forests

Review

A Systematic Review of Logging Impacts in the Amazon Biome

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Abstract: Every year, logging in the world's largest tropical forest, located within the Amazon biome, continues unabated. Although it is a preferred alternative to deforestation, the residual stand and site are impacted by logging. The objective of this review was to determine and assess the current state of research throughout Amazonia on the subject of logging impacts. To achieve this goal, a systematic approach was utilized to gather, assess and categorize research articles conducted in the Amazon biome over the last decade. Eligibility for inclusion of articles required demonstration of a direct impact from logging operations. A total of 121 articles were determined to meet the eligibility requirements and were included in this review. Articles were subdivided into three environmental categories: forest (n = 85), wildlife (n = 24) and streams (n = 12). The results of this review demonstrated that impacts from logging activities to the forest site were a direct result of the logging cycle (e.g., how often logging occurs) or logging intensity (e.g., how many trees are felled). The impacts to wildlife varied dependent on species, whereas impacts to streams were affected more by the logging system. Overall, research suggested that to attain sustainability and diminish the impacts from logging, a lower logging intensity of 10–15 m^3 ha^{-1} and a longer logging cycle of 40–60 years would be essential for the long-term viability of forest management in Amazonia.

Keywords: forest management; timber harvesting; sustainable forestry; cutting cycle

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1. Introduction

The Amazon biome covers an area of approximately 6.7 million km^2, with a forested area (94% humid, 4% flooded, 2% dry) of approximately 5.8 million km^2 [1]. The biome covers portions of eight South American countries including Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname and Venezuela, as well as the French overseas territory of French Guiana. The commercial volumes in the forests of Amazonia are generally considered low at approximately 5–50 m^3 ha^{-1} (sometimes exceeding 100 m^3 ha^{-1}) when compared to tropical forests in Asia at 60–200 m^3 ha^{-1} [2–4]. Thus, to sustain a viable timber industry in the Amazon, an expansive forest area must be entered annually. In 2020, it was estimated that Brazil, which occupies more than half of the Amazon forest [5], produced 29.2 million m^3 of tropical industrial roundwood, excluding plantations [6]. Considering that current Brazilian law permits a maximum of 30 m^3 ha^{-1} [7], a substantial area is affected by timber-harvesting activities every year. These logging operations entail a reduction in forest canopy, damage to residual trees and soil disturbance from skid trails and logging roads [8].

In an effort to study the impacts of silviculture treatments and logging, numerous large-scale research projects were established throughout the Amazon. Those projects were Curuá-Una, Brazil in 1958; the CELOS Management System, Suriname in 1965; Alexander von Humboldt National Forest, Peru in 1971; Tapajós National Forest, Brazil in 1979; ZF-2, Brazil in 1980; Paracou Project, French Guiana in 1982; and Palcazu Valley Project, Peru also in the 1980s [9,10]. However, most of these studies, such as the CELOS Management System, Tapajós National Forest, ZF-2 and the Paracou Project utilized logging intensities greater than 30 m^3 ha^{-1} [11–14], which today would be considered excessive or even above authorized cutting limits in Brazil, Guyana and Suriname [15]. Furthermore, the Palcazu Valley Project implemented a clearcutting system that was found to be unsustainable, as regeneration of commercial species was not sufficient under the proposed rotation of 30–40 years [16]. Although the experimental logging operations at these research sites were of a higher intensity than that practiced currently, they still provide valuable information on logging impacts to the stand, as well as the subsequent recovery. In fact, Higuchi [17] states that any decisions on silviculture or forest management for the Brazilian Amazon must consider the research from CELOS in Suriname and the Paracou Project in French Guiana. That is because field research conducted there occurred in forests that are similar to the forests of the Brazilian Amazon.

The long-term research at the Paracou research station has revealed some impacts of logging in the forests of Amazonia, such as all plots in their experimental logging site continued to be a source of carbon emissions 10–12 years after logging and recovery of carbon stocks was projected to take at least 45 years [18]. Also, at Paracou, researchers determined that to reduce impacts to the residual stand, low intensity harvesting of up to 30% of stand basal area with a minimum 60 years reentry cycle would be sufficient to protect and ensure continued commercial regeneration in the Amazon [13]. In Suriname, logging under the CELOS Management System caused mortality of commercial trees of up to 20% in stems over 5 cm in DBH [12]. In spite of that, Jonkers [12] suggests that a logging intensity of 15 m^3 ha^{-1} with a 25-year reentry cycle could be sufficient for sustainable yield.

Since the initial research stations were established, numerous studies have presented various impacts related to logging in the Amazon. Some of these impacts have been favorable to the residual stand. For example, canopy disturbance increases solar radiance in the residual forest, leading to increased forest growth [19]. Even so, this increase in forest growth rates is generally short-lived, lasting less than a decade as the canopy closes [14,20,21]. To the contrary, many detrimental impacts have also been encountered. Logging always causes some form of damage to the site, but without proper prior planning the impacts are substantially greater. In the eastern Amazon, when logging was not planned, there was a substantial increase in area of canopy openings and soil disturbance, as well as incidental damage to trees in the under and overstory [22]. Researchers in the Brazilian Amazon have also found that planned logging operations in and of themselves are not always sustainable and recommend longer cutting cycles of 40 years and lower harvest intensities of 10–14 m^3 ha^{-1} [23]. In Guyana, results from the Tropenbos logging experiment support a slightly higher cutting intensity of 20 m^3 ha^{-1} or eight trees per hectare to reduce overall canopy gap openings and a cutting cycle of 31 years [24].

Much of the early research on logging at the aforementioned Amazonian research sites focused on the impacts to forest growth. Nevertheless, for adequate forest management planning it is necessary to take a more holistic approach to make well-informed decisions. This entails evaluating and assessing all impacts to the site, which includes the wildlife and streams. In this context, the present review was written to help guide future logging operations and forest management within the Amazon biome. Therefore, the objectives for this review were to determine what current research has revealed about the impacts of legal logging operations to (i) the forest, (ii) the wildlife and (iii) the streams within the Amazon biome with key questions of interest including the impact of logging volume and cycle on stand variables such as forest regeneration, growth and mortality, as well as impacts to wildlife habitat, including aquatic species.

2. Materials and Methods

The database search, record screening, exclusion and eligibility guidelines were based on the approaches found in the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) [25].

2.1. Eligibility Criteria

Only research articles were utilized for this review. Articles had to be written in English, or written in Portuguese with an English title or abstract. They also had to be published within 10 years of July 2022. A decade was chosen to capture the most recent up-to-date research ongoing in Amazonia. The topic of study needed to be related to logging in the Amazon biome and the subsequent impacts to the environment. Any study including impacts as a result of logging was considered, whether beneficial or detrimental.

2.2. Information Sources and Search Strategy

A comprehensive literature review was conducted on 29 July 2022 and 30 July 2022. The three databases used for the searches were Scopus, Science Direct and Web of Science. The date range was 1 July 2012 to 1 July 2022. The database search string was [("Amazon" OR "Amazonia") AND ("logging" OR "forest management") AND "impacts"]. A filter was applied to limit search results to the title, key words or abstract. An additional search string was also applied: [("Colombia" OR "Guyana" OR "French Guiana" OR "Suriname" OR "Venezuela") AND ("logging" OR "forest management") AND "impacts"]. This was done to encompass the entire Amazon biome, because even though the biome largely follows the basin boundary, the northern biome is largely outside of the Amazon basin.

2.3. Selection Process

In the screening process, all research conducted outside of the Amazon was excluded. Once all articles were determined to have occurred within the Amazon biome, they were further screened to determine if results presented an environmental impact from logging. Thus, numerous studies were excluded due to an exclusive focus on economics, fire, social issues, climate change, remote sensing technology or modeling, although research connecting logging to these issues was assessed for inclusion, or when modeling was based off actual logging data, those studies were also included. In the final determination of eligibility, twenty-two articles were excluded for the following reasons: 1. 'Salami splicing', where multiple studies were made from a single dataset repeating nearly the same results [26]; 2. Exclusively focused on silviculture; 3. Not directly correlated with logging; 4. Logging impacts to the forest that were confounded with fire or logging impacts to wildlife that were confounded with hunting; 5. Remote sensing technology comparisons for use in the study of logging impacts; 6. Data from the Amazon basin included with data from outside of the biome; 7. Solely illegal logging impacts; 8. Survey before logging and 9. Lack of logging information such as harvest intensity or whether the logging was considered an illegal and/or legal operation.

2.4. Data Collection Process

Results were compiled and duplicated results were removed. The subject was determined from the results. The next step entailed subdividing the articles into three general categories: forest, wildlife and streams. The forest category included the terrestrial environment (e.g., soil and plants). The wildlife category included animals including terrestrial insects (e.g., beetles and butterflies). The streams included the physical environment of the watercourse and the aquatic and semi-aquatic life found in the streams.

2.5. Data Presentation in Map

For data visualization presented in a map, ArcGIS Pro was utilized, with the following steps taken:

1. Acquisition of coordinates for the study sites: (a) coordinates explicitly available in texts or tables were converted to alpha-numeric format and recorded into Excel; (b) in some cases, articles did not provide explicit coordinates and only mentioned the name of the local where the study was conducted, so they were identified with Google Earth Pro (GEP). If the location area was clearly recognized, the coordinates were placed in central position; if not, logging infrastructure was identified in satellite images and the coordinates were assigned to a point over them (as centralized as possible).
2. All records of coordinates initially recorded in Excel for each study/category were converted to decimal degrees;
3. Using the Add XY Data function, the table containing all studies/categories and coordinates were added into ArcGIS Pro and then converted to a shapefile;
4. The Amazon ecoregion (i.e., Amazon biome) and South American countries from ArcGIS Online database were used as background features for preparing the map.

3. Results

3.1. Quantitative Analysis

A total of 121 research articles that fit the search criteria and were considered eligible for further analysis were selected for inclusion in this review (Figure 1; Supplementary File S1). This equates to an overall average of approximately 12 publications per year on logging impacts within the Amazon biome. There was an increasing trend of publications on the subject, with the last two years having an average of 20 publications per year. These articles were published in a total of 60 different scientific journals. Journals only publishing one article on the subject were 34.7% of the total, journals that published two were 11.6%, three 12.4% and four or more 41.3%. The vast majority were published in Forest Ecology and Management (*n* = 27), followed by Ciência Florestal (*n* = 5), Forests (*n* = 5), Scientia Forestalis (*n* = 5), Biological Conservation (*n* = 4) and Biotropica (*n* = 4). The regions where these studies occurred were primarily in Brazil (*n* = 89), which accounted for 73.6% of all studies conducted in the biome. The remaining studies were encountered in French Guiana (*n* = 9), Guyana (*n* = 7), Peru (*n* = 6), Bolivia (*n* = 2), Ecuador (*n* = 2), Suriname (*n* = 2), Venezuela (*n* = 1) and multiple regions (*n* = 3). For the multiple regions, the studies included: Guyana and Suriname; French Guiana and Brazil; and Bolivia, Guyana and Brazil. No studies fitting the search criteria for this review were found in Colombia.

When the research papers were divided by environmental category, studies related to aspects encountered in the forest category (*n* = 85) dominated (Figure 2). Far fewer studies were published in the wildlife category (*n* = 24) and the streams category (*n* = 12). Spatially, the studies evaluated aspects of the forest category were concentrated principally in the eastern region of the biome. The studies in the wildlife category, although few in number, were fairly well dispersed throughout the biome. To the contrary, research sites in the streams category were limited to three distinct areas. These areas were limited to Brazil and French Guiana. In fact, only one study on logging impacts to streams was found in the Amazon basin, whereas the rest were located in the outer Amazon biome.

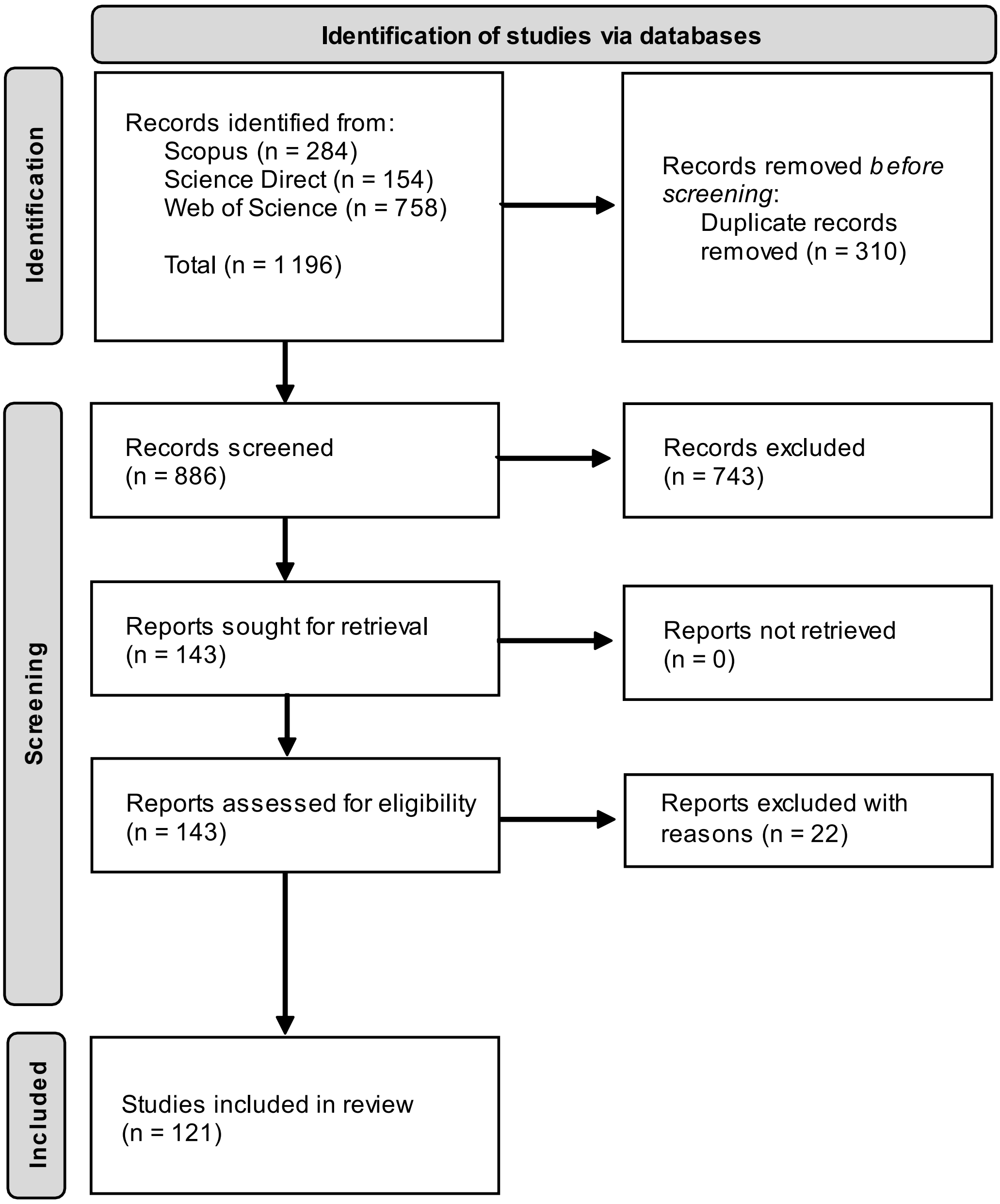

Figure 1. PRISMA 2020 flow diagram [25].

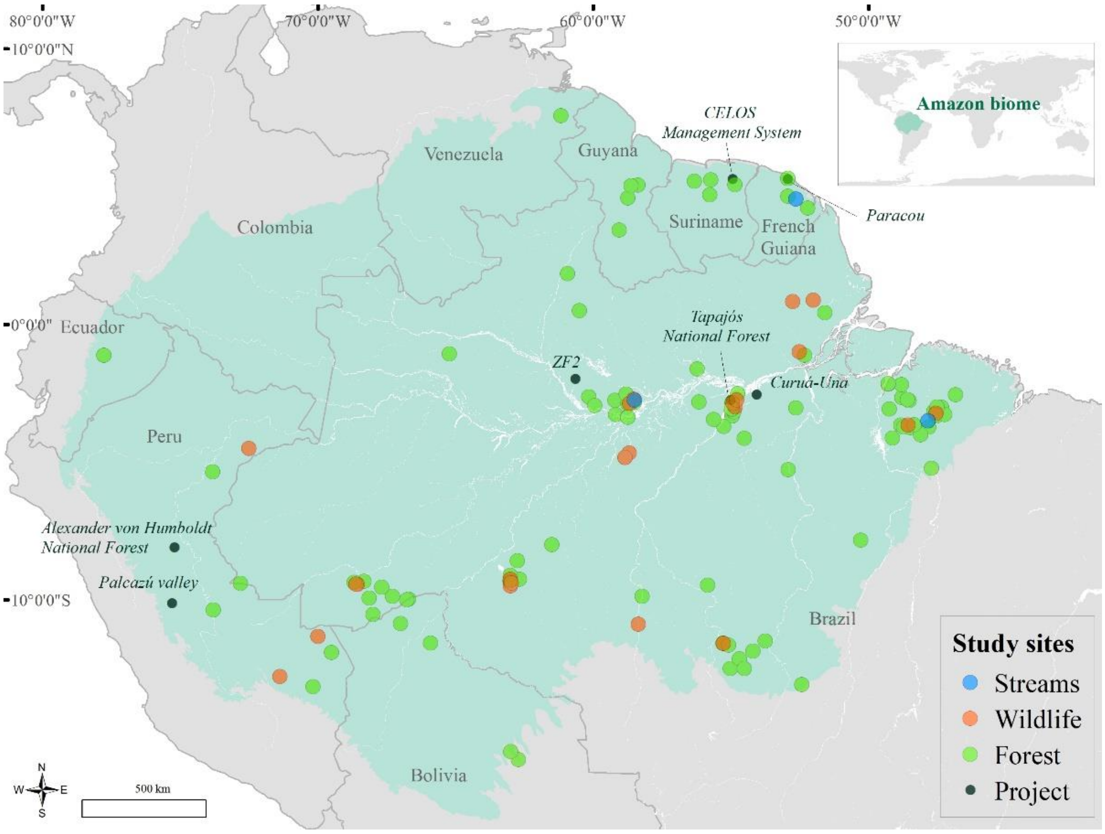

Figure 2. Locations of study sites throughout the Amazon biome included in review.

3.2. *Qualitative Analysis*

3.2.1. Forest

The majority of research in the forest category used a study design where an unlogged stand (e.g., control, reference) was compared to a logged stand (23.5%). The other most common design used a control to compare against a chronosequence of various years of logging (15.3%), but not comparing the change over time. Even so, time series (with at least one remeasurement) in combination with a before and after logging measurement or a control were highly utilized (40%). Solely before and after designs were less common (10%), with the remainder of studies being assessments based on comparisons of various areas that had been logged without a control or before and after design.

The initial impacts to forest attributes from logging included decreased canopy cover, basal area, above-ground biomass and increased tree mortality, pioneer species, herbivory and soil compaction (Table 1). Many of the impacts such as canopy cover loss was found to persist for nearly a decade or longer [27–30], although a study of litterfall production in logged areas showed no difference with controls after a decade [31]. Increased canopy openness from logging has been found to increase herbivory rates in seedlings [32], although small trees $\geq$10 cm in diameter were fairly resistant to herbivory after logging [33]. The loss of canopy cover occurs mostly from logging infrastructure such as landings, skid trails and roads [34], greater frequency of tree felling gaps [35], as well as greater gap size [36]. The soil compaction caused from logging infrastructure also persisted for up to several decades, although skid trails were found to have had recovery in topsoil of skid trail ruts after 24 years [37,38]. In logging gaps where heavy machinery stayed on the periphery when yarding logs, no compaction was found [39]. Even so, logged forests still had lower soil available water than their unlogged counterparts [40].

Table 1. Initial impacts from logging in the Amazon within 5 years after logging.

Forest Attribute	Characterization †	Reference
Above-ground biomass	↓↓↓↔↓	[41–45]
Above-ground C density	↓↓	[46,47]
Allele loss	↑	[48]
Bamboo culm density	↔	[44]
Basal area	↓↓↓↔	[42,44,46,49]
Canopy cover	↓↓↓↓↔↓↓	[28,32,50–54]
Carbon emissions	↑	[55]
Carbon stocks	↔↓	[56,57]
Coarse woody debris	↔	[58]
Ecosystem respiration	↓	[42]
Fire severity	↑	[59]
Floristic composition	↓	[56]
Ground disturbance	↑↑	[34,60]
Herbivory	↑	[32]
Lianas	↑↑	[61,62]
Litterfall	↔	[63]
Mortality	↑↑↑↑↑↑	[64–69]
Palm regeneration	↑	[70]
Periodic annual increment	↑↑	[49,68]
Pioneer species	↑↑↑↑	[21,71–73]
Residual tree damage	↑↑	[56,67]
Soil carbon	↔↔↑	[27,39,74]
Soil compaction	↑↑↔	[21,39,60]
Species diversity	↔↔↔↔	[56,74–76]
Species richness	↓	[57]
Understory ambient temperature	↑	[77]

† Upward arrow conveys an increase, downward arrow a decrease and two horizontal arrows equals no difference.

An attribute that received substantial attention was carbon. Results varied from study to study. For example, some studies found no difference in coarse woody debris and litter carbon pools in logged stands [57,78], whereas others did [42]. Nonetheless, generally speaking, post-logging above-ground carbon stocks were found to be lower [42,47,54,57]. The recovery of carbon stock or above-ground biomass was found to be a longer process in heavily logged forests [79,80]. In fact, modeling showed that a timber harvesting level of 30 m^3 ha^{-1} on a 30-year cutting cycle would result in lower stand above-ground biomass each entry which would increasingly contribute to CO_2 emissions [81]. This same author found that a 30-year cutting cycle of 15 m^3 ha^{-1} would alleviate the diminishing biomass over time and subsequently the emissions. In Guyana, above-ground carbon stocks were recovered after 20 years in planned logging areas with intensities ranging from 14 m^3 ha^{-1} to 24 m^3 ha^{-1} [82]. To the contrary, similar cutting intensities in Suriname were still not recovered after 32 years [83]. Authors also noted that above-ground biomass and carbon stock recovery modeling was influenced by the sudden increase in fast-growing pioneer species and their subsequent mortality [84,85]. Regional differences were also noted within the biome concerning carbon emissions and impacts. For example, Guyana had nearly five times the gross carbon emissions from logging than Brazil [86].

The forest attributes that received the greatest attention were recruitment, regeneration, growth and mortality. To a lesser degree, taxonomic, phenological and floristic differences were studied [56,72,76,87–89]. Twelve papers evaluated a combination of these factors exclusively for a single species (Table 2), whereas others focused on two or three species per paper such as: *Dipteryx odorata* (Aubl.) Willd., *Eschweilera coriacea* (DC.) S.A. Mori, *Eschweilera ovata* (Cambess.) Mart. Ex Miers, *Jacaranda copaia* (Aubl.) D.Don, *Lecythis idatimon* Aubl., *Minquartia guianensis* Aubl., *Protium hebetatum* Daly, and *Zygia racemosa* (Ducke) Barneby & J.W. Grimes [32,48,90]. Important differences in species autecology were revealed in many of the papers evaluated. Research showed that density and abundance were highly dependent on species and level of logging disturbance [69,91–93]. This knowledge of different species growth and minimum density in response to logging was useful to determine sustainable cutting cycles in Amazonian tidal floodplain forests [94]. In non-flooded forests, long-term studies of more than a decade in Brazil, Guyana and Suriname found that logging intensities greater than 20 m^3 ha^{-1} of commercial volumes could not guarantee the initial harvested volumes in a 30-year cutting cycle [45,66,82,83,95]. On the other hand, logging intensities below 20 m^3 ha^{-1} did recover after 20 years, but with insufficient increase in light to stimulate growth of residual timber species [82]. Generally, studies found that there was a sufficient increase in light from canopy opening in Amazonia to favor undesirable non-commercial short-lived pioneers, as well as some commercial long-lived pioneers [49,72,85,95,96]. However, as the short-lived pioneers succumb to mortality, long-lived species (e.g., *J. copaia*) continued to persist [21]. Overall, mortality increased after logging, especially in damaged large trees ≥ 60 cm [97]. On the contrary, large undamaged trees may benefit from logging during droughts due to diminished competition for water [98,99].

Table 2. The effect of logging impacts on specific species.

Species	Result	Reference
Astronium gracile	Shade-tolerant species unaffected by gap size	[100]
Bagassa guianensis	Decreased pollen dispersal distance	[101]
Bertholletia excelsa	No decrease in genetic diversity	[102]
Bertholletia excelsa	Increased population density and growth	[103]
Copaifera spp.	Substantial increases to regeneration	[104]
Hymenaea courbaril	Thirty-year cutting cycle not sustainable	[105]
Hymenaea courbaril	Reduction of total number of alleles	[106]
Manilkara huberi	Height and growth unaffected by gap size	[107]
Manilkara huberi	Increased mortality for stems ≥ 75 cm DBH	[108]
Pseudopiptadenia suaveolens	Increased mortality for stems ≥ 45 cm DBH	[109]
Swietenia macrophylla	Decreased reproductive neighborhood density	[88]
Theobroma subicanum	Growth highest on gap edge vs. gap center	[110]

3.2.2. Wildlife

The majority of research in the wildlife category (58.3%) used a study design where an unlogged stand (e.g., control, reference) was compared to a logged stand. The other most common design used a before and after logging design (25.0%). The remainder of designs employed a chronosequence (12.5%) or a comparison of different land management activities, with at least one being logging (4.2%). The wildlife was collected or identified through various means such as walking transects, mist nets, camera traps, pitfall traps, cylindrical traps, baited traps, recorders, hunting registers and/or visual and audible confirmation. The wildlife sampled included birds (n = 6), mammals (n = 5), amphibians (n = 2), as well as various insects: beetles (n = 3), butterflies (n = 3), ants (n = 1) and termites (n = 1). Additionally, three studies covered more than one type of wildlife.

Logging impacts to the avian community varied markedly throughout the Amazon. Depending on the attribute under study, such as richness, many times there were no observable differences between controls or before logging [111–113]. Despite no differences in richness or number of individuals, Soares et al. [113] still encountered ongoing recovery in assemblages five years after the cessation of logging operations. Other differences in avian populations that were observed were a decrease in specialists and an increase in generalists [114], but this was not always the case. For example, the indicator species and gap specialist *Hypocnemis cantator* actually increased in abundance after logging [115]. There were also differences found for the same genera. In one study, *Tinamus* spp. were more abundant in unlogged forest [116], whereas in forests with a bamboo component, the only difference for *Tinamus guttatus* was the level of bamboo coverage, not logging [117]. Preferences also varied within woodcreepers with some, such as *Xiphorhynchus obsoletus*, having higher densities with canopy openness and *Campylorhamphus procurvoides* presenting lower densities [118]. Only one study included the largest raptor in the Amazon, the

Harpy Eagle (*Harpia harpyja*), and logging impacts, which was detected in both logged and unlogged areas [116].

The mammalian community was less studied, and the few studies there were had contrasting results. In one study utilizing a camera-trap, logging was negatively related to occupancy of large carnivores *Leopardus wiedii*, *Leopardus paradalis*, *Panthera onca*, *Puma concolar* and *Puma yagouaroundi* [119]. To the contrary, another study that also utilized a camera-trap found that logging had a strong positive effect on detection of *P. concolor*, *P. onca* and *L. pardalis* [120]. Still, a study employing walked transects observed that *L. wiedii*, *L. pardalis*, *P. yagouaroundi* and *P. concolor* only occurred in unlogged primary forest [121]. Fewer studies evaluated impacts to primates, but the squirrel monkey (*Saimiri sciureus*) was only detected in unlogged forest [116,122], although one study found these same squirrel monkeys in a secondary forest that was less than 20 years old [121]. In Brazil, four species of primates were exclusive to primary forest and not found in logged forest: *Cebus olivaceus*, *Sapajus libidinosus*, *Saimiri collinsi* and *Ateles paniscus* [121]. In Peru, density and abundance of *Cebus albifrons*, *Sapajus macrocephalu* and *Saimiri sciureus* declined after logging, whereas *Lagothrix poeppigii* increased substantially. Impacts to bats were mixed. In one case, the assemblages changed pre- and post-logging, but were no different than the control [115], whereas in another case, five species present prior to logging were absent after operations [123].

There were only two studies fitting the review's criteria for amphibians. Both noted the influence of artificial lentic waterbodies (e.g., water filled ruts). In Central Guyana, these artificial waterbodies contributed to a shift in abundance by creating breeding sites for *Leptodactylus petersii* and *Physalaemus ephippifer* [124]. In the Brazilian Amazon, logging roads and log landings were found with generalist species occupying the temporary waterbodies [125]. These same authors speculated that due to these temporary breeding areas created by the logging infrastructure, there was the potential for increases to other populations of animals (e.g., snakes, lizards, frogs) due to the temporary growth in the food supply.

The study of insects was mainly limited to dung beetles and butterflies. These were found to be potentially suitable as indicator species to assess anthropogenic disturbance, such as logging [126,127]. Dung beetle species richness and species biomass were lower post-logging in a study with a harvest intensity up to 50 m^3 ha^{-1} [128], whereas a study with a maximum harvest intensity up to 16.2 m^3 h^{-1} found species abundance and richness to be no different than the control [129]. In Guyana, dung beetle assemblages were more uniform inside the forest outside of tree fell gaps [126]. The differences in dung beetle assemblages were more pronounced in the dry season for logged areas vs. the control in the Central Amazon [130]. For butterflies, logging areas in the Brazilian Amazon had more species than the primary forest, riparian zones, with canopy open-habitats having three times more species than other areas [131,132]. Studies in Peru also corroborated increased abundance of butterfly species in logged areas [127]. Termites were affected differently by logging with litter feeders lowest and wood feeders highest in timber harvesting areas [133]. Ants, on the other hand, were unaffected by logging operations [134].

3.2.3. Streams

All of the research sites in the streams category used a study design where an unlogged stand (e.g., control, reference) was compared to a logged stand. Notably, a majority of the studies (75%) were carried out in the same watershed, the Capim River Basin in the eastern Amazon. Two studies were carried out in the northern Amazon biome and one in the central Amazon. The study that was carried out in the central Amazon was the only study to fall within the boundaries of the Amazon basin. Of the studies conducted on streams in Brazil, seven made the distinction between "reduced impact" logging (a.k.a. planned logging) and "conventional" logging (a.k.a. unplanned logging). These studies were also all located in the Capim River Basin, with the different logging (planned vs.

unplanned) being separated by approximately 75 km or more from each other, with the control interspersed amongst the "reduced impact" logging areas.

Several studies found no difference between species richness, composition, beta diversity or local contribution to beta diversity when comparing fish in unlogged forest and logged forest [135,136]. Though in French Guiana there were lower numbers of phytophagous species encountered in streams in logged forest [137]. Also, in Brazil there were differences between the ecomorphological structure of fish assemblages in streams where timber harvesting had occurred [138]. Moreover, when evaluating streams with a habitat integrity index that includes various components such as fish cover, stream canopy and dissolved oxygen, there were differences for the controls and all logged areas, planned or unplanned [139], although when analyzing logged streams for chemical differences, turbidity or suspended sediment, none were found [140]. Concerning the potential food source of many fish, aquatic and semi-aquatic insects, there were some impacts from logging. Tolerant semi-aquatic species tended to greater richness and abundance in logged areas [141]. Some species appeared to be only slightly impacted by logging, such as those from the Odonata order, which showed no difference in richness and abundance [142], although another study in the same watershed demonstrated lower diversity for Odonata in logged areas [143]. In some studies, aquatic insect abundance, richness and species composition was not much different between logged areas and controls [144,145]. Logging impacts to aquatic insects were found to be associated with riparian vegetation loss and lower dissolved oxygen [146].

4. Discussion

4.1. Forest

The results of this review demonstrated that impacts from logging activities to the forest site were a direct result of the logging cycle (e.g., how often logging occurs) or logging intensity (e.g., how many trees are felled), and sometimes a combination of both. Heavy logging intensities ($\geq$40 m^3 ha^{-1}) diminished the standing volume of the residual stand enough that recovery of species composition, aboveground C stocks and commercial volumes was not possible in a 30-year logging cycle [72,82,95]. In fact, prior research found that even a logging intensity of $\geq$30 m^3 ha^{-1} was not sustainable over time regardless of the degree to which the logging was planned [147]. Recently, a large-scale evaluation across the Amazonian biome found that even 20 m^3 ha^{-1} was not sufficiently low to recover cut volume [148]. Volume recovery was not the only challenge encountered. Due to slow growth rates, some species were depleted in the initial logging entry, which requires the use of different species than were initially harvested [95]. This is especially apparent with species such as *Manilkara elata* (Allemão ex Miq.) Monach, which can take more than 700 years to reach a commercial cutting size of a 50 cm diameter at breast height [149]. A potential solution to this challenge has been suggested in the form of species-specific diameter cutting limits [150,151]. In some cases, the minimum cutting diameter would increase and in other cases it could decrease, all dependent on the species biological rotation age or maximum current annual increment. Overall, the results of the review agreed with existing research that a lower harvest intensity and longer logging cycle would be more sustainable over time than many current practices of 20–30 m^3 ha^{-1}. Some authors have suggested a harvest of 10 m^3 ha^{-1} with an entry every 60 years as sustainable [23,152,153].

There was a sizable knowledge gap concerning the influence that logging has on subsequent fire behavior in the Amazon, although this may be due to the limited search window of a decade. This lack of recent research is concerning as the frequency and severity of fires have been increasing, especially in El Niño years [154]. In fact, during the 2015–2016 El Niño, forest stands that had been logged in the Brazilian Amazon and subsequently burned, experienced a much higher fire severity than unlogged forest [59]. Moreover, a single fire after logging was shown to increase mortality for at least a decade in regeneration of saplings < 20 cm DBH in the eastern Amazon, although 15 years post-fire, recruitment was higher in burned areas [64]. Nevertheless, the loss in recruitment for even a decade would be detrimental to many slow-growing commercial species and forest management throughout Amazonia, as many cutting cycles are between 20–30 years. There is also the concern of reoccurring fires because if the forest burns once, it is much more likely to burn again, as has been shown in the eastern Amazon [155]. After three to five fires, the majority of pre-existing forest trees were lost in southern Amazonia [54]. Therefore, it is necessary to take into account the potential dynamics of fire activity to the site after the completion of logging operations.

Another issue observed in the literature for the last decade was the challenge posed by the competition of fast-growing pioneer species. Although pioneer species contribute to the aboveground biomass recovery of the stand [11,79], their susceptibility to drought and competition devalues their long-term potential for carbon sequestration [84,148]. Furthermore, the fast-growing, short-lived pioneers fill in canopy gaps at the expense of desirable commercial species, which suppresses their growth [12]. Pioneer species outcompeted shade-tolerant species for years [66]. Even so, there were long-lived pioneers that demonstrated competitive growth rates: *J. copaia* and *Goupia glabra* Aubl. [28,71]. These long-lived pioneer species, as well as others such as *Schizolobium parahyba* var. amazonicum (Huber ex Ducke) Barneby, have the potential to be used in enrichment plantings of gap openings due to their exceptional growth rates [156]. Still, the short-lived pioneer species did play an important ecological role in the rehabilitation of the logging site infrastructure. Many authors observed high concentrations of these pioneer species, especially *Cecropia* spp., on skid trails, secondary roads and landings [21,61,73]. The challenge of the influx of pioneer species is also related to logging cycle and intensity. When the logging intensity is too heavy, there is a "proliferation" of these species into the residual stand [157]. Also, consideration needs to be given to the length of occupancy of the site for the short-lived pioneer species, as some live longer than a 30-year cutting cycle, even up to 50 years [158,159]. Therefore, increases in light from logging disturbance should be limited to increase growth rates of desired species, while at the same time limited to prevent pioneer establishment [160].

4.2. Wildlife

The logging impacts to wildlife throughout the biome varied depending on species, which could be expected. For the avian community, many studies found few differences between logged and unlogged stands. This aligns with previous research that found no difference in the abundance of threatened bird species in the eastern Amazon [161]. Interestingly, the largest raptor in the biome, the Harpy Eagle (*Harpia harpyja*), although not endangered currently, is listed as vulnerable under the IUCN Red List of Threatened Species [162] and there was almost no research on the logging impacts to this species in the last decade. The Harpy Eagle may potentially be susceptible to habitat modification from logging, as this raptor prefers the largest emergent trees for nesting, which are sometimes the commercial trees preferred by loggers [163].

The recent research on the effect of logging on primates was similar to what has been shown in the past. Namely, that some species benefit while others suffer loss. A specific primate species, *Cebus olivaceus*, was only detected one time and only in old-growth forest [121], so it is difficult to know if the scarcity is due to logging. Even so, in Guyana, this species was less abundant in logged areas, whereas other primate species, *Tinamus major* and *Crypturellus variegatus*, increased [164]. In Peru, the primate *Lagothrix poeppigii* also increased in numbers in hunting registries four to seven years after logging began in the area [122]. The research on primates generally focused on presence or absence in various habits rather than on the relationship of the species with the components of the habitat. Knowing the components of the habitat would be beneficial for species preservation. For example, in Bolivia it was determined that only a few of the harvestable timber species actually contributed to nearly 50% of spider monkeys (*Ateles chamek*) diet [165]. For carnivorous mammals, results also showed different outcomes: one positive [120] and one negative [119]. This was possibly due to the difference in harvest intensity, as a low harvest intensity, 2–3 m^3 ha^{-1}, had a significant increase on the area occupied by *Leopardus pardalis* and

Puma concolor in Peru [166]. The impacts to bat communities were also found to be different between logging in Brazil and Guyana. This is potentially due to site differences, as variation between sites can be greater than within the same site even before and after logging [161,167].

The greatest impact from logging on amphibian communities appeared to be the creation of artificial waterbodies in heavy machinery ruts, as well as increased standing water on log landings [124,125]. Due to the extent of skid trail rut creation every year in the Amazon, further studies to ascertain the effect on the food web from increases to the amphibian population are a worthy endeavor. Moreover, in the study of logging impacts on the amphibian population in Bolivia, differences were found between the dry season and the transition period between dry and wet seasons [168]. Seasonal differences were also encountered in the study of dung beetles [130]. Therefore, it is prudent to consider the seasonal influence on the particular species under study in the Amazonian biome when conducting future research.

4.3. Streams

Regardless of whether logging was "reduced impact" or "conventional" (a.k.a. planned vs. unplanned), results indicated that physiochemical characteristics of streams showed a low response to the logging system [140]. Moreover, although there was greater riparian vegetation in planned logging areas than in unplanned, both were still lower than unlogged forest [136,138]. However, overall, planned logging operations had lower assessed impacts to streams [139,142,146]. These lower impacts were likely due to the greater protections afforded to streams in the form of increased buffer strips along streams that help protect overstory canopy [146]. In fact, planned logging resulted in a greater similarity in semi-aquatic species with unlogged forest than with unplanned operations [141]. There were still slight differences encountered in planned logging sites in insect and fish populations [137,144]. These differences between logging systems are likely related to differences in riparian vegetation and canopy affected by the stream protection zone. Unfortunately, there was a general lack of information on stream buffer strips (e.g., stream protection zones), which made comparisons between studies or even sites within the same study challenging. Even stating the law governing widths of protection zones would be helpful, but likely not sufficient. This is because site variability differs, especially in regards to topography. Depending on the topography, side slopes within a riparian buffer strip could cause the protection zone to be far greater than the law. For these reasons, it is important to assess the width of the riparian zone under study and whether or not heavy equipment or felled trees entered the zone when comparing logging systems. However, even when not considering the buffer zones, stream studies can still provide valuable information on the impacts from overall impacts to water quality in the watershed, such as levels of dissolved oxygen, turbidity and suspended sediment.

5. Conclusions

The enormity of forest coverage within the Amazon biome likely precludes a one-size-fits-all logging system. Nonetheless, lower logging intensities of 10–15 m^3 ha^{-1} and longer logging cycles of 40–60 years were projected to cause less damage to the stand, which would help ensure sustainable timber harvests for the foreseeable future. Though this is without taking into account the potential for an increasing frequency and severity of post-logging fire activity. This is where future studies could ascertain best management practices to lower the risk of fire danger to logged stands in Amazonia. Even with sustainable yield, there is still the challenge to maintain the species diversity of commercial species encountered in the stand prior to logging operations. However, with lower logging intensities, retention of the vast array of valuable species becomes more feasible. Moreover, diminished disturbance also afforded greater protections for wildlife and streams. Therefore, prudence suggests minimal alterations to stand structure should be implemented during logging operations to maintain species balance and biodiversity.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f14010081/s1, Supplementary File S1: List of studies included in review.

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