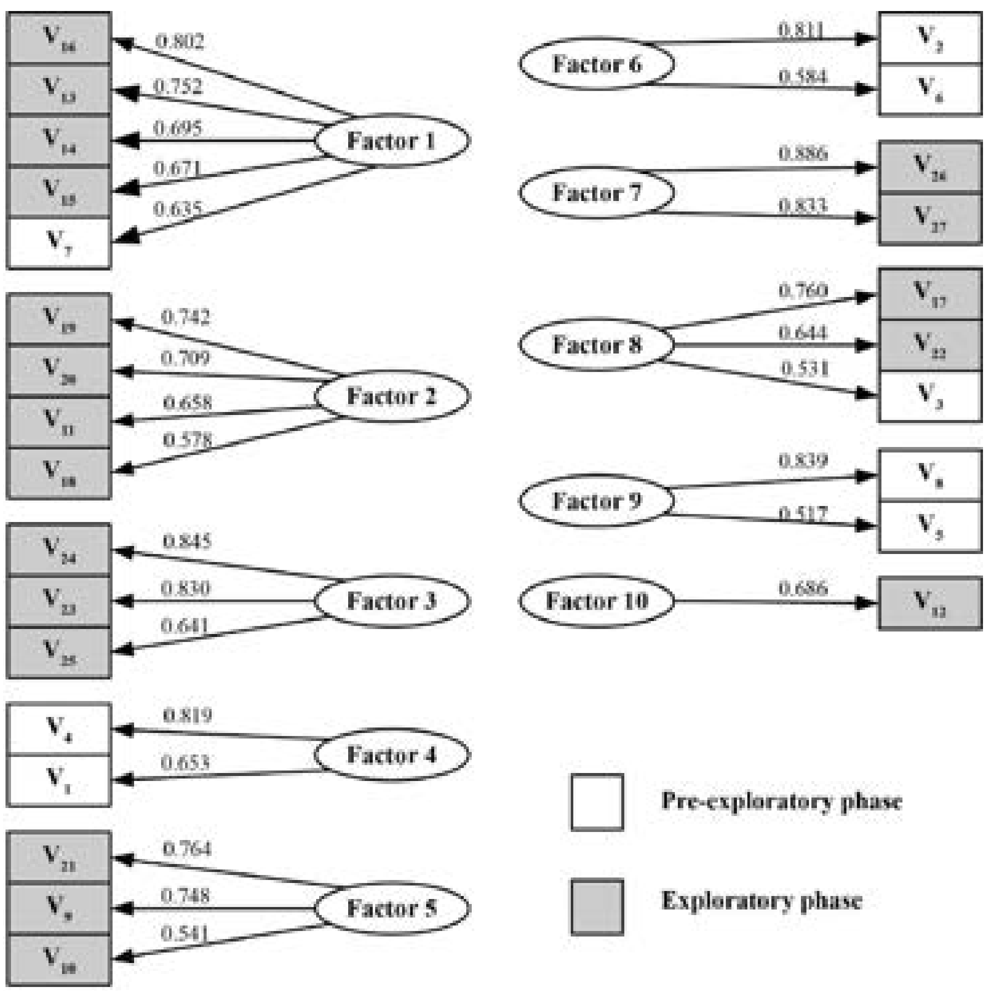

Fig. 6. Graphical representation of the EFA through principal component analysis containing rotated factor loadings using the Varimax rotation method with Kaiser normalization.

irregularities, and together, these activities carry out the necessary procedures for "*woodwashing*," which is defined as illicit actions carried out in forest management through the improper use of documents and control systems through the issuance of virtual credits for covering up illegally sourced wood.

3.4. Factor analysis

The EFA of irregularities in the SFMP uses principal component analysis as an extraction method. One of the initial steps in EFA is the application of the *Bartlett* test of sphericity and the *Kaise-Meyer-Olkin* (KMO) sample adequacy test. Both tests demonstrated the feasibility of applying this technique, and the Bartlett test confirmed the existence of a correlation between the variables, demonstrating that the correlation matrix was not an identity matrix ($p < 0.001$). The KMO test indicated that the factor analysis for the studied variables was appropriate, as the value obtained was 0.790, greater than 0.5.

Most studies related to EFA indicate a minimum value of 0.5 for communality to be considered satisfactory (Fávero et al., 2009; Hair *et al.,* 2009; Matos and Rodrigues, 2019). Thus, for a variable to be

Table 4
Name of the factors generated through the AFE, infraction classification of the factors obtained concerning the legislation, and description of the environmental infraction in each case.

Factors	Variable	Factor name	Framework Federal Decree No. 6,514/2008	Description of the environmental infraction
Factor 1	V_7, V_{13}, V_{14}, V_{15} e V_{16}	Cutting procedures	Art. 51-A	Perform management in disagreement
Factor 2	V_{11}, V_{18}, V_{19} e V_{20}	Dragging and storage procedures	Art. 51-A	Perform management in disagreement
Factor 3	V_{23}, V_{24} e V_{25}	Irregular forest interventions	Art. 51-A	Perform management in disagreement
Factor 4	V_1 e V_4	Authorization documents and forest inventory	Art. 82	Prepare or present false or misleading information
Factor 5	V_9, V_{10} e V_{21}	Procedures for covering up illegal timber	Art. 82	Prepare or present false or misleading information
Factor 6	V_2 e V_6	Management area delimitation procedures	Art. 82	Prepare or present false or misleading information
Factor 7	V_{26} e V_{27}	Land use conversion procedures	Art. 50	Destroy or damage forests
Factor 8	V_3, V_{17} e V_{22}	Compromise of traceability principles	Art. 82	Prepare or present false or misleading information
Factor 9	V_5 e V_8	Forest stock overestimates	Art. 82	Prepare or present false or misleading information
Factor 10	V_{12}	Slaughter technique	–	–

significant in the EFA, it must have a large proportion of common variance. The communality of the 27 variables analyzed was greater than 0.5; consequently, all technical and legal irregularities met the criteria established in the literature and were used in the EFA.

Among the various methods for choosing the number of factors, we chose a method that explained a specified proportion of the total variance. The cumulative percentage of variance used was 74.3 % (total variance explained), which was the same for unrotated factors as for factors rotated by the varimax method (Table 3). The total explained variance was composed of 10 factors that facilitated the analysis and understanding of the patterns or latent relationships of the 27 variables studied.

After orthogonal rotation, the component matrix shows the values of extreme loadings, where each variable is associated with only one factor (Fávero et al., 2009). Generally, to identify statistically significant factor loadings based on sample size, Hair et al. (2009) state that samples greater than or equal to 150 must have a factorial load of 0.45. All selected factor loadings were greater than 0.5 (Fig. 6), indicating statistical significance in the results and the formation of factors for the sample size used (184).

Of the factors generated by the EFA, 50 % consisted of variables solely from the exploratory phase, 30 % were composed of variables from the pre-exploratory phase, and 20 % contained variables from both phases, represented by factors 1 and 8.

When interpreting the results, the generated factors must make sense from theoretical and practical perspectives. There are no rules for naming factors; however, they must be performed in a way that represents the variables within them (Table 4). Each factor contains one or more irregularities. Therefore, each irregular act may cause an environmental infraction, as typified in a specific article of Federal Decree No. 6,514/2008. Generally, each factor was classified according to its possible legal framework; 10 % fell under Article 50, 30 % under Article 51-A, and 50 % under Article 82.

The factors grouped the variables appropriately and demonstrated the relationship between the various irregularities highlighted by IBAMA, reducing the significant amount of information to a more easily manageable size composed of ten factors that explained 74.3 % of the total variance (Fig. 7). The graphical representation of EFA through a coordinate system demonstrates the arrangement of variables based on factor loadings. When more than three factors exist, the three-dimensional space is exceeded; therefore, the dimensions are represented in a multidimensional way.

Concerning the severity of environmental impacts, factors 3, 4, 5, and 8 are more relevant, as they do not only affect the authorized SFMP, transcend its limits, and act as vectors of environmental damage in other areas, amplifying the negative effects. Practical actions and effective regulatory mechanisms must be implemented to combat irregularities grouped into factors 3 (irregular forest interventions), 4 (authorization documents and forest inventory), 5 (procedures for covering illegal

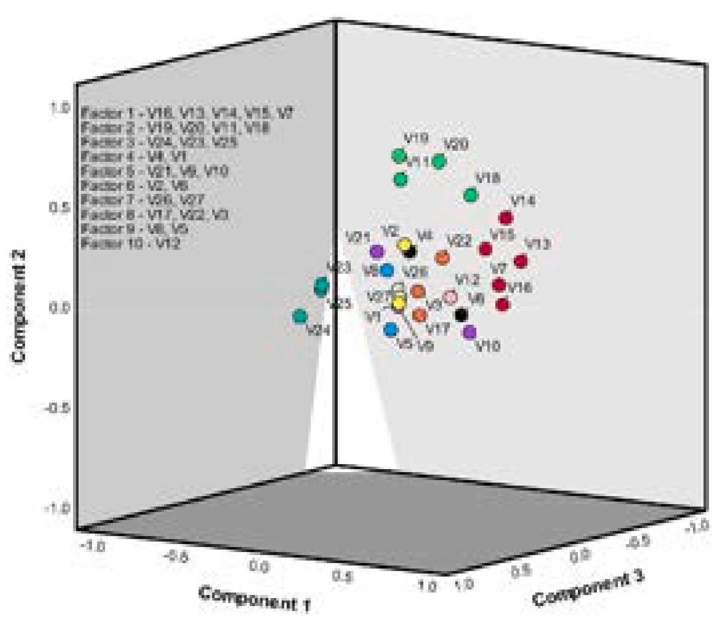

Fig. 7. Component graph in rotated space obtained through exploratory factor analysis.

timber), and 8 (compromise of traceability principles).

Irregularities in Factor 3 (irregular forestry interventions) are generally related to illegal forestry exploitation in areas outside the plan or within the SFMP that do not have authorization for intervention. This factor explained that, on average, 8.08 % of the total variance and irregularities occurred in 17.6 % of the SFMP. Factor 4 (authorization documents and forest inventory) consisted of incidents carried out in the pre-exploration phase and was characterized by untrue information. Theoretically, the consenting environmental body analyzes these documents and information; sometimes, glaring irregularities cannot be validated, and the SFMP is approved. Factor 4 explained 6.97 % of the variance, and its irregularities were present on average in 20.4 % of the plans.

The irregularities correlated with Factor 5 (procedures to cover up illegal wood) were carried out in the exploratory phase, defined as 6.97 % of the total variance, and occurred, on average, in 43.3 % of the SFMP. These incidents represent serious illegalities committed by the SFMP and strongly characterize *woodwashing*. According to Perazzoni et al. (2020), SFMP in the Brazilian Amazon are the targets of commercial transactions and/or simulated transport in official control systems to legalize forest products illegally extracted from other areas.

Factor 8 (a compromise of the principles of traceability) makes it unfeasible to trace the origin of forest products, highlighting that the chain of custody is one of the fundamental principles of management. On average, this factor explained 5.96 % of the variance, and its irregularities occurred in 29.7 % of the SFMP.

When considering the relevance of the fraudulent movement of credits and irregularities in transportation, virtual credits related to the volume authorized for exploration must be released for gradual use over time, according to the exploration and transportation logistics capacity described in the sustainable forest management plan.

Without an efficient authorization process and effective supervisory control, incidents carried out in the SFMP, especially those intended to cover illegal timber, are difficult to verify. Most of the time, these illegal acts are successful, and forest products that have suffered *woodwashing*, especially when they involve high-value wood, reach the final stage and are sometimes destined for foreign markets with fraudulent documents.

4. Conclusions

The analysis demonstrated the relevance of the main technical and legal irregularities detected by IBAMA, highlighting the fraudulent movement of credit, problems in the chain of custody, irregular forest transport, and unauthorized forest exploitation. Furthermore, the data show that the exploratory phase has the highest number of nonconformities, and effective actions should be implemented during this phase. However, an effective authorization process prevents inconsistencies in the pre-exploratory phase. SFMPs with single APUs contradict the precepts of forest management and tend to facilitate the commission of illegal acts. The importance of forest management and conscious use of forests in the Amazon is irrefutable; however, the first step towards the sustainability of forestry activities is intrinsically related to respect for legislation and technical parameters. Based on the results obtained, it is inferred that when misused, SFMPs can act as a vector for the covering of wood without a legal origin.

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CRediT authorship contribution statement

Vinicius Otavio Benoit Costa: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft. **Henrique Soares Koehler:** Writing – review & editing, Supervision. **Renato Cesar Gonçalves Robert:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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