remote sensing

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Review

Assessing Forest Degradation Through Remote Sensing in the Brazilian Amazon: Implications and Perspectives for Sustainable Forest Management

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Abstract: Forest degradation and forest disturbance are distinct yet often conflated concepts, complicating their definition and monitoring. Forest degradation involves interrupted succession and a severe reduction in forest services over time, caused by factors like fires, illegal selective logging, and edge effects. Forest disturbance, on the other hand, refers to abrupt, localized events, natural or anthropogenic, such as legal selective logging, tropical blowdowns, storms, or fires, without necessarily leading to long-term degradation. Despite the varying intensity and scale of forest degradation and disturbance, systematic studies distinguishing its types and classes are limited. This study reviews anthropogenic impacts on forests in the Brazilian Amazon, analyzing 80 scientific articles using remote sensing techniques and data. Most research focuses on the "arc of deforestation," characterized by intense human activity, showcasing methodological advancements but also revealing gaps in monitoring less-studied regions like the central and western Amazon. The findings emphasize the need for advanced remote sensing tools to differentiate degradation types, particularly in sustainable forest management (SFM) contexts. Expanding research to underrepresented regions and refining methodologies are crucial for better understanding forest dynamics and improving conservation strategies. These efforts are essential to support effective forest management and informed policy development across the Amazon.

Keywords: forest disturbance; selective logging; anthropogenic impacts; conservation strategies

1. Introduction

1.1. Sustainable Forest Management in the Amazon: Importance and Challenges

Tropical forests are one of the world's largest and most productive ecosystems. They also play an essential role in the global carbon cycle, containing 44% of the world's aboveground biomass [1,2]. The Brazilian Amazon contains one-third of the world's tropical forests. Its commercial roundwood stocks are estimated to be around 60 billion m^3 (2118 trillion ft^3), making it the world's largest tropical timber reserve [3–6].

Sustainable forest management (SFM) is an approach to managing forests that balances environmental, social, and economic objectives to meet the needs of present and future generations [6]. SFM encompasses practices that maintain and enhance forest health, productivity, biodiversity, and ecological functions [6]. Reduced impact logging (RIL) is a forest management practice designed to minimize the ecological damage that typically accompanies selective logging and is widely applied in SFM in the Amazon [6,7]. RIL involves practices that significantly reduce impacts compared to conventional logging; some of these practices include pre-harvest planning, targeted felling techniques, log drag control, and continuous monitoring [7]. Selective logging is a stage of management that aims to harvest specific trees while preserving the structure of the forest, contributing to sustainability when rigorously planned and monitored [7,8]. These practices minimize unnecessary canopy openings, protect surrounding vegetation, and maintain the overall forest structure, thereby mitigating the ecological impacts typically associated with logging activities [7].

In contrast, conventional logging often results in significant forest degradation due to uncontrolled felling, poorly planned roads, and extensive canopy gaps [7]. This unregulated approach compromises forest health and biodiversity, leading to a decline in ecosystem services, prolonged carbon emissions, and challenges in forest regeneration [8–11]. By comparison, RIL reduces these impacts, promoting sustainability and aligning with the principles of SFM.

Pereira-Jr [7] highlights the differences in canopy gap fractions caused by conventional logging (CL) and reduced impact logging (RIL) in 1996 and 1998. CL consistently resulted in higher canopy gaps, with total gap percentages of 16.5% and 21.6% in 1996 and 1998, respectively, primarily driven by tree felling and skidding activities. In contrast, RIL demonstrated significantly lower impacts, with total gap percentages of 4.9% and 10.9%, emphasizing its effectiveness in minimizing forest canopy disruption. The data reinforce the value of RIL as a sustainable logging practice that reduces environmental impacts while maintaining forest structure.

Nevertheless, under Brazilian standards, specific values are established for harvesting intensity per hectare [6]. The authorized harvesting intensity of Brazilian forests is not associated with data on the heterogeneity of the original forest structure, i.e., the volumes determined for extraction are fixed and standardized [9]. In the SFM for the Saracá-Taquera National Forest in the Brazilian Amazon, logging intensity surpassed 100 m^3 ha^{-1}, with more than 20 trees harvested per hectare in certain areas [9]. Putz et al. [10] mentioned that the challenge in managing tropical forests stems from their complex and diverse ecosystems. According to Chazdon et al. [11], improper use of natural forests can disrupt logging cycles and harm ecosystems.

SFM is recognized as a forest conservation strategy, but gaps remain in evaluating indicators that point to more appropriate ways of exploiting forest resources [7,12].

These challenges related to conducting SFM raise the following guiding questions: (i) What is the temporal trend in publications on remote sensing techniques and sustainable forest management? (ii) Which institutions and countries are leading this research? (iii) Which approaches are most commonly used? (iv) What are the main techniques and sensors used? (v) What is the spatial distribution and territorial scope of the studies throughout the Amazon biome?

1.2. Remote Sensing in Tropical Forest Monitoring

Remote sensing (RS) plays an important role in monitoring and quantifying canopy disturbance caused by selective logging [13–15]. Studies have shown that high spatial and temporal resolution images are necessary to monitor selective logging in the Amazon [14,16]. In addition, the remote sensing techniques and products used for mapping and monitoring studies of selective logging have been insufficient for large-scale assessments [17–19].

Abdollahnejad et al. [18] have proposed an advanced approach integrating geographic information systems (GISs) and remote sensing using high-resolution images to monitor logging areas. Their research suggests that high spectral and spatial resolution images are necessary to increase the accuracy of volume estimates. Petri et al. [20] also tested using images from the PlanetScope nanosatellite constellation for vegetation studies in the Amazon. They concluded that high spatial and temporal resolution images are essential for understanding forest dynamics in the Amazon. Yet, for extensive areas like the Amazon, these costs can quickly escalate, posing a challenge for continuous and large-scale monitoring efforts [18].

Advances in remote sensing technologies, such as high-resolution satellites, drones, and LiDAR (Light Detection and Ranging) sensors, combined with machine learning techniques, have provided new possibilities for effectively and sustainably monitoring and managing forests [18,21]. These technologies enable precise detection and monitoring of changes in forest cover, making it easier to identify illegal activities and assess the impacts of logging [21,22]. However, the application of high spatial resolution sensors to the analysis of forest degradation in sustainable forest management (SFM) is still limited to smaller areas, as evidenced by the scope of the studies conducted.

1.3. Defining Forest Degradation and Forest Disturbance

The literature is rife with dozens of definitions of forest degradation regarding partial changes to the forest canopy. Categorizing forest degradation is challenging due to its dependence on the study's objective, biophysical conditions, causes, and spatiotemporal scales [23,24]. Simula [25] and Thompson et al. [24] argue that the lack of scientific consensus on forest degradation has led to many definitions and multiple ways of measuring it, particularly by remote sensing. More recently, the term forest disturbance has been increasingly used to describe more subtle changes in forest structure and function [7,9,14,16]. These disturbances often include events that do not result in outright deforestation but still alter the forest's composition, canopy cover, or ecosystem services, such as selective logging, fires, and small-scale natural events. This shift in terminology reflects an effort to capture a broader spectrum of forest dynamics and to better align with advances in remote sensing technologies that can detect such nuanced changes [9,14,16,18].

In this analysis, forest degradation can be defined as a condition of interrupted succession due to human actions, leading to a severe reduction in the forest's services over a certain period. It is a temporal process in which forest services decline and can be caused by forest fires, illegal selective logging, and edge effects, among others [24–27]. In contrast, forest disturbance refers to any abrupt and localized event, natural or anthropogenic, that disrupts forest structure or function, such as legal selective logging, tropical blowdowns, storms or even forest fires, without necessarily causing long-term degradation [9,14,16,18]. Thus, while forest degradation implies a sustained loss of ecosystem services, forest disturbance can be temporary and sometimes even a part of natural forest dynamics [7,14,16].

In this context, the Reducing Emissions from Deforestation and Forest Degradation (REDD+) program is an international initiative aimed at combating climate change by addressing forest loss and degradation. Figure 1 illustrates the relationship between degradation, deforestation, and sustainable practices such as SFM in the context of REDD+. Each component of the acronym REDD+ represents a key focus area. The first D (deforestation) focuses on preventing the permanent removal of forests (clear-cut), which releases significant amounts of stored carbon into the atmosphere (line C, Figure 1). The second D (degradation) addresses the decrease in forest quality and carbon storage capacity caused by activities such as illegal selective logging, fires, edge effects, or other human-induced action. At this stage, the services provided by the forest are significantly reduced and CO_2 emissions are prolonged over time, but the vegetation is not completely removed (line B, Figure 1). The plus sign (+) extends the scope of the program to include some sustainable practices like the conservation of forest carbon stocks and the sustainable management of forests (line A, Figure 1) [28]. Here, forest disturbances resulting from legal selective logging are represented as critical factors, emphasizing the need to mitigate their impact to ensure the effectiveness of these sustainable practices. This expanded framework aims to address a broader set of activities to promote sustainable development while mitigating climate change impacts [28–30].

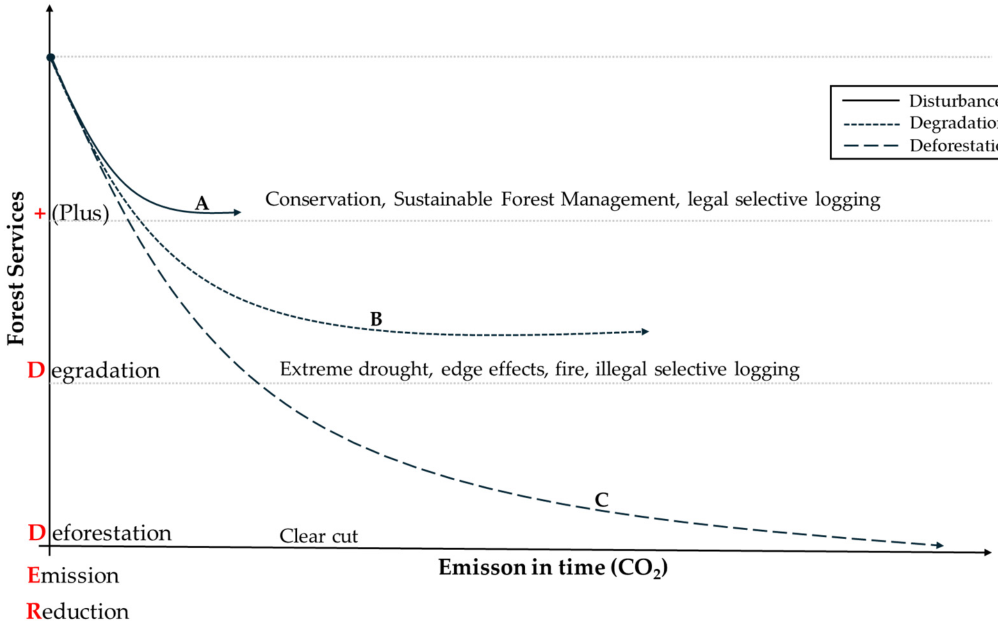

Figure 1. The graph illustrates the impact of human activities on forest ecosystem services in the context of REDD+ (red letters on the Y axis). Curve A (disturbance) represents forest carbon stock conservation practices and sustainable forest management, where forest interventions cause low CO_2 emissions and favorable variations in forest services, represented by the REDD+ "plus" (+) symbol. Curve B (degradation) represents a forest degraded by anthropogenic events such as extreme droughts, edge effects, fire, and illegal logging that persist over time. Curve C (deforestation) represents the maximum stage of anthropogenic intervention and the complete absence of forest services, since at this stage the vegetation has been completely removed (clear-cutting), represented by the first D in the REDD+ acronym. Source: adapted from [24,26,27,31].

However, the term "forest degradation" is often used to describe legal selective logging activities [22,32–35]. It is essential to point out that although legal selective logging can be considered forest degradation from an anthropological perspective or by generic definitions, this classification is inadequate [36]. The selective extraction of legal timber is an activity integrated into SFM and is considered a mechanism of REDD+ policies and, therefore, in first approximation, should not be categorized as forest degradation [36], but rather as forest disturbance, as it should not cause de-characterization or damage to the environmental function of the managed forest ecosystem [16,36].

It is essential to consider a more comprehensive approach that considers broader ecological processes, regardless of their impact on human society, such as forest dynamics and resilience [26,27,30]. Ecosystem resilience is the capacity to return to its original state in terms of structure and function after a disturbance without requiring external intervention [27].

1.4. Mapping Forest Degradation and Legal Selective Logging

The techniques, methods, and data sources used for mapping and monitoring forest degradation and selective logging in the Amazon are essentially the same, as both detect and analyze changes in forest cover when the forest is not entirely removed [16,19,34]. Although, from the point of view of remote sensing, the equivalence in detection between these two actions is to be expected, and several studies treat both in a similar way [16,22,33,34], some important points need to be kept in mind.

The intensity and types of disturbance are different in the various types of degradation, including the partial loss of living biomass and forest quality, without the complete removal of vegetation cover. This can include the death of trees, damage to soil and understory vegetation, and a reduction in biodiversity [16]. However, in legal selective logging with reduced impact, the disturbances are smaller and relate to the specific removal of trees of high commercial value, usually with openings in the forest, logging trails, and collateral damage to other trees and understored vegetation [7,37,38]. Therefore, disturbances caused to forests by selective logging are of lesser intensity in cases of forest management implementation and, for this reason, should be distinctly mapped and considered [7,16,38]. Although using RIL reduces disturbance, these disturbances can still be classified as low intensity, since they cause changes to the forest's structure and the ecosystem's dynamics [16,37].

Taking the above points into account, it should be noted that the simplest and most effective way of differentiating the intensities of forest degradation processes is by observing selectively logged areas in sustainable management plans, where there are Forest Management Unit (FMU) boundaries, as well as timber unit (TU) boundaries, allowing for auxiliary information in classifying the changes detected. In SFM, the FMU represents the designated portion of the property allocated for forest management. The specific area designated for logging activities is referred to as a timber unit (TU) [6,9].

In contrast, in areas affected by fire or high-intensity or illegal selective logging, the intensities of forest degradation are much higher, indicating that monitoring systems must be more specific in order to discriminate between the different types of forest disturbance, which result in very different impacts and levels of degradation [16]. Figure 2 shows a cross-section of forest change detection alerts from the systems (A) DETER/INPE, (B) SAD/IMAZON, and (C) Brazilian Forestry Service (BFS)/SCCON, respectively, which intersect the TU in the FMU inside the Saracá-Taquera National Forest. Systems A and B are used in command-and-control policies and operate throughout the Amazon using low and medium spatial resolution images. System C monitors and maps forest disturbances in specific areas within the limits of the SFM boundaries using PlanetScope high spatial and temporal resolution images carried out by the Brazilian Forestry Service (BFS). System C shows greater consistency and precision in relation to the extracted areas of vegetation, using selective logging practices, and consequently with more coherent classification related to the phenomenon [39–41].

Misclassifications of different levels of forest disturbance can underestimate or overestimate the extent of the impacts caused on forests, particularly in the case of selective logging in the Amazon. When conducted legally and under sustained management, selective logging is thought to have a low intensity of disturbance and minimal effects on the forest ecosystem [7]. However, generalized classifications of forest degradation areas without distinguishing between different types of disturbance can compromise the credibility of regulated forest conservation and management initiatives in the Amazon [42,43].

The lack of differentiation between forest extraction practices associated with SFM and other degradation processes with different impacts can lead to difficulties raising funds for conservation projects and discourage investment in sustainable management practices in the Amazon. Public policies and regulations based on incorrect data can be ineffective or harmful [44,45]. This can result in an inadequate allocation of resources for forest conservation and management, as well as hindering the implementation of effective strategies for forest protection [44]. Accuracy in classifying the different intensities of forest disturbances or degradation is crucial for environmental, economic, and social sustainability in forest management in the Amazon [23,30].

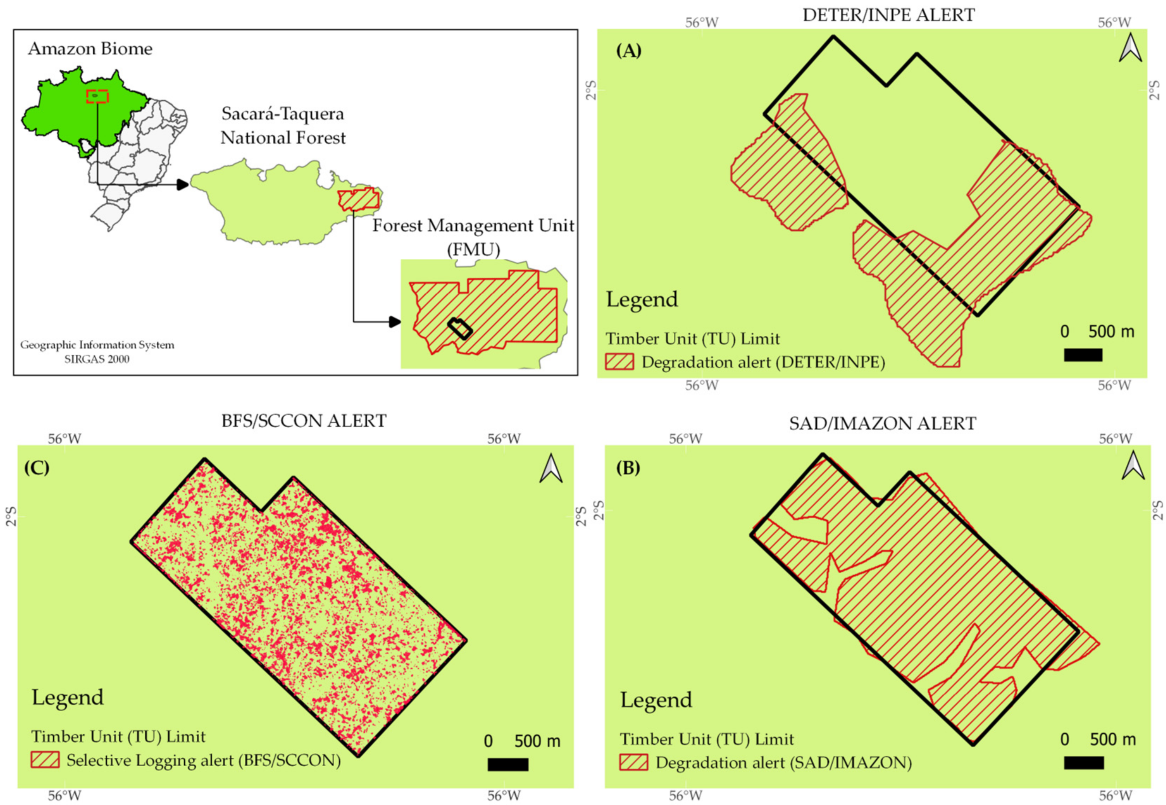

Figure 2. Forest degradation alerts from the systems (**A**) DETER/INPE (Real-Time Deforestation Detection System, developed by the National Institute for Space Research—INPE); (**B**) SAD/IMAZON (Deforestation Alert System, developed by the Amazon Institute for Man and the Environment—IMAZON); and Selective Logging alert (disturbance) (**C**) Brazilian Forestry Service (BFS)/SCCON (Brazilian Forestry Service system, developed by SCCON Geospatial). These systems intersect the timber unit in the Forest Management Unit inside the Saracá-Taquera National Forest, Brazilian Amazon.

1.5. Objective

In order to better distinguish anthropogenic forest disturbances and degradation in different intensities, spatial dimensions, and temporality, detected by remote sensing in the Amazon forest, we aim to map the spatial distribution and temporal evolution of studies in the Amazon biome by means of remote sensing and identifying the main techniques and sensors used to better understand the patterns, trends, and gaps associated with monitoring anthropogenic forest disturbances, generically referred to as forest degradation.

2. Materials and Methods

2.1. Search Process and Article Selection

We conducted a systematic literature review on the remote monitoring of anthropogenic forest disturbances and their impact on sustainable forest management. The review was based on a spatiotemporal evaluation of the main techniques and sensors used to monitor and map forest degradation and legal selective logging in the Amazon. As they have a specific focus on conservation and environmental management, the systematic review guidelines proposed by Pullin and Sterward [46] were followed.

This study used only articles that explicitly applied remote sensing (RS) techniques and images aimed at detecting anthropogenic forest disturbances, in order to contribute to advancing the discussion on distinguishing forest degradation from legal selective logging in the Amazon. In this way, the main approaches, trends, and gaps in research on anthropogenic forest disturbances, notably, forest degradation and legal selective logging in the Amazon, were analyzed.

Only peer-reviewed articles published between January 2003 (the year the first article appeared) and July 2024 were selected from the Scopus and Web of Science databases [47,48]. The search considered synonyms found in the literature based on the keywords in the title, abstract, and keywords, and the ALL option was chosen in the search (Table 1). These terminologies are widely used in the literature for remote monitoring studies of forest disturbances and degradation in the Amazon. Reviews, conferences, and book chapters were excluded, as peer-reviewed articles are considered the most reliable source for reviewing the literature among the documents available [49,50].

Table 1. Search expression encoded in Web of Science and Scopus and applied to titles, abstracts, and keywords.

Criteria		Search Expression
What?		"Selective Logging" OR "Selective Harvesting" OR "Selective Cutting" OR "Disturbance" OR "Forest Disturbance" OR "Illegal Logging" OR "Degradation" OR "Forest Degradation"
How?	AND	"Monitoring" OR "Remote Sensing" OR "Satellite"
Where?	AND	"Amazon"
Limited to?		Articles
Data range		2003/January to 2024/July

Adapted from [31].

In addition to articles written in English, papers written in Portuguese were also analyzed, as the subject is geographically related to Brazil, and some references are in Portuguese. We expanded the language filter to ensure that a thorough analysis of the scientific literature identifies and synthesizes relevant evidence, regardless of geographical origin or language of publication. Non-English publications may contain ideas or provide context not available in English articles [51].

2.2. Data Selection and Integration

With the keywords mentioned, 136 articles were identified in Web of Science and 81 articles were identified in Scopus (as of 1 July 2024), which were compiled into CSV (comma-separated values) and TXT (text format) files from the respective databases. After debugging duplicate articles in different databases with the help of RStudio software (Version 4.3.1) using the mergeDbSouce and remove.duplicated functions of the Bibliometrix package [52], 158 articles remained.

After carefully selecting articles, we reviewed each paper to remove duplicates from the database. We specifically checked each article to ensure it focused on the Amazon biome and used remote sensing products, techniques, and images to map and monitor forest degradation and forest disturbances. After this thorough process, we selected 80 articles for analysis (Figure 3).

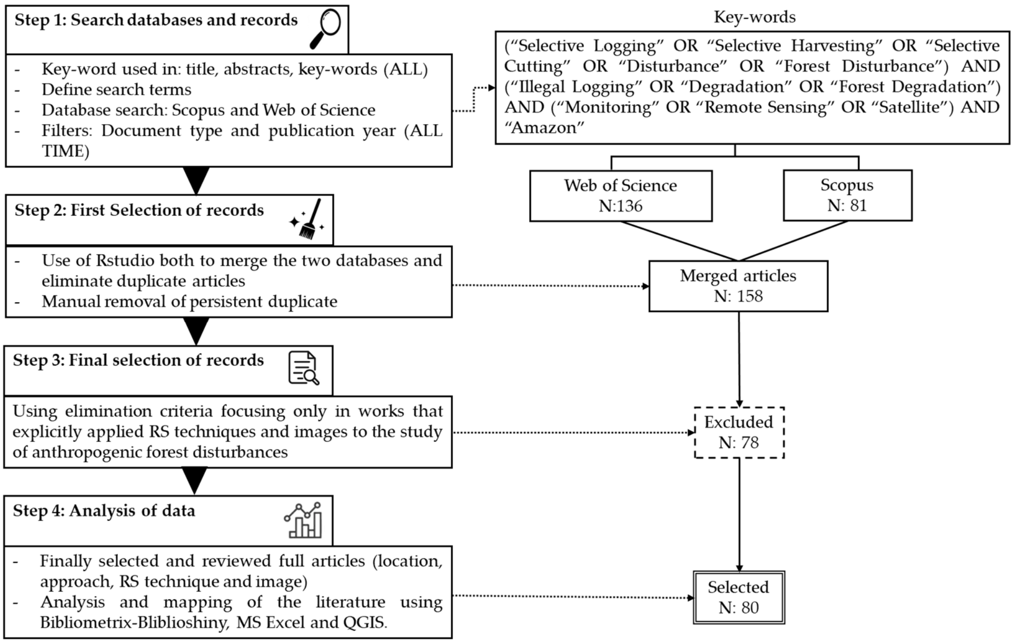

Figure 3. An overview of the criteria and procedure for the bibliographic search for a systematic review of the literature on works that explicitly apply RS techniques and images to the study of anthropogenic forest disturbances. N = Number of articles.

2.3. Classification, Organization of Information, and Data Analysis

Based on this number, we proceeded to organize and classify the information contained in the articles. To systematize the evaluation of the approaches used, trends, and gaps in research, the information was listed in chronological order, starting with the most recent year. The information gleaned from the articles was categorized in terms of the exact location of the study area (geographical coordinates), the digital processing techniques used in the satellite images, and the sensors used.

Additionally, the articles were categorized based on the type of anthropogenic forest disturbance presented and classified accordingly:

(a) Legal selective logging: for works that applied RS techniques to map or monitor anthropogenic forest disturbances arising exclusively from logging activities in authorized sustainable forest management areas.
(b) Forest degradation: for works that applied RS techniques to map or monitor anthropogenic forest degradation of any nature other than legal selective logging.
(c) Legal selective logging + forest degradation: for works that applied RS techniques to map or monitor both anthropogenic actions simultaneously.

Based on the criteria provided, we have established the following analysis parameters: (a) annual global publication trend; (b) analysis of emerging patterns and trends; (c) spatial distribution and approach of the work; (d) the main techniques used for mapping or monitoring; (e) the main RS images used for monitoring or mapping; and (f) teaching and research institutions that have published the most on the subject.

3. Results

3.1. Global Publication Trends

The red dotted regression line shows a positive slope, indicating a general increase in the number of scientific publications over time. This reflects the growing attention to monitoring degradation and anthropogenic forest disturbances in the Amazon biome. This upward trend suggests growing interest and research activity in this topic area over the years. Although there is an overall upward trend, individual years show considerable variation in production. For example, the years that showed the highest scientific productivity were 2019, 2020, and 2023, accounting for 26 articles, approximately one-third of all publications (32.5%). Among these, 2019 and 2023 have stood out with nine publications each. Conversely, 2003, 2004, 2011, and 2015 had the lowest number of publications, with only one article each year (5%) (See Figure 4).

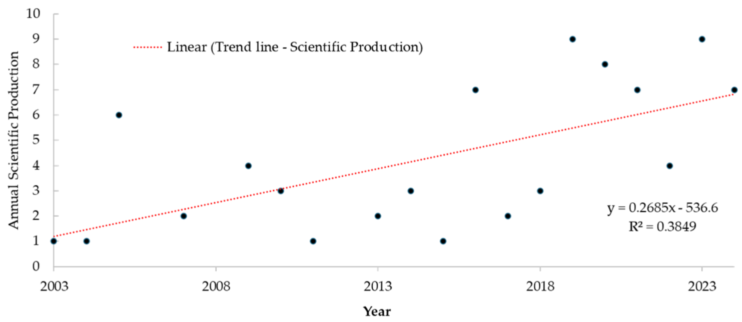

Figure 4. Evolution of annual scientific production per year for monitoring and mapping anthropogenic forest disturbances and forest degradation in the Amazon biome (2003-July/2024).

3.2. Keyword Analyses of Emerging Patterns and Trends

Review articles often use keyword analyses to identify central themes, patterns, and trends in different research fields [53–55]. Figure 5 illustrates the relative occurrence of key terms—*biomass*, *carbon*, *degradation*, *disturbance*, *logging*, and *selective*—in texts from 2003 to 2024. Each color in the stacked bars represents one of the selected words, with the height of each color segment within a given year indicating the proportional frequency of that word. These words were selected for their relevance to the discussion of forest management topics, highlighting trends and shifts in focus over time. The graph enables a visual assessment of the prominence of each word across different years, reflecting evolving research or policy interests in these areas.

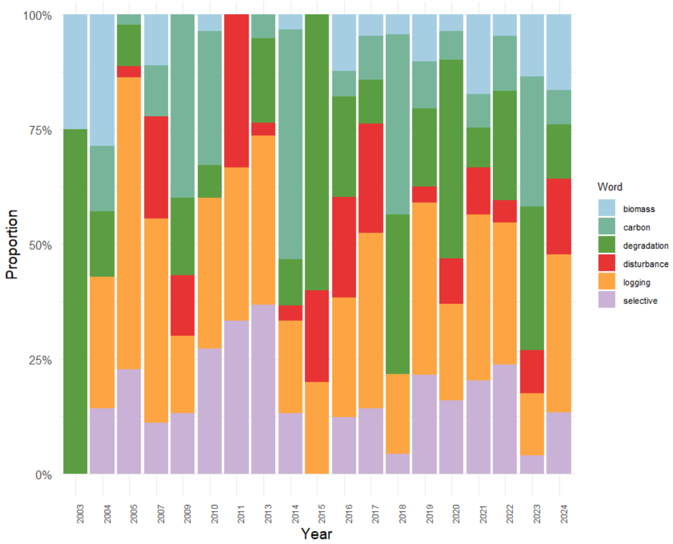

Figure 5. Relative occurrence of key terms—*biomass*, *carbon*, *degradation*, *disturbance*, *logging*, and *selective*—in texts from 2003 to 2024.

The results show that each year presents a different distribution of proportions among the words, suggesting a shift in focus over time. *Carbon* and *degradation* maintain a consistent presence throughout the years, indicating a continuous interest during the entire period analyzed. The term *biomass* gains prominence, starting in 2016, possibly reflecting a growing interest in its role in carbon sequestration. Although *disturbance*, *selective*, and *logging* are consistently present over time, these terms show a marked increase from 2020 to

2024, indicating a rise in discussions about logging and the impacts of forest disturbances. *Carbon* and *biomass* have gained relevance in recent years, especially between 2016 and 2024. This increase may be related to the role of biomass and carbon in climate change mitigation policies, with biomass increasingly being considered a renewable energy alternative.

3.3. Spatial Distribution of Studies and Approaches

A total of 25 studies were applied to the entire Amazon biome. Of these, we found that 72% (18 articles) used forest degradation exclusively (even though they may have included SFM areas) to map anthropogenic forest disturbances. Five articles studied forest degradation and selective logging together. Only two articles discussed the region's selective extraction of legal timber and its impacts. Figure 6 presents the spatial distribution of studies on mapping forest degradation and forest disturbance in the Amazon biome by type of detection.

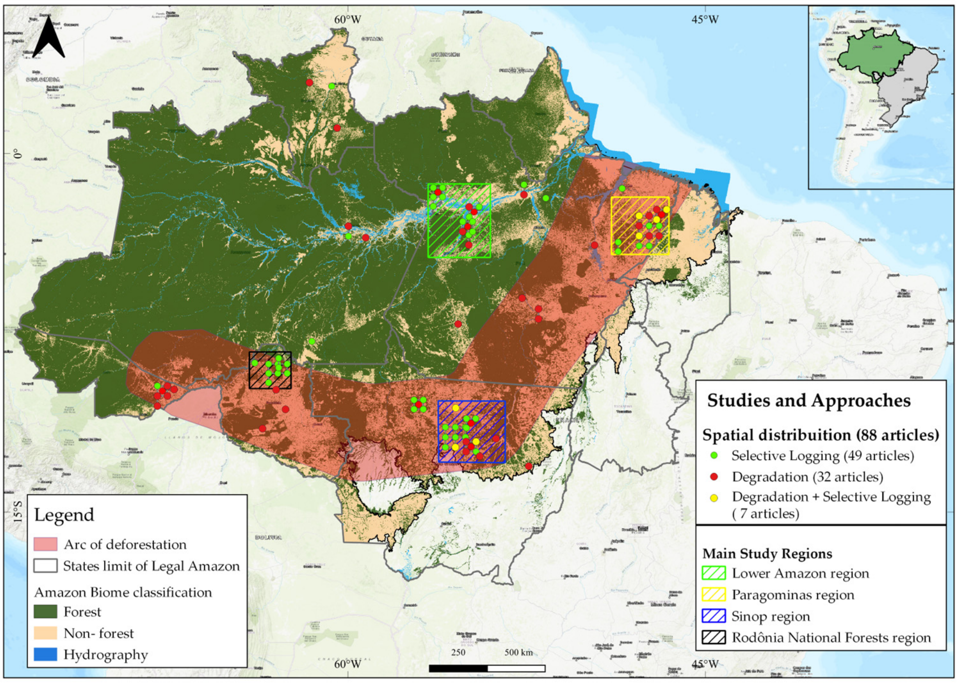

Figure 6. Categorization of the spatial distribution of studies on mapping degradation forest and selective logging in the Amazon biome by type of disturbance.

For regional studies (55 articles), the assessment of the categorization and spatial distribution in the Amazon biome revealed that out of the 88 study areas sampled (where coordinates were available), 75 were concentrated in just three states (85.2%): Pará (44.3%); Mato Grosso (26.1%); and Rondônia (14.7%). In Pará, there were two notable regions. The Paragominas region in the northeast of the state had 14 articles, including studies on the former selective exploitation of legal timber (4), forest degradation (6), and articles dealing with both selective exploitation and forest degradation (4). Additionally, in the far west of Pará, the Lower Amazon region also featured 14 articles, with the focus being on legal selective logging (11) and some studies on forest degradation (3).

The state of Mato Grosso, particularly the region around the municipality of Sinop, had the second-highest number of research papers, totaling 23 articles. Most of these articles focused on studies related to legal selective logging (11), followed by forest degradation (4). The region of the National Forests (Flona) located in the state of Rondônia had 13 articles, all of which dealt with the monitoring and mapping of legal selective logging within the Jamari and Jacundá National Forests (Figure 6).

3.4. Main Techniques Used

The results show the main approaches used in the studies evaluated and demonstrate the frequency of various techniques employed in scientific articles focused on monitoring anthropogenic forest disturbances and forest degradation. Each technique plays a specific role in monitoring and mapping (Figure 7).

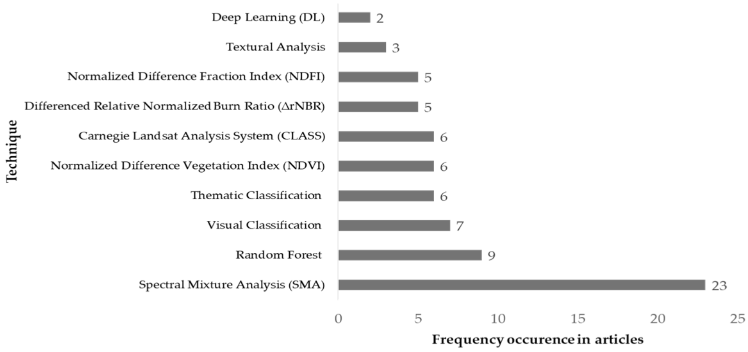

Figure 7. Frequency of occurrence of the ten main techniques used in the 80 articles evaluated.

The Linear Spectral Mixture Model (LSMM) is the most used technique, with 23 occurrences, highlighting its importance in decomposing spectral signals into individual components (fraction images). Random Forest appears with nine occurrences, which shows that it is a frequently used technique for classifying vegetation and monitoring changes in forest cover. Visual classification, although a more traditional technique and a pioneer in this type of study [56], is still relevant (seven occurrences), especially in areas where human interpretation is required to identify specific vegetation characteristics. The Carnegie Landsat Analysis System (CLASS), with six occurrences, is highly frequent in the studies evaluated.

The Normalized Difference Vegetation Index (NDVI) is widely used to monitor vegetation vigor, which is essential for identifying areas of degradation and helping to implement practices that promote forest recovery (six occurrences) [57,58]. The Normalized Difference Fraction Index (NDFI) (five occurrences) helps to detect and monitor forest degradation in areas subject to sustainable forest management, allowing targeted interventions to recover intensely degraded areas. This is an essential component of sustainable management [40]. The Difference Relative Normalized Burn Ratio (ΔrNBR) (five occurrences) is essential for assessing the severity of forest fires and their impacts, providing important data for post-fire recovery and the prevention of future fires [59,60]. Texture analysis (three occurrences) allows for a detailed assessment of the structural complexity of vegetation, helping to distinguish between different types of vegetation and levels of degradation [16,19,32,61]. Deep Learning—DL (two occurrences) is a set of machine learning techniques that uses deep neural networks to recognize complex patterns in large datasets [22].

3.5. Main Satellites Used

For SFM, it is essential to use remote sensing (RS) products to monitor and manage forests. An analysis of the frequency of occurrence in articles reveals the importance of different satellites and technologies in forest management research and practice (Figure 8).

The main satellites' classification results to monitor anthropogenic forest disturbance and degradation indicate that the Landsat series is the most used (55 occurrences). This is mainly because of its extensive historical data and its capability to offer detailed multispectral data over several decades [62–65].

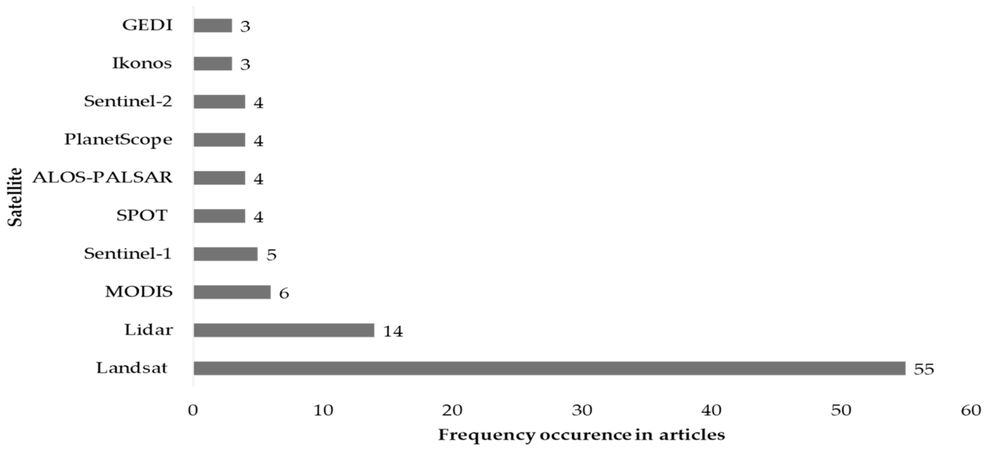

Figure 8. The frequency of occurrence of the ten main satellites used in 80 articles was evaluated.

LiDAR technology, with 14 occurrences, recently incorporated into forest cover monitoring studies, is highly valued for its ability to accurately measure the three-dimensional structure of forests [21].

The MODIS (Moderate Resolution Imaging Spectroradiometer), with six hits, despite its low spatial resolution, is widely used to monitor large areas of forest cover due to its high temporal frequency, which enables rapid detection of changes such as forest fires and large-scale forest degradation [66,67].

The Sentinel-1 and Sentinel-2 satellites mentioned nine occurrences when combined, providing optical (Sentinel-2) and radar (Sentinel-1) data. This combination is crucial for monitoring forests in adverse weather conditions and detecting subtle changes in forest cover [68,69].

ALOS-PALSAR, SPOT, GEDI, and IKONOS had a combined 14 occurrences. These satellites and sensors provide valuable additional data, complementing the information obtained by the main satellites mentioned. They are used for specific applications, such as detecting small changes in forest cover, assessing biomass, and monitoring small area changes. ALOS-PALSAR helps with monitoring in tropical regions using synthetic aperture radar (SAR). SPOT is mainly used for monitoring land use, land cover, and vegetation changes. GEDI (Global Ecosystem Dynamics Investigation), which is NASA's tool to measure how deforestation has contributed to atmospheric CO_2 concentrations, is an innovative orbital LiDAR technology that helps assess the vertical structure of forests, including tree height and biomass. Ikonos, with its high spatial resolution, is used for detecting small changes in forest cover, detailed mapping, and monitoring specific areas of interest [70–73].

PlanetScope is the only satellite mentioned comprising a constellation of imaging nanosatellites. It provides daily high spatial resolution images of the Earth's entire land cover. Its capability to capture detailed daily data makes it a powerful tool for monitoring forest disturbances and sustainable forest management [9,22,41].

3.6. Main Research Institutions

Based on our dataset, Figure 9 shows the affiliations of the top 10 institutions worldwide that have published the most on this subject. These institutions significantly generate knowledge and advance technology for implementing and monitoring tropical forests and sustainable forest management practices.

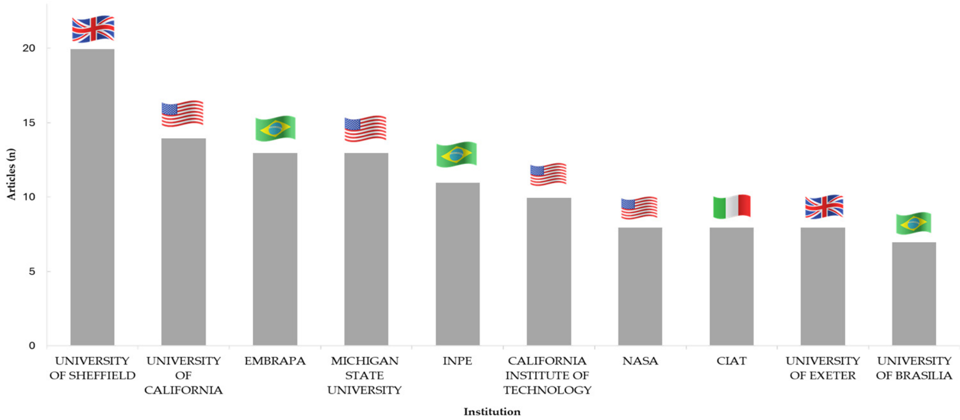

Figure 9. A hierarchical graph displays the top 10 countries and institutions worldwide with the highest publications on monitoring anthropogenic forest disturbance and degradation in the Amazon biome.

The University of Sheffield (20 articles) is known for its significant research in ecology and environmental science, focusing on understanding the impacts of human activities on forests and developing strategies to promote forest sustainability [74,75]. The University of California's research (14 articles) has focused on emerging remote sensing technologies, such as terrestrial and orbital LiDAR, environmental data analysis, and methods for monitoring changes in forest cover.

In Brazil, EMBRAPA (13 articles) has played a vital role in developing robust technologies, including sustainable forest management practices, pioneering studies into post-harvest forest monitoring, and implementing reduced impact logging (RIL) practices in the Amazon, most recently working with LiDAR technology [76–78].

Several studies from Michigan State University (13 articles) focus on using emerging remote sensing technologies for managing natural resources, particularly forests [79]. The National Institute for Space Research (INPE) (11 articles) is crucial in monitoring and developing remote sensing methodologies for the Amazon and other tropical forests. INPE uses a series of satellites to gather data on deforestation, forest degradation, and biomass, which are crucial for the sustainable management of Brazilian forests [39,80,81]. NASA (eight articles), through its satellite missions such as GEDI and Landsat, provides essential data used to monitor global forest cover and study the impacts of climate change, deforestation, and anthropogenic disturbances [21,82].

The Alliance Biodiversity & International Center for Tropical Agriculture (CIAT) (eight articles) promotes biodiversity conservation and the sustainable use of tropical resources, including forests. CIAT's research often deals with the sustainability of agroforestry systems and sustainable forest management [83]. The University of Exeter (eight articles) researches biodiversity conservation and the development of environmental policies that promote forest sustainability [17,84].

Finally, the University of Brasilia (seven articles) conducts significant research into tropical forest ecology and sustainable management practices, contributing to the development of public conservation policies in Brazil [16,19,32,61].

These institutions, with their research and innovations, play a key role in advancing sustainable forest management, helping to develop and implement practices that balance the conservation of forest ecosystems with economic and social needs.

4. Discussion

4.1. Need to Differentiate Forest Degradation from SFM and Policy Implications

The concept of forest degradation has not yet reached a scientific consensus, resulting in a variety of definitions and different approaches to its detection and measurement, especially by means of remote sensing, as demonstrated in this literature review [24–27].

The impacts of activities related to forest management and the monitoring of selective logging have mainly been viewed from an ecological standpoint [11,14]. As a result, the term "forest degradation" is often used to describe the effects of selective logging activities [19,22,32–34], fire [16,19,32], and landscape fragmentation [19]. It is important to note that although legal selective logging can be considered degradation from an ecological perspective or by generic definitions, it is temporary degradation. Selective logging is an activity that is part of SFM and, therefore, at first glance, should be categorized distinctly within the term forest degradation [36].

A group of experienced researchers from Embrapa Amazonia Oriental have emphasized the need for a deeper reflection on the concept of forest degradation and its role in decision-making. They suggest that forest management, when based on good forest practices and techniques, causes temporary forest disturbances responsible only for a low level of forest degradation, contributing to forest conservation from a broad perspective when good management practices are applied [36]. Another point is the fact that production forests, such as areas oriented for SFM, at the same time as generating environmental impact, advocate ways of mitigating them, such as reduced impact techniques and enrichment of clearings [85,86].

Pereira-Jr [7] provides a comparative analysis of canopy gap fractions resulting from CL and RIL in 1996 and 1998. The study demonstrates that CL consistently caused greater canopy disruption, with total gap percentages reaching 16.5% in 1996 and 21.6% in 1998, predominantly driven by tree felling and skidding operations. Conversely, RIL exhibited significantly lower impacts on the canopy, with total gap percentages of 4.9% and 10.9% for the same years. These findings underscore the efficacy of RIL in minimizing disturbances to forest canopy structure, highlighting its role as a sustainable logging practice that mitigates environmental degradation while preserving forest integrity.

Matricardi et al. [16] observed that selective logging impacted, on average, less than 4% of the forest canopy in the Amazon between 1992 and 1999, while in forest degradation caused by forest fires, forest canopies were affected by more than 30% in the same period of analysis. In addition, recurrent fires and the opening up of the forest canopy intensify the drying out of the soil and biomass, degrading the forest and creating favorable conditions for subsequent fires [87,88]. This cycle compromises the recovery capacity of tropical forests, making them more susceptible to clear-cutting. This highlights the need for management and protection strategies to break this cycle of degradation and conservation [89–92].

Recently, Matricardi et al. [19] identified and classified two types of forest degradation in the Brazilian Amazon: forest degradation dependent on deforestation, which is closely associated with landscape fragmentation (fragment size and edge effect) in the region, and degradation independent of deforestation, which is driven by selective logging and forest fires. The authors observed that most forests selectively logged between 1992 and 2014 remained in the Brazilian Amazon, even when later affected by fires. As a result, they argue that the conversion of forests for other land uses, such as agriculture or pasture (deforestation), is a distinct process from selective logging, even though selective logging of valuable trees is part of the deforestation process [19].

In this context, an important contribution of this study is to indicate that although several studies treat forest disturbances from legal selective logging as forest degradation, in practice there are several types of dynamics in the forest canopy, varying in intensity, size, and impacts resulting from anthropogenic interventions. Therefore, the different types of anthropogenic interventions need to be properly differentiated and considered, especially for cases of selective logging and timber harvesting in SFM projects.

Even though areas with SFM have high logging intensities of more than 30 $m^3 \cdot ha^{-1}$ and more than 20 individuals logged per hectare, resulting in large and persistent clearings, these areas are supported by technical and legal aspects, which ensures the sustainability/legality of the activity and guarantees that the area has a legal obligation to remain intact for at least 35 years, as determined by law [9,92]. In this sense, as proposed by Oliveira et al. [9], areas within SFM with high logging intensities should be monitored after logging to assess the dynamics and resilience of the trees and, if necessary, possible adjustments to improve the current legislation, which defines the temporal, physical, and ecological parameters for extracting native timber in the Amazon [6,9].

It is therefore important to clearly distinguish disturbances that occur within the boundaries of sustainably managed areas from those in areas that do not follow these practices. This definition suggests that any human intervention that occurs outside sustainable management areas, which does not result in total deforestation, can be considered forest degradation. On the other hand, sustainable management activities, even if they are intense, are processes of temporary forest disturbance in which the forest recovers and can be exploited again within cutting cycles, and are therefore not associated with deforestation [19,92]. Analyzing forest disturbances from the perspective of forest dynamics and resilience offers numerous opportunities, but also presents significant challenges [7,11]. In particular, this approach would allow this definition to be generalized and distinguished from any biases introduced by biased human perspectives [11,93,94].

Furthermore, mistakes in identifying degraded areas and selective logging can undermine the credibility of forest conservation and management efforts. This can make securing funding for conservation projects harder and discourage investment in SFM practices [95]. Public policies and regulations based on incorrect data can be ineffective or have negative consequences [96]. This can lead to inadequate allocation of public resources for forest conservation and management and hinder the implementation of effective strategies for forest protection [97,98]. Improving the accuracy in classifying forest degradation and selective logging is crucial for the environmental, economic, and social sustainability of SFM. Investments in modern monitoring technologies, such as remote sensing and GIS, combined with robust field validation, are essential to ensure the integrity of forest ecosystems and the effectiveness of management and conservation policies [9,21,22].

4.2. The Evolution of Monitoring Approaches for Forest Degradation

The evolution of forest degradation mapping highlights significant advancements in technology, methodology, and understanding of forest dynamics over time. This progress reflects a transition from traditional techniques to sophisticated technologies like machine learning and advanced satellite systems.

Early efforts, such as the pioneering study by Nepstad et al. (1999), relied on indirect methods like sawmill records to estimate forest areas impacted by selective logging due to the scarcity of remote sensing technologies. These methods, while innovative at the time, provided limited spatial and temporal insights [13].

The late 1990s and early 2000s marked the beginning of remote sensing applications for forest degradation mapping. Souza and Barreto (2000) introduced a remote sensing approach to detect forests impacted by selective logging in Pará, Brazil, utilizing a linear mixture model and buffer zones [99]. Shortly after, Souza et al. (2003) advanced these techniques with the use of Spectral Mixture Analysis and Landsat imagery [56]. Matricardi et al. (2005) further refined the use of Landsat images, employing texture analysis to estimate selectively logged areas in Mato Grosso, Brazil [61]. These studies signaled the transition to satellite-based mapping, enabling broader spatial coverage and more detailed assessments.

The mid-2000s saw a leap in the adoption of new satellite technologies. The Landsat series became essential for forest monitoring due to its extensive historical archive and multispectral capabilities. Asner et al. (2005) utilized the Carnegie Landsat Analysis System (CLAS) to map selectively logged forests across the Brazilian Amazon [14], while Matricardi et al. (2013) applied semi-automatic approaches and texture analysis to achieve similar goals [16]. These advancements highlighted the growing reliance on Landsat's medium-resolution imagery for large-scale assessments. Low-resolution satellites like MODIS also contributed, particularly in monitoring large-scale degradation due to its high temporal frequency [66,67]. Yet, limitations in spatial resolution meant these technologies were less effective in detecting subtle disturbances, such as low-intensity selective logging [82].

However, studies began identifying limitations in detecting low-intensity logging and subtle degradation using medium-resolution sensors, as they often failed to capture approximately 50% of canopy damage caused by logging operations [7,61].

The past two decades have seen the integration of high-resolution satellites and advanced technologies into forest monitoring [9,15,18,21,22]. Platforms like PlanetScope and Sentinel-2 now provide daily, high-resolution imagery, enabling more detailed assessments of forest structure and disturbances [20,22,68,69]. LiDAR technology has become highly valued for its ability to capture three-dimensional forest structure, tree height, and biomass [21,100]. LiDAR-based platforms like NASA's GEDI have revolutionized large-scale carbon and biomass quantification [73].

Simultaneously, advancements are marked by the introduction of machine learning and artificial intelligence (AI) techniques [21,22,98]. These technologies have revolutionized forest monitoring by enabling the processing of vast datasets and improving accuracy when detecting and classifying disturbances [33,74]. Algorithms such as Random Forest and Deep Learning have been increasingly employed to differentiate between natural disturbances (e.g., storms) and anthropogenic impacts (e.g., selective logging and fires), offering a higher level of precision than traditional methods [21,22,33,74]. Moreover, machine learning models have been integrated with data from high-resolution satellites and LiDAR, providing a multi-faceted approach to monitoring forest degradation [21,100].

Key research institutions have driven these advancements. For example, EMBRAPA and INPE in Brazil have been pivotal in developing methodologies for monitoring tropical forests and implementing sustainable forest management practices [36,76–78]. Internationally, universities like that of Sheffield and California have contributed to ecological research and the application of remote sensing technologies [74,75], while NASA has played a central role through missions like Landsat and GEDI [73,82].

Despite these advancements, challenges persist, particularly the costs and high computational demands associated with high-resolution data and LiDAR technologies. These limitations restrict their accessibility to well-funded projects and institutions. Nevertheless, initiatives like Brazil's RedeMAIS and Norway's NICFI program have made high-resolution satellite data more accessible to public institutions [101,102]. These efforts have democratized forest monitoring by providing high-resolution imagery for use in conservation and sustainable management [9,22].

The evolution of forest degradation to disturbance mapping reflects a dynamic trajectory of technological innovation. From early manual methods to the adoption of satellite platforms and the integration of machine learning, these advancements have significantly enhanced the capacity to monitor and manage forest resources. These technological innovations also allow for better categorization of forest degradation, enabling the distinction between different types and intensities of disturbances, such as selective logging, fires, and edge effects. Moving forward, the combination of high-resolution imagery, advanced algorithms, and collaborative global initiatives will continue to shape the future of forest monitoring, ensuring more effective and sustainable management practices

4.3. Regional Focus of Studies and the Need for Expansion

SFM areas within conservation units have played a key role in advancing techniques and tools capable of capturing and quantifying in detail the dynamics of disturbances and forest regeneration resulting from the selective logging of trees [9,21,22,69]. These studies are essential to refine and validate strategies that can eventually be applied more widely across the Amazon biome. This includes developing remote sensing tools that accurately capture changes in forest cover and different disturbance intensities, regardless of geographical location [14]. In protected areas, like in the National Forests of Rondônia, Flona Jamari was the country's first forest concession in 2008 and Flona Jacundá began logging in 2014. Both units' conservation are managed by the Brazilian Forest Service and operated by private companies [103–105]. The Lower Amazon region has several sustainable use conservation units with a long history of forest management, making it a natural source of research of this nature [9,106].

On the other hand, the Paragominas region in the northeast of the state of Pará is a model for forest management in the private areas and for being a pioneer in studies of SFM and the mapping of selective logging using remote sensing [56,107,108]. The Sinop region has the highest concentration of SFM plans in private areas within the Amazon. It is one of the largest timber-exporting regions, with numerous companies operating in the timber sector [61,109,110].

In this regard, studies monitoring anthropogenic forest disturbances and degradation are mainly focus on the "arc of deforestation" in the Brazilian Amazon (Figure 6) [111–113]. The concentration of studies in this area is largely due to the intense human activity and rapid land use changes occurring there [43,113]. This region, which spans the southern and eastern edges of the Amazon, has become a focal point for deforestation due to factors such as mechanized agriculture, cattle ranching, and logging—often conducted illegally [113]. These activities contribute to a high visibility of forest loss, making it an attractive region for researchers aiming to study anthropogenic impacts on tropical forests [62–65,113].

However, despite regional focus, this study has been significantly advanced through remote sensing techniques, each offering distinct capabilities for monitoring and analysis. The Linear Spectral Mixture Model (LSMM) excels in decomposing spectral signals into individual components, enabling the detection of subtle changes in forest composition [56,80]. Random Forest is widely used for classifying vegetation and monitoring changes in forest cover [98], while visual classification remains relevant in scenarios requiring human interpretation of specific vegetation characteristics [56]. Tools like the Carnegie Landsat Analysis System (CLAS) and indices such as the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Fraction Index (NDFI) are critical for monitoring vegetation vigor and identifying degraded areas, particularly within SFM contexts [40,58,59]. Additionally, the Difference Relative Normalized Burn Ratio (ΔrNBR) is vital for assessing fire severity and informing recovery efforts [59,60], while texture analysis provides detailed insights into vegetation structure [16,19,32,61]. Advanced techniques such as Deep Learning (DL) leverage neural networks to detect complex patterns in large datasets, further expanding the potential of remote sensing in forest monitoring [21,22,114].

To enhance the practical value of this research for decision-makers, there is a need to align technical advancements with real-world applications. For instance, integrating NDVI and ΔrNBR can provide actionable insights for post-fire recovery planning and monitoring the impacts of climate change on vegetation health [58,60]. Similarly, advanced techniques like Deep Learning could be applied to predict degradation hotspots under future climate scenarios by combining satellite data with local environmental variables [22]. By combining advanced remote sensing techniques, such as LSMM, NDVI, and Deep Learning, with on-the-ground validation in less-studied regions, researchers can generate a holistic understanding of forest dynamics [21,22,58,60]. This comprehensive approach will inform adaptive management strategies and policies that promote the resilience of Amazonian forests, ensuring their ecological, economic, and social benefits for future generations [111,112].

With climate change intensifying extreme events and altering climate patterns in the Amazon, there is an increasing need to expand the focus of forest degradation and disturbances studies beyond the "arc of deforestation" [17,34,111]. Although this region is a critical point of research due to intense human activities, forests located in more remote and dense areas of central and western Amazon are also vulnerable to the impacts of climate change and anthropogenic actions [115]. These historically less-studied areas may face new challenges, such as severe droughts and more frequent fires, which compromise the natural regeneration of forests and increase the risks of degradation [17,31,115,116]. Expanding research to include less-studied, densely forested regions in the central and western Amazon, where traditional, community-based, and low-impact logging practices may be more prevalent, would provide a more comprehensive understanding of forest disturbance and degradation patterns across the Amazon [116]. This broader approach could improve forest management practices by incorporating the diversity of forest conditions and disturbances across different parts of the biome [21,117]. Comprehensive data from underrepresented regions can guide public policies and management practices, promoting the resilience and long-term sustainability of Amazonian forests [17,31,118,119].

Expanding the focus of studies to include these less-impacted regions is essential for understanding how different parts of the biome respond to the combined pressures of human activities and extreme climate events [120–122]. This enables the development of adaptive monitoring and management strategies that consider the diverse environmental conditions across the Amazon, ensuring a more robust approach to conservation [123]. Comprehensive and context-specific data on these areas could guide public policies and management practices that promote the resilience of Amazonian forests to climate change, supporting the long-term sustainability of the entire ecosystem [17,31,114,115].

In summary, while the focus of research has been on the arc of deforestation, it is crucial to expand research and discussion to monitor degradation and anthropogenic disturbances in the forest on a broader scale [116]. This expansion should include other regions of the Amazon that are less studied but equally important, as they are heavily forested and face serious challenges that warrant balanced scientific attention [33,112,115]. Notably, further research is needed to monitor selective logging across the entire Amazon. To date, only one notable study [16,19] has distinguished selective logging from fire-affected areas throughout the legal boundaries of the Amazon. Here, we have addressed the main achievements of remote sensing and new technologies in assessing forest disturbances in tropical regions, as well as the challenges related to the concepts of forest degradation and forest management. Altogether, this work provides a valuable contribution to researchers, policymakers, and forest practitioners, helping to improve forest management, regulation, and conservation.

5. Conclusions

This study highlights advancements in monitoring forest degradation and disturbances within the Amazon biome, emphasizing the critical role of remote sensing technologies and sustainable forest management (SFM) practices. By synthesizing key methodologies, such as Linear Spectral Mixture Models (LSMM), Normalized Difference Vegetation Index (NDVI), and emerging techniques and technologies like Deep Learning and LiDAR, we demonstrate how these tools have transformed our ability to monitor and assess forest dynamics. These advancements allow for more precise categorization of disturbances, distinguishing temporary impacts associated with SFM from more severe degradation caused by illegal logging, fires, and other anthropogenic activities.

While much of the research remains concentrated in the "arc of deforestation", the need to expand the geographic focus of studies to include less-impacted and under-researched regions is critical. Areas in the central and western Amazon, characterized by dense forests and traditional or low-impact logging practices, offer valuable insights into forest resilience and the diverse impacts of anthropogenic and climatic pressures. Addressing this research gap would provide a more comprehensive understanding of forest degradation across the entire biome, ensuring that findings are representative of the Amazon's full complexity.

Climate change adds urgency to this endeavor, as the intensification of extreme events, such as severe droughts and fires, threatens the regeneration capacity of Amazonian forests. Expanding studies to underrepresented regions will enable the development of adaptive management strategies that are responsive to local environmental conditions and resilient to climatic variations. This approach is essential to support the long-term sustainability of the Amazon and its vital ecological, economic, and social functions.

Policymakers and forest practitioners can benefit greatly from the integration of advanced monitoring tools with field-based validation. Providing actionable insights, such as identifying degradation hotspots and assessing post-disturbance recovery, will help refine forest management policies, improve REDD+ initiatives, and promote more effective conservation strategies. The distinction between forest degradation and SFM must be clear in policy frameworks to ensure that temporary, managed disturbances are not conflated with permanent degradation, preserving the credibility and sustainability of SFM practices.

The proposal presented here, which calls for differentiating types of forest disturbance, especially to separate low-impact sustainable management areas from other forms of medium- and high-intensity degradation, represents a significant advancement in assessing forest disturbance in terms of intensity, size, agents, causes, and impacts. These criteria help make a clearer distinction between sustainable management practices and other levels of disturbance that structurally compromise forest integrity and conservation.

Future research should focus on refining definitions of forest degradation and enhancing monitoring methods. This includes developing more precise, standardized criteria for defining and assessing forest degradation across different regions and contexts. Further research could also explore advanced remote sensing techniques, such as machine learning models integrated with high-resolution data, to improve the classification and discrimination of various forest disturbance types. Additionally, long-term studies on the ecological recovery and resilience of forests after different intensities of disturbance could provide valuable insights for sustainable management practices. Such research would contribute to a more comprehensive understanding of degradation processes, ultimately supporting more effective conservation and management strategies.

In summary, this study underscores the need for a broader, more inclusive research agenda that captures the full spectrum of forest dynamics across the Amazon. By combining technological innovations, regional insights, and robust monitoring strategies, researchers and practitioners can contribute to the resilience and sustainability of Amazonian forests, ensuring their preservation for future generations. This comprehensive understanding is indispensable for shaping effective public policies and advancing global efforts to mitigate climate change and protect tropical forests.

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