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Review

Managing harvesting residues: a systematic review of management treatments around the world

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Abstract

Dead woody materials are naturally part of the forest ecosystem introduced through the process of tree mortality or intentionally through stand management practices which result in harvesting residues. The management of harvesting residues includes a range of solutions that vary from site to site, from context to context. The purpose of this review is to determine the current state-of-the-art of harvesting residue management treatments at a global scale. Our review indicates that there are few studies that compare residue management and treatment options, considering the variety of impacts and effects that can be generated. This is surprising as residue management affects residue quantity and distribution and is relevant for numerous ecological processes. The retention of fine and coarse residues can generate positive effects and impacts on various aspects of forest ecosystems including (i) biodiversity, by promoting stand regeneration and providing habitats for fauna at different levels; (ii) soil properties, by decreasing the risk of erosion and soil compaction while retaining moisture at ground level; and (iii) soil nutrients, by replenishing C, N, and micronutrient stocks. On the contrary, harvesting residues can provide material for bioenergy production and potentially other fiber industries. The removal of residues can also reduce wildfire risks and dampen insect outbreak dynamics. In this work, we provide a general outline of the role of residues as well as a summary of current management options adopted around the world. The intention of the work is to provide an information base for stakeholders including forest managers and policymakers in identifying and assessing potential alternatives for their current local practices.

Keywords: harvesting residues; artificial intelligence; management; treatments; logging

Introduction

The adoption of sustainable forest management practices is widely considered as the best approach to balance the diverse multifunctional services of forests. Sustainable forest management refers to the application of management practices that aim to obtain products and services from the forest without affecting their capacity and functions, providing future generations the opportunity to do the same (EC 2021; FAO 2020).

One of the valuable functions of the forest is the ability to capture and store carbon in the trees and the surrounding soil (Bauer et al. 2000). Almost half of the total organic carbon in terrestrial ecosystems in the world is stored in forest soils (Lal 2005; Mayer et al. 2020). Soil carbon storage is a result of the balance between inputs of organic matter and the outputs due to leaching, decomposition, and erosion of organic matter. The main source of organic material input includes decomposing deadwood and woody materials found in the litter layer (Mayer et al. 2020).

Deadwood and woody materials are naturally introduced to the forest floor through the process of tree mortality and litter fall (Merganičová et al. 2012), or intentionally introduced through stand management practices, such as leaving residues after timber harvesting, pre-commercial thinning, or forest restoration treatments (Harmon et al. 1986; Harmon and Sexton 1996). Harvesting residues can be defined as woody materials left in the forest after timber harvesting or stand management treatments. This might include minor components such as leaves, twigs, and bark, as well as more substantial tree elements including branches, treetops, and even stumps and roots (Titus et al. 2021), resulting in a variety of forms and quantities (Harmon and Sexton 1996). In addition, non-merchantable materials resulting from salvage logging after various disturbance events, such as fire, windstorm, diseases, and insect infestation, can also be considered as residues (Riffell et al. 2011). Various terms exist for referring to harvesting residues, such as "forest residues," "harvesting residues," "woody debris," and "slash."

The quantity, composition, and distribution of harvesting residues varies greatly with the harvesting systems, machine configurations, and stand management treatments employed (Huber et al. 2017). Moreover, the occurrence of extreme natural disturbance events (e.g. high-severity fires or windthrows) plays an important role in shaping the dynamics of organic material input (Lindner et al. 2010). The expansion of forest disturbance areas due to more frequent disturbance events induced by climate change may lead to an increase in salvage logging and corresponding increased quantities of harvest residues. In this

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Table 1. Search string used for selecting publication records.

TITLE-ABS-KEY((“harvest residue” OR “harvesting residue” OR “harvesting residues” OR “logging residue” OR “logging residues” OR “slash” OR “woody residue” OR “woody residues”) AND NOT (“slash pine” OR “slash-pine” OR crop OR agr)) AND TITLE-ABS-KEY (management OR treatment*)*

context, environmental concerns have been raised, including potential risks of soil degradation (Labelle et al. 2022) and the loss of nutrients, carbon, and stand productivity (Valipour et al. 2021).

Residues are an important reservoir of carbon, nitrogen, and various nutrients unique to local tree species and sites. From an ecological perspective, harvesting residues including branches, tops, and stumps with root systems, along with pre-existing deadwood, serves as significant sources of macronutrients (e.g. nitrogen, phosphorus, calcium, magnesium, and potassium) (Janowiak and Webster 2010) that are important for the establishment of future stands (Bače et al. 2012; Motta et al. 2006; Zielonka and Niklasson 2001). Certain harvest residues, such as leaves, cambium, and root tips, contain disproportionately large nutrient quantities compared to tree stems (Janowiak and Webster 2010; Palviainen et al. 2010). Yet, only a few examples of guidelines pertaining to the management of harvesting residues from forest operations are available.

According to Titus et al. (2021), there are 32 guidelines available covering countries, provinces, and regions in North America, Europe, and East Asia. Most of the guidelines primarily focus on the removal of residues after final felling operations; however, they often lack a precise definition of what constitutes residues. Some of them include (e.g. whole-tree thinning for Austria, Denmark, and Finland) or exclude harvesting residue treatments (e.g. whole-tree chipping in New Brunswick, Canada). While many of these guidelines were designed to address a wide range of environmental sustainability issues (e.g. water, biodiversity, soil, and carbon) and public concerns and interests (e.g. aesthetics, recreation, and the preservation of cultural and historical sites), there is a lack of a comprehensive science-based perspective regarding the benefits and drawbacks of managing harvesting residues.

The objective of this article is to conduct a systematic review of the current state-of-the-art of harvesting residue management and practices on a global scale. Through this analysis, this review seeks to provide an overview on the benefits and drawbacks associated with the existing management practices concerning forest harvesting residues around the world.

Methods

Database and search process

A systematic review was performed following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement, a protocol designed for systematic reviews and meta-analysis to help in the reporting of information in a transparent way through the means of detailed checklists (Page et al. 2021). Our review exclusively concentrated on scientific literature; thus, we conducted searches for published research papers using the Scopus and Web of Science databases. After a series of trials and iterations, we adopted the final search string, as shown in Table 1. We selected previous studies concerning forestry that included keywords within the title, abstract, or keywords section, provided they met the following criteria: (i) peer-reviewed articles; (ii) relevance to subject areas, such as “Agricultural and Biological Sciences,” “Environmental Sciences,” or “Engineering”; (iii) being written in English.

Each publication record was then screened to identify exact matching keywords and synonyms related to forest residue and management activities as found and used in the literature. These were logging residues, harvest residues, logging (forestry), woody biomass, timber harvesting, forest residue, coarse woody debris, biomass harvesting, slash management, slash, woody debris, dead wood, forest harvesting, fuelwood, forest biomass, debris, and harvest residue management. It is widely acknowledged that fine woody debris typically refers to logging residues with a diameter <8 cm, whereas coarse woody debris refers to those with a diameter >8 cm (Brown 1974; Woodall and Monleon 2008). In this paper, all these various terms will be collectively referred to as “residues” or “harvesting residues.”

Analysis, synthesis, and reporting

The total output of the search phase resulted in 436 papers from the Scopus database and 305 from Web of Science database, for a total of 741 (25 February 2023). After this, the returns have been saved and exported in an Excel spreadsheet also containing information related to author names, title, year of publication, source title, DOI, abstract, keywords, and source (either Scopus or Web of Science). Figure 1 is the flowchart of the PRISMA statement used to identify the included studies. The results were filtered and checked for duplicates (58) resulting in 683 unique papers. We then further selected papers from this according to the following steps:

- Initial pool of 683 after duplicate control.
- Titles and abstracts were first checked to ensure that the topic of the article was related to forest harvest residues and/or their management. We narrowed down the number of studies by excluding studies mainly related to life cycle assessment and modeling (477 excluded).
- From the remaining records (206), the full articles were read and screened. The main exclusion criteria were the availability of quantitative data related to residue estimations or information on management strategies and techniques. From this group, an extra set of studies have been excluded after the reading of the full text (11).
- Finally, we added two more relevant papers we identified after the initial search, bringing the total number of records in the working database to 197.

The selected research papers were then categorized by topics to facilitate the synthesis and discussion of their content. To achieve this, text mining and analytics techniques were developed and employed using KHCoder 3, an R-based software (Koichi 2016, 2017a, 2017b). These techniques involve the analysis of unstructured information, extracting quantitative data and numeric indices. They have the potential to yield high-quality and relevant results while providing insights for interpreting the textual content. The text mining processes developed for this study comprise the following four steps:

- Lemmatization and tokenization: Abstracts underwent a lemmatization and tokenization process to extract individual words and calculate their frequency of appearance.

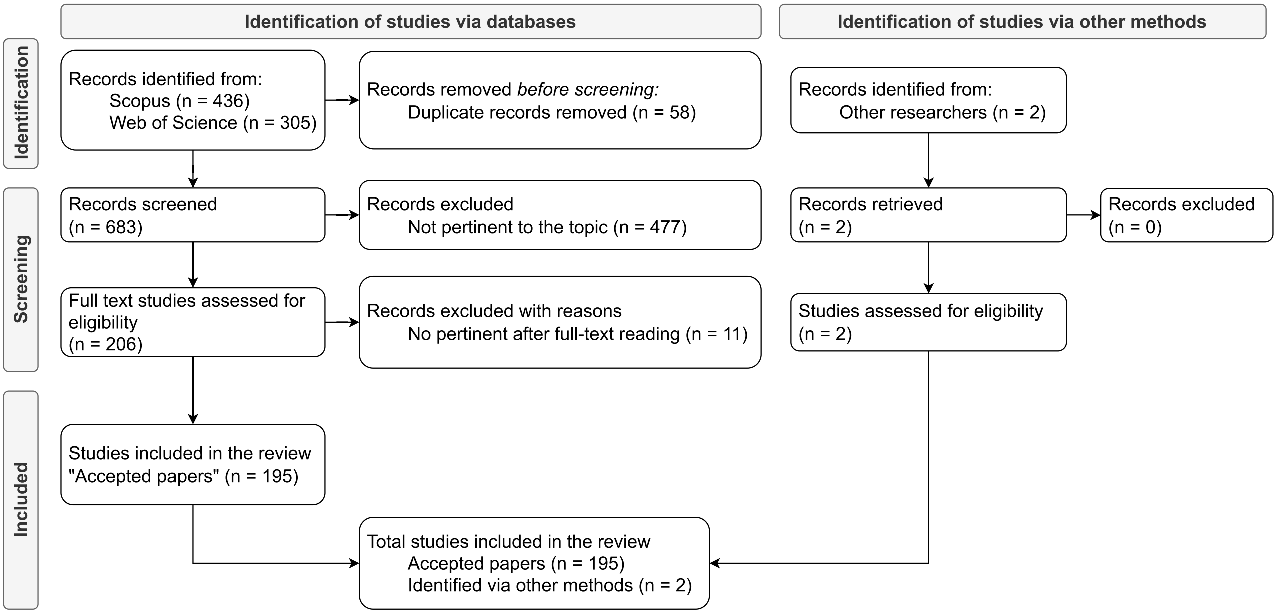

Figure 1. Flowchart of the research paper selection process for review, adapted from the PRISMA 2020 guidelines.

Table 2. Example of question used to inquiry the AI bot.

Assign the following papers to one of these categories: Plantation-Energy, Biodiversity, Fire, Carbon, Soil-Erosion.
[List of papers. Example:]
[1. Zaninovich S.C.; Fontana J.L.; Gatti M.G. Atlantic Forest replacement by non-native tree plantations: Comparing aboveground necromass between native forest and pine plantation ecosystems
2. . . .]

- Extraction of compound words: Following text cleaning to remove stop words, numbers, and punctuation, compound words were identified based on close context appearance in the target text (e.g. harvesting residues, slash piles, etc.). The occurrence frequency for these compound words was also recorded.
- Latent Dirichlet Allocation (LDA) modeling: The corpus of words was then modeled using a LDA model to identify patterns among words that co-occur frequently and exhibit similarity, therefore extracting themes or topics.
- Topic visualization: To visualize the distribution of words according to the identified topics, we created a co-occurrence network of words.

Based on the frequency of the words for each topic, several topics emerged related to the application of harvesting residue treatments and their effects and impacts. The identified studies were categorized accordingly (Table 3). A significant portion of the selected and analyzed papers engaged in multidisciplinary studies, integrating knowledge from various subjects and exploring problems from diverse perspectives. Consequently, further categorizing the papers into subtopics was not conducted as it was deemed unnecessary.

Table 3. Categorization of the identified studies according to the networking of words from KH Coder and the use of ChatGPT.

Topic	Number of studies	Label
1	40	*Energy-Plantation*
2	61	*Biodiversity*
3	22	*Fire*
4	74	*Soil-Nutrients*
Total	197	

In addition, we engaged an Artificial Intelligence bot (OpenAI GPT-3.5, also known as ChatGPT) to categorize the selected research papers into the topics identified through text mining. The AI was queried multiple times (Table 2) and fed each time with eight excerpts constituting the authors and title of research papers. The selected number of eight excerpts for each query was considered optimal in ensuring that the bot functioned without distorting information or overloading the system capacity. After categorization, the bot was also requested to retrieve the location of the trials in the study.

Finally, we recorded the harvesting system, stand management treatment, and residue treatment for each paper, and organized the data in a tabular format.

Results

Database search

A total of 197 studies related to harvesting residue management and treatments were identified. The text mining networking, as depicted in Fig. 2, helped to identify five categories including (i) *Plantation-Energy*, (ii) *Biodiversity*, (iii) *Fire*, (iv) *Carbon*, and (v) *Soil-Erosion*. Next, through ChatGPT, the studies were categorized as reported in Table 2. To assess the performance of the AI, we went through the full text of each study and assigned each one to a category, with an agreement of 87% if compared to the categorization produced by the AI, changing only 26 studies. In this phase, the

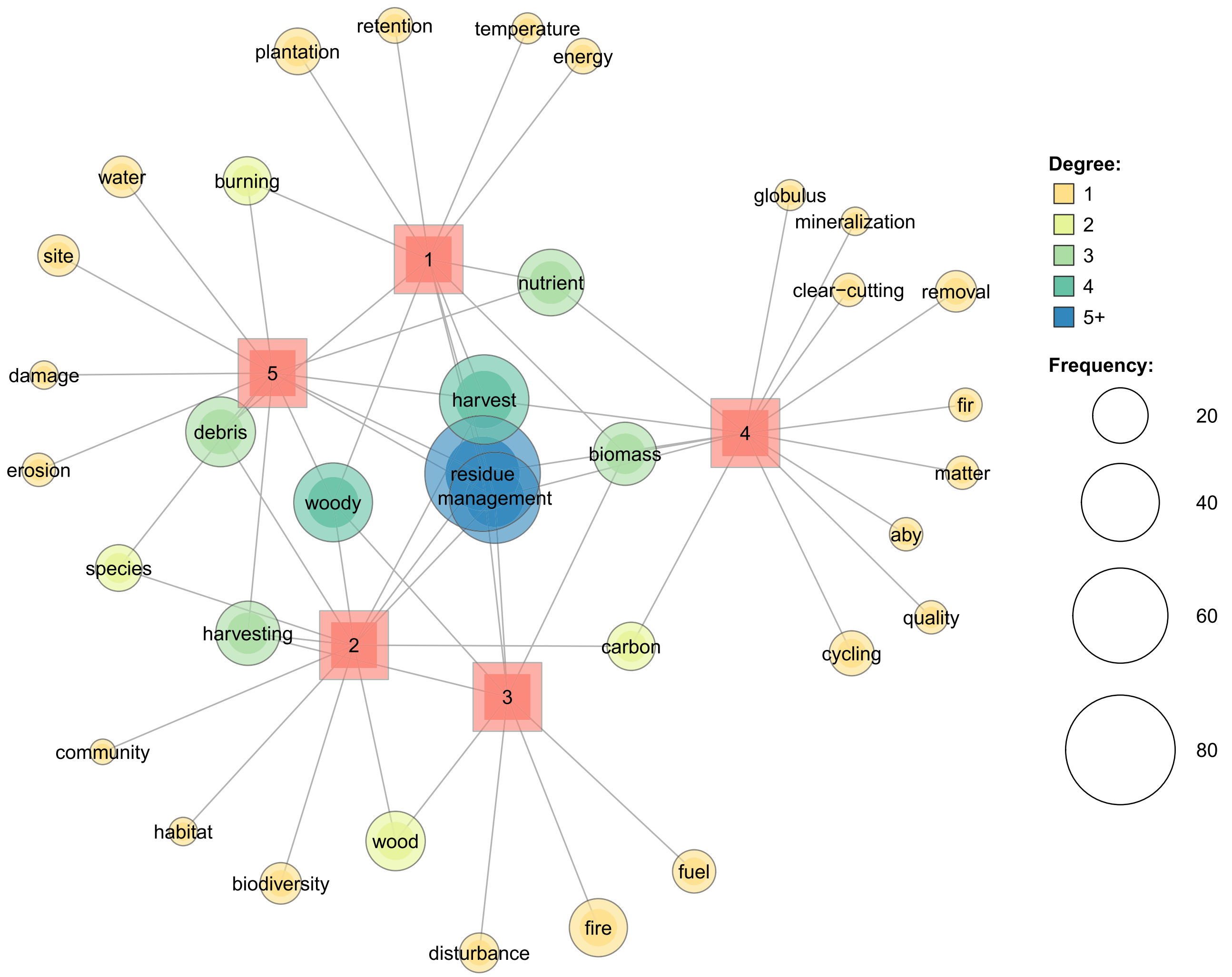

Figure 2. Visualization of the networking of words using KH Coder around the 5 identified topics (showed in the boxes).

categories were reduced to four by joining *Carbon* and *Soil-Erosion* into *Soil-Nutrients* because of the overlapping information reported in the studies falling into those categories.

Figure 3 illustrates the regional distribution of the accepted papers and their topics based on the study areas identified using ChatGPT. The AI bot's performance was assessed by verifying the information in the studies, resulting in a 91% accuracy (i.e. 180 out of 197 papers were correctly identified for their study region).

The review and analysis of the papers revealed the emergence of three main harvesting systems, with varied levels of mechanization. These systems range from full-mechanized to semi-mechanized systems, encompassing at various degrees ground-based vehicles, such as harvesters, forwarders and skidders, and cable-based systems involving motor-manual felling and cable yarders.

Harvesting systems involve a sequence of operations, including felling, processing, and extracting logs to a landing area for subsequent transportation to a mill facility. In terms of harvesting residues, the distinction among these systems is based on where the residues are generated. We have classified harvesting systems into the following three categories based on the location of residue production. Moreover, the number of studies that consider the harvesting system is also reported, considering that a single study can present more than one harvesting system.

- Cut-to-length (CTL): Trees are felled, delimbed, topped, and cross-cut into logs at the stump. In some regions, particularly in eucalyptus plantations and in spruce stands in mountainous forests, trees may also be debarked at the stump. Only the logs are then extracted from the forest stand, resulting in the dispersal of harvesting residues throughout the stand (reviewed studies $n = 5$).
- Full-tree (FT) or whole-tree harvesting: Trees are felled and extracted with their branches and tops to the roadside, where the processing operations take place. This results in an accumulation of residues in piles or rows at the roadside that can be either left or chipped and transported away ($n = 30$).
- Tree length or stem-only harvesting (SOH): Trees are felled, delimbed, and topped at the stump before being extracted to the roadside. Only the stems are extracted, resulting in the dispersal of harvesting residues throughout the stand ($n = 25$).

Further manipulation of harvesting residues may be practiced based on stand treatment and residue management objectives. For example, more residues may be produced through "fuel-adapted" CTL operations (Strandgard and Mitchell 2019), while excessive residues that resulted from CTL may be mechanically collected and disposed for ground fuel reduction purposes.

Based on our analysis of selected papers, stand management treatments were classified into four categories, ranging from clearcutting to salvage logging.

- Clearcutting: a logging practice that involves the uniform cutting of most or all trees in a forest stand or harvest unit ($n = 55$).

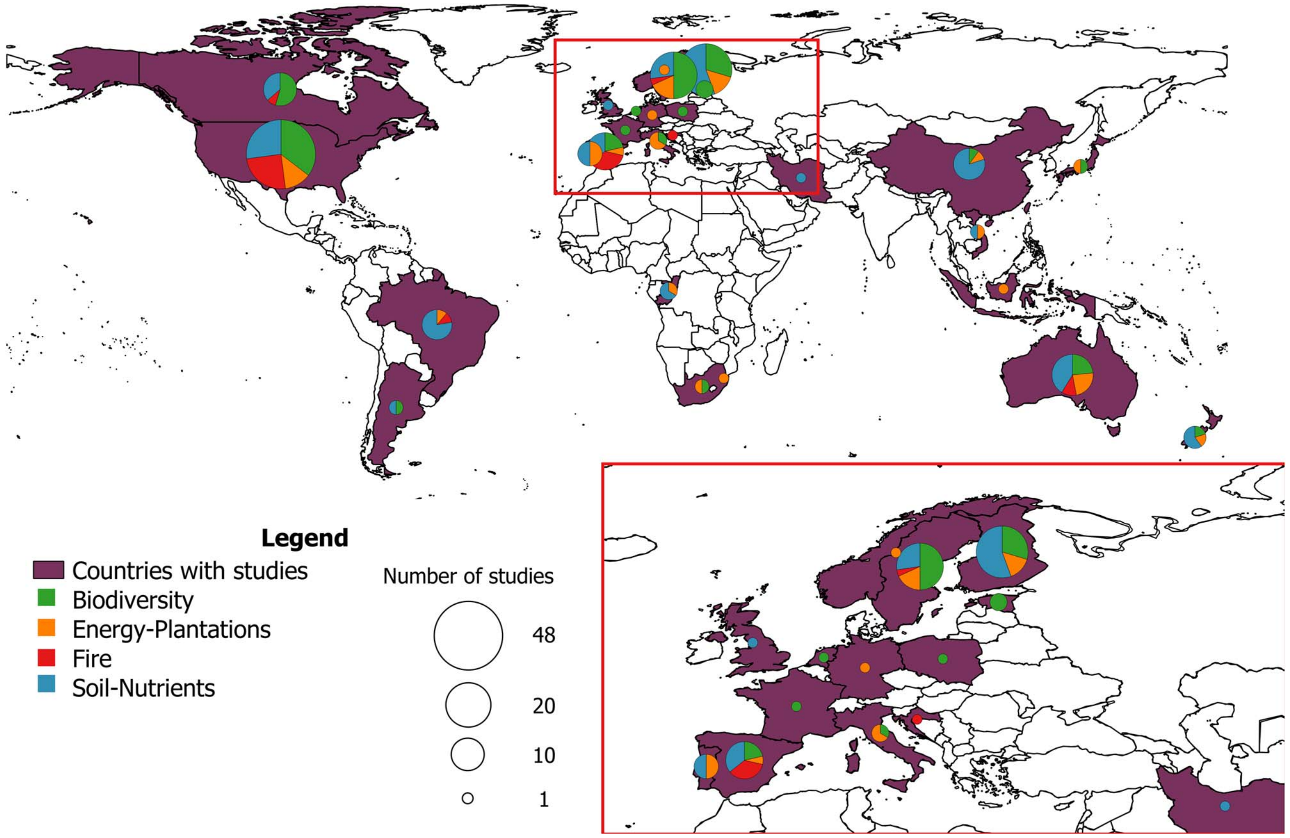

Figure 3. Regional and topical landscape of analyzed studies.

- Thinning: a selective tree removal practice to improve the growth rate, quality, or health of the remaining trees (*n* = 27).
- Shelterwood cutting: a progression of cuttings leading to the establishment of a new cohort of seedlings before the removal of the mature trees (*n* = 2).
- Salvage logging: This practice involves the removal of damaged trees from disturbed forest areas to minimize the loss of commercial timber (*n* = 10).

Furthermore, harvesting residue treatments were classified into the following four categories, which may or may not be integrated with the stand management treatments described above.

- Burning: This category includes different burning practices, such as slash pile and burn and prescribed burn. Slash pile and burn involves hand or mechanical piling of slash after stand management treatment either throughout the stand or at the log landing, and burning the piles when weather permits. Prescribed burn, on the other hand, typically involves burning harvesting residues while they are still scattered across the stand. These practices are often used to reduce the risk of wildfires (*n* = 52).
- Litter treatment: This treatment involves the removal or addition of litter (or forest floor) cover materials to the site (*n* = 37).
- Residue management: This category encompasses general practices related to the removal or introduction of residues after a cutting operation (*n* = 37).
- Conversion to bioenergy and bio-based products: This category includes various utilization methods for harvesting residue piles, focusing on their process, transportation, and conversion into bioenergy or bio-based products, including the studies focused on "fuel-adapted" methods (*n* = 5).

Impacts and effects of residue treatments

While the terms "impacts" and "effects" are often used interchangeably, we use them distinctly carrying different meanings in the context of specific actions or phenomenon. In this paper, "Impact" refers to the influence of an action or phenomenon on something, whereas "effects" refer to the consequences or outcomes of such actions or phenomena. For example, in the context of this study, residue management treatments produce an impact in terms of residue quantity and distribution, while simultaneously resulting in multiple effects on biodiversity, soil, nutrients, and other factors.

Biodiversity (n = 61)

Forest harvest residues are related to various facets of forest biodiversity. In general, residues provide crucial habitats for various species, including insects, fungi, small mammals, and birds, and also serve as fodder, leading to a complex ecological network. Dead woody debris, for instance, serves as a substrate for fungi and provides nesting sites and food sources for insects and birds. Moreover, residues' presence influences ecological succession processes, providing the initial substrate for new plant growth, facilitating the regeneration of forests, and supporting the establishment of diverse plant communities.

The identified studies contribute to show how the use of different harvesting systems and stand management techniques, each generating different residues quantities, results in different effects on vegetation, plant, and animal communities. Similarly, different residue treatments can yield different effects and impacts. A synthesis of impacts is reported in Table 4, including the considered studies.

Table 4. Summary of impacts assessment for papers in the Biodiversity category

	Action	Impact	References
Plant, vegetation, and fungal communities	Harvesting system		
	• Full-tree	↓↓	(Hamberg et al. 2019; Zaninovich et al. 2016)
	• Stem-only	↑↑	
	Stand management		
	• Clear-cut	↓↓	(Gibb et al. 2007; Lõhmus et al. 2013; Lombardi et al. 2008; Lutze and Faunt 2013; Omari and Maclean 2015; Rabinowitsch-Jokinen et al. 2012; Siitonen et al. 2000; Trottier-Picard et al. 2016; Tullus et al. 2019)
	• Shelterwood	↑	
	Residue treatment		
	• Burning	↑↓	(Béland et al. 2011; Caruso et al. 2008; Dickinson and Kirkpatrick 1986; Fornwalt et al. 2018; Hansson 2006; de Jong and Dahlberg 2017; Langvall et al. 2001; Law and Kolb 2007; Majdi et al. 2008; Olsson and Kellner 2002; Peter and Harrington 2018; Premer et al. 2016; Puerta-Piñero et al. 2010; Rabinowitsch-Jokinen and Vanha-Majamaa 2010; Scherer et al. 2000; Selmants and Knight 2003; Stoddard et al. 2008; Suominen et al. 2019; Tarvainen et al. 2020; Toivanen et al. 2012; Vega et al. 2008; Yamashita et al. 2014)
	• Residue management	↑↑	
	• Fuel harvesting	↓	
Small animals	Stand management		
	• Clear-cut	↓↓	(Andringa et al. 2019; Collier and Bowman 2003; Grodsky et al. 2018a, 2018b; Grodsky et al. 2020; Gunnarsson et al. 2004; Lassauce et al. 2012; Michaels and Bornemissza 1999; Mlambo et al. 2019; Molinas-González et al. 2019; Nadeau et al. 2015; Rousseau et al. 2018; Wang et al. 2022a)
	Residue treatment		
	• Residue management	↓↓	(Castro and Wise 2009; Edenius et al. 2014; Fettig et al. 2013; Fritts et al. 2017; Govender 2014; Grodsky et al. 2018a, 2018b; Grodsky et al. 2020; Hayes et al. 2008; Hedin et al. 2008; Kacprzyk 2012; Klepzig et al. 2012; Lassauce et al. 2012; Nadeau et al. 2015; Nittérus et al. 2007; Oblinger et al. 2011; Six et al. 2002; Sullivan and Sullivan 2018; Zolotarjova et al. 2016)
	• Fuel harvesting	—	
Mammals	Residue treatment		
	• Residue management	↑↓	(Edenius et al. 2014; Fritts et al. 2017; Sullivan and Sullivan 2018)
	• Fuel harvesting	—	

The impact was classified as follows: "↑", a positive impact; "↓", a negative impact; "—", negligible or no impact.

Plant, vegetation, and fungal communities

When it comes to plant and vegetation communities, considering harvesting systems and stand management, FT harvesting has been found to have more impact than SOH on understory vegetation due to the removal of larger residues, altering nutrients and carbon cycling, posing potential risks to plant biodiversity. In uneven-aged silvicultural systems, where residues are retained from harvesting operations to improve structural diversity and replicate the characteristics of overmature and mature stands, a higher level of species diversity is present. For example, shelterwood cutting has been shown to have a positive impact on the richness and diversity of vascular plants and bryophytes in Scots pine (*Pinus sylvestris* L.) forests in Estonia (Tullus et al. 2019). On the contrary, clearcutting and removal of harvesting residues have significantly negative effects on understory vegetation.

Considering residue treatments, performed after harvesting operations, residue burning (either in pile or prescribed burning) has been observed to temporarily reduce plant cover and diversity in the short term. However, if implemented with techniques such as woodchip mulching and soil scarification on burning scars, these have been shown to reduce the recovery period of plant communities (e.g. Fornwalt et al. 2018). Over a longer period of observation, residue treatments such as pile-and-burn, chopping, and lop-and-scatter, applied after clearcutting, have shown the potential to yield positive effects on the understory plant community (e.g. Selmants and Knight 2003). Moreover, if applied after burning, mechanical treatment increases the recruitment of seedling for certain tree species, such as maritime pine (Vega et al. 2008) and oak (Puerta-Piñero et al. 2010).

Slash retention or removal can lead to both positive and negative effects on the herbaceous layer. In a study conducted in northern Arizona, the removal of residues increased plant cover and species richness (Stoddard et al. 2008), while research in Montana suggested that leaving residues on the ground could help maintain or enhance understory vegetation diversity and productivity (Scherer et al. 2000). The retention of residues plays an important role in promoting seedling establishment and growth in disturbed ecosystem (e.g. Law and Kolb 2007).

The effects of fuel harvesting, i.e. the removal of coarser debris and stumps for bioenergy production, have been more investigated on fungal diversity and lichen communities, with most results being species and site specific (*cf*. Majdi et al. 2008; Suominen et al. 2019). Overall, this practice tends to favor more resilient species compared to generalist species (Tarvainen et al. 2020; Toivanen et al. 2012; Yamashita et al. 2014). The retention of stumps tends to favor more lichen communities compared to slash left on site (Caruso et al. 2008; Olsson and Kellner 2002).

Small-animal communities

For small-fauna biodiversity, the effects of clearcutting coupled with the removal of harvesting residues have been extensively investigated. Many previous studies indicated negative effects on the abundance and diversity of insect communities, mesofauna, and microbial communities. It is noteworthy, however, that the extent of these impacts can vary based on forest type and stand regeneration practices employed. The burning and removal of deadwood negatively influences soil macro-arthropod communities, reducing their abundance and diversity; this was observed in southeast Spain by Molinas-González et al. (2019).

Residue harvesting, as a removal treatment, has been found to reduce beetle populations, but with mild impacts on their species diversity (e.g. Zolotarjova et al. 2016). In contrast, other studies have shown that residue removal after clearcutting could significantly affect diversity and community composition of certain ground-beetle species (e.g. Govender 2014; Nittérus et al. 2007).

In contrast to residue removal, the retention of residues can generate preferential habitats for diverse communities, depending on the characteristics of the residues (i.e. type, size, and degradation phase). Residue retention particularly favors communities with an essential role in material degradation, such as ground-beetle species (Grodsky et al. 2020), saproxylic beetles (Lassauce et al. 2012), and Coleoptera species (Nadeau et al. 2015), but also other animal groups such as spiders (Castro and Wise 2009) and invertebrates (Andringa et al. 2019). Conversely, the retention of residue material can also act as a hot spot for insect infestations, such as saproxylic beetles, for oak stands (Hedin et al. 2008), or bark beetle species, such as the northern spruce engraver beetle (*Ips perturbatus* Eichhoff) in interior Alaska (Fettig et al. 2013), and pine engraver beetle (*Ips pini* Say) in northern Arizona (Hayes et al. 2008) and Montana (Six et al. 2002).

Mammal communities

Communities of larger animals, such as mammals and birds, tend to be more influenced by residue treatments compared to stand management treatments and harvesting systems. Specific configurations of residues favor certain fauna families; linear arrangements similar to traditional windrow structures can provide habitat for small mammals (Sullivan and Sullivan 2018). When retained in high volume, they may also improve forage availability, leading to potential increase in ungulate populations (Edenius et al. 2014).

From the reviewed studies, several limitations can be deducted regarding the possibility of studying the relationship between forest harvest residues and biodiversity, including

i. Spatial and temporal variation: Biodiversity patterns can vary spatially and temporally within forests, making it challenging to generalize findings across different locations and time periods. Many studies are limited in scope and may not capture the full range of variation present in natural ecosystems.
ii. Scale: The scale at which studies are conducted can influence results. Some studies may focus on small-scale plots, while others examine larger landscapes. This variation in scale can affect the detection of biodiversity patterns and may lead to differing conclusions.
iii. Methodological differences: Studies often employ different methodologies for measuring biodiversity, making comparisons between studies difficult. Variations in sampling techniques, taxonomic resolution, and data analysis methods can influence results and hinder the synthesis of findings.
iv. Confounding factors: Forest ecosystems are influenced by multiple factors besides harvest residues, such as climate, soil conditions, and management practices. Untangling the effects of residues from other variables can be challenging and may require complex statistical approaches.
v. Short-term studies: Many studies have a short-term focus, providing insights into immediate responses of biodiversity to changes in residue management. However, long-term studies are needed to understand the full implications of residue management practices on biodiversity dynamics and ecosystem functioning.
vi. Limited taxonomic coverage: Some studies may focus on specific taxonomic groups, such as birds or insects, while neglecting other components of biodiversity. This limited taxonomic coverage can lead to incomplete assessments of biodiversity responses to residue management.
vii. Publication bias: There may be a tendency for studies with significant or positive results to be published, while studies with null or negative findings may remain unpublished or overlooked. This publication bias can skew the overall understanding of the relationship between residues and biodiversity.

Soil-nutrients (n = 74)

With regard to soil, most of the reviewed studies underscored the correlation between alterations in soil physical properties and nutrient availability, yet did not necessarily explore the reciprocal relationship, as influenced by fertilizer application, for example. Soil physical properties are characterized using e.g. texture, structure, bulk density, porosity, consistency, temperature, color, and resistivity (Gardner et al. 1999). These are deeply linked to nutrient availability and the suitability of soil to grow either grass vegetation or trees. In general, the retention of residues after harvesting operations has been shown to reduce soil erosion processes and to mitigate nutrient losses, especially in the case of salvage logging. However, in particular cases like after large disturbances such as high-impact wildfires, the retention of material alone was proven to not be effective. Most impacts and effects presented in the literature tend to be site specific and differ based on tree species present, local climatic and site conditions, and background prior to harvesting. These findings are reflected in several best-management practices available also in the scientific literature (e.g. McClure et al. 2004; Garren et al. 2022). In this case, from the analysis of the literature, we were able to define two main areas of interest including relationships between harvest residues and soil physical properties, and soil nutrient availability, especially carbon, nitrogen, and micronutrients. Within this last area, a focus was put into effects on stand growth and productivity. The impacts are summarized in Table 5.

Impacts on soil physical properties

The adoption of harvesting systems, machine configurations, and residue treatments (i.e. retention or removal) can alter the soil properties over both short- and long-term periods. When ground-based machines are involved, the retention of residues helps to reduce soil erosion, regardless of the technique adopted. Among different post-harvesting treatments, in the case of SOH compared to FT harvesting, the dispersion of slash helps to reduce soil erosion (Fernández et al. 2004) and soil temperature, maintaining soil moisture even at microsite levels (Devine and Harrington 2007). In the case of ground-based logging operations in recently burned areas, there are no major differences in the choice of machinery (i.e. feller-bunchers, skidders, and forwarders) in terms of soil compaction and increased soil water repellence in the short and mid-term (Wagenbrenner et al. 2016). Eventually, the retention of woody material of logging trails can help to reduce sediment production and erosion without any additional effects on the recovery of soil properties (Labelle et al. 2022).

In clear-cut areas, the retention of loose coarse woody debris results in reduced soil disturbance and increased moisture; however, these effects are jeopardized by the use of heavy machinery (Halpern and McKenzie 2001). In the case of salvage logging, the retention of residues can effectively reduce erosive processes of

Table 5. Summary of impacts assessment for papers in the Soil-Nutrients category.

	Action	Impact	References
Soil physical properties	Harvesting system		
	• Full-tree	↓↓	(Devine and Harrington 2007; Egnell and Leijon 1999; Fernández et al. 2004; Kaarakka et al. 2014; Wagenbrenner et al. 2015, 2016; Zabowski et al. 2000)
	• Stem-only	↑↑	
	Stand management		
	• Clear-cut	↓	(Fernández et al. 2007, 2008; Guo et al. 2010, 2016; Prats et al. 2019; Robichaud et al. 2020)
	• Salvage logging	↓↓	
	Residue treatment		
	• Burning	—	(Van Bich et al. 2020; Edeso et al. 1999; Fernández et al. 2004; Halpern and McKenzie 2001; Mazri et al. 2020; Prats et al. 2017; Tarvainen et al. 2015; Thomas et al. 2000; Trindade et al. 2021; Walmsley and Godbold 2010; Wang et al. 2022b)
	• Litter treatment	↑	
	• Residue management	↑↑↓↓	
	• Fuel harvesting	—	
Soil nutrients	Harvesting system		
	• Full-tree	↓↓	(Adamczyk et al. 2015; Avera et al. 2020; Garrett et al. 2021a, 2021b; Kiikkilä et al. 2014; Maillard et al. 2019; Palviainen and Finér 2012; Rocha et al. 2019; Webster et al. 2021; Wu et al. 2014; Zhu et al. 2020)
	• Stem-only	↑	
	Stand management		
	• Clear-cut	↓↓	(Hedwall et al. 2013; Hyvönen et al. 2016; Olsson et al. 1996; Ouro et al. 2001; Repo et al. 2020; Smolander et al. 2013, 2019; Törmänen et al. 2018, 2020)
	• Thinning	↑	
	Residue treatment		
	• Burning	↓↑	(Adamczyk et al. 2016; Blumfield and Xu 2003; Eisenbies et al. 2009; Fernández et al. 2009; Ferreira et al. 2016; Garrett et al. 2021a, 2021b; Gómez-Rey et al. 2008a, 2008b; Homyak et al. 2008; Huang et al. 2013; Iwald et al. 2013; Jones et al. 2011; Jurevics et al. 2016; Lacey and Ryan 2000; Mathers et al. 2003; Mendham et al. 2003; Menegale et al. 2016; Moore et al. 2021; Numazawa et al. 2017; Pitman and Peace 2021; Pu et al. 2002; Roberts et al. 2005; Smolander et al. 2010, 2008, 2015; Souza et al. 2016; Staaf and Olsson 1991, 1994; Strukelj et al. 2018; Xiang et al. 2009; Yang et al. 2005; Zhang et al. 2018)
	• Residue management	↓↑	
	• Fuel harvesting	—	

The impact was classified as follows: "↑", a positive impact; "↓", a negative impact; "—", negligible or no impact.

the soil and sediment production on skid trails (Prats et al. 2019). However, in the case of highly damaged ecosystems, such as after a wildfire, residue retention alone was found not effective in reducing soil degradation and erosion.

In plantations, residue burning has limited effects on bulk density in the short term, with the exception of a small decline in potassium (Van Bich et al. 2020), but resulted in better growth in following rotations compared to residue retention (Lacey and Ryan 2000). In countries where residues and stumps can be also harvested for bioenergy production, such as northern European countries, the impacts of these operations on forest soils and soil properties have been well documented (Walmsley and Godbold 2010); e.g. soil respiration decreases in the short term, but recovers within a year.

Impacts on soil nutrients: carbon, nitrogen, and micronutrients

In general, it is well known that fine woody residues, i.e. buds, foliage, and small branches together with small roots, are the tree component with the highest concentration of nutrients (e.g. N, P, Ca, Mg, and K), while C accumulates in coarser elements, such as the trunk, branches, and roots. Therefore, the size and type of residual material left after the harvesting is important in determining the nutrient quality and quantity that will be available in the soil in the future. However, residue management treatments can exhibit notable variability in available nutrients, with identical actions yielding disparate outcomes, or divergent approaches leading to similar results. For example, soil acidification, i.e. the excessive presence of nitrogen in the soil, can be triggered by either residue retention (Pu et al. 2002) or removal (Iwald et al. 2013; Staaf and Olsson 1991) depending on the site and context. More to that, it is difficult to assess the impacts of management over a single nutrient since studies in the literature seldom focus only on one single component (e.g. carbon) but rather provide information on multiple components, e.g. C and N or several nutrients at once.

Regarding the influence of harvesting system on nutrient availability, researchers have explored both the application of harvesting systems alone and integrated with residue treatments. In general, the intensive removal of residue in plantations, regardless of the tree species considered—either via the adoption of FT systems, also integrated with litter removal, or through the collection of woody material after the harvesting—negatively impacts nutrient availability (Eisenbies et al. 2009; Hedwall et al. 2013; Rocha et al. 2019). The adoption of a SOH approach with evenly distributed residues over the area decreases nitrogen cycling and losses (Smolander et al. 2019). In the long run, the differences on soil C and N storages generated by FT and SOH were reported to be not significant, but the harvest intensity plays a major role on N quantities at site level (Olsson et al. 1996).

The effects and impacts of stand management techniques were not clearly investigated in the literature, being mostly associated with residue treatments or considered with harvesting systems. For example, the harvesting of a plantation stand often implies a clear-cut scenario; in this case, the clear-cut combined with slash and stump removal has a negative impact on nutrient availability and, more specifically, on soil carbon and nitrogen stocks over long time periods (Hyvönen et al. 2016; Repo et al. 2020).

Debating about residue treatments, the burning of residues has negative impacts on nutrients; in particular, it accelerates C losses (Kranabetter and Macadam 2007) and nutrient leaching (Jönsson and Nihlgård 2004). The impact of the removal of coarser material, such as slash and stumps, is a subject of debate in the literature, especially when it comes to carbon and nitrogen stocks; overall, over a long period of time the effects of the removal seem to be insignificant (Jurevics et al. 2016; Zhang et al. 2018). However, in the short term, the removal of logging residues can lead to a significant decrease in organic matter and nutrient inputs, in particular C and N, accelerating the mineralization and losses of soil C and N (Adamczyk et al. 2016; Smolander et al. 2008). The retention of residues, either chipped or in slash, has been shown to have positive effects on the rate of carbon and nitrogen cycling in the soil, as well as on the quantity and quality of soil organic matter inputs (Homyak et al. 2008; Mathers et al. 2003; Smolander et al. 2010). Again, the retention of residues seems to have larger positive impacts in the short term between the harvesting and the planting, reducing N losses (Blumfield and Xu 2003). In the long term, the decomposition of retained residues increases nutrient availability for plant uptake.

Some key limitations retrievable from the studies investigating the relationship between forest harvest residues and soil physical properties and nutrients comprise the following:

i. Short-term studies: Many studies have a short-term focus and may not capture long-term changes in soil properties and nutrient dynamics resulting from residue management practices. More long-term studies are needed to assess the cumulative effects of residues on soil fertility and health over time.
ii. Variability in residue characteristics: Forest harvest residues vary in their chemical composition, decomposition rates, and spatial distribution, which can influence their effects in particular on nutrients. Studies often fail to account for this variability, leading to inconsistent results.
iii. Scale dependency: The effects of forest harvest residues on soil properties and nutrients can vary depending on the spatial and temporal scales at which studies are conducted. Small-scale studies may overlook landscape-level effects, while large-scale studies may miss finer-scale interactions.
iv. Confounding factors: Soil properties and nutrient dynamics are influenced by multiple factors besides forest harvest residues, including climate, soil type, vegetation composition, and management practices. Untangling the effects of residues from these confounding factors can be challenging and may require complex experimental designs.
v. Limited taxonomic coverage: Some studies focus on specific soil properties or nutrient cycles, neglecting others. This limited coverage hinders our understanding of the full range of effects that forest harvest residues may have on soil fertility and ecosystem functioning.

Plantation and energy (n = 40)

The topics of Plantation Forestry and Bio-Energy are well interconnected through residues or in general biomass utilization. Biomass and residues from dedicated forest plantations provide abundant sources of raw biomaterial that can be converted into bioenergy through different processes (e.g. combustion, gasification, or fermentation), contributing to renewable energy production and sustainable resource management. In plantation forestry, effective site preparation is key to a proper establishment of seedlings. Research has shown that a combination of multiple site preparation techniques to facilitate species establishment leads to faster growth compared to relying on a single technique (e.g. Martiarena et al. 2013; Van Bich et al. 2019). As an example, in pine plantations, intensive site preparation that involves seedling positioning and management of herbaceous vegetation has shown to overall improve early growth and productivity (Ndlovu et al. 2019).

For planning of biomass harvesting activities for energy production, accurately estimating available residues is important. A particular case, in which the planning of operations is accurately crafted, is the "fuel-adapted" harvesting in Scandinavian countries, which involves the optimization of logging practices to enhance bioenergy production. It focuses on selectively harvesting trees and stands with high energy potential, such as those with optimal size and species composition. This method minimizes waste by utilizing logging residues and low-quality wood for bioenergy production, contributing to sustainable forest management and renewable energy generation in the region. The impacts are summarized in Table 6.

Effects of residue management on plantation establishment

In plantation forestry, effective site preparation is key to a proper establishment of seedlings. Research has shown that a combination of multiple site preparation techniques to facilitate species establishment leads to faster growth, compared to relying on a single technique. For example, studies have demonstrated the effectiveness of combined practices, such as slash burning and fertilizer application, and burning or residue retention and fertilizer application for initial growth and establishment (e.g. Van Bich et al. 2019). On the contrary, the exclusive retention of residues showed limited long-term effects, whereas it helped in reducing nutrient losses and leaching in between rotation (Gómez-Rey et al. 2008a, 2008b; Tutua et al. 2008).

In more productive contexts, such as *Pinus patula* D. Don plantations in South Africa, intensive site preparation involving the seedling positioning (e.g. pitting, ripping, with or without chopper rolling) and weed management has shown to improve early growth and productivity. However, these interventions together with slash management treatments showed little effect on end-of-rotation productivity (Ndlovu et al. 2019). Similarly in other areas such as New Zealand and Swaziland, both residue management and fertilization resulted in increased productivity, with the effects being more pronounced in younger stands (Garrett et al. 2021a, 2021b; Mavimbela et al. 2018).

Long-term effects (e.g. on site productivity, stand growth and development) are more difficult to grasp. In general, retaining residues on site increases soil fertility (Ghaffariyan and Dupuis 2021), improves tree growth (Egnell and Valinger 2003; Mendham et al. 2003, 2014; Smolander et al. 2013; Smolander, Saarsalmi, and Tamminen 2015), increases stand biomass (Laclau et al. 2010; Ruiz-Peinado et al. 2013), and reduces soil erosion compared to residue removal. However, different effects are ought to be site specific with a more complex interplay of various factors coming into play (e.g. Ferreira et al. 2016; Wei et al. 2020). To mitigate the loss of nutrients due to management practices, fertilization has emerged as a common way to replenish the nutrients pools in forest soil (Garrett et al. 2021a, 2021b; Moore et al. 2021). However, some researchers have highlighted that retaining residues alone is enough to replenish carbon (Huang et al. 2013) and other nutrient pools (Xiang et al. 2009) in case of felling and burning treatments (Yang et al. 2005).

Biomass harvesting

For biomass harvesting, operational planning and accurate estimation of available residues become crucial. Related to the planning, harvesting and transportation costs are key variables (e.g. Fu et al. 2020; Nonini and Fiala 2021). The literature provides different examples of residue biomass estimation, including local

Table 6. Summary of impacts assessment for papers in the Plantation and Energy category.

	Action	Impact	References
Plantation establishment	Harvesting system		
	• Full-tree	↓	(de Dieu Nzila et al. 2002; Egnell and Leijon 1999; Fleming et al. 2014; Helmisaari et al. 2011; Hytönen and Moilanen 2014)
	• Stem-only	↑	
	Stand management		
	• Thinning	↑	(Ruiz-Peinado et al. 2013)
	Residue treatment*		
	• Burning	↑	(Van Bich et al. 2019; Carneiro et al. 2007, 2009; Fleming et al. 2014; Garrett et al. 2021a, 2021b; Gómez-Rey et al. 2008a, 2008b; Harrington et al. 2020; Harrington et al. 2018; Laclau et al. 2010; Martiarena et al. 2013; Mavimbela et al. 2018; Mendham et al. 2014; Ndlovu et al. 2019; Piatek et al. 2003; Ruiz-Peinado et al. 2013; Tutua et al. 2008; Versini et al. 2013; Wei et al. 2020)
	• Residue management	↑↑↓	
Biomass harvesting	Harvesting system		
	• Cut-to-length		(Strandgard and Mitchell 2019)
	Stand management		
	• Clear-cut	↓	(Briedis et al. 2011; Eräjää et al. 2010; Fu et al. 2020; Heikkilä et al. 2007; de Lima et al. 2020; Long and Boston 2014; Nonini and Fiala 2021; Nonini et al. 2022; Qiao et al. 2021; Straub and Koch 2011)
	• Thinning	↑	
	Residue treatment		
	• Residue management	↓↑	(Egnell 2016; Han et al. 2018; Inail et al. 2022; Jurevics et al. 2018; Yoshioka et al. 2002)
	• Fuel harvesting	↓↑	

The impact was classified as follows: "↑", a positive impact; "↓", a negative impact; "—", negligible or no impact. *In this case, the treatments are to be intended as combined rather than single used. For more detail, please refer to the main text for examples.

models based on permanent plots (e.g. for *Pinus radiata* D. Don plantations in New South Wales, Australia (Qiao et al. 2021)), the use of national forest inventory data (e.g. the use of airborne laser scanning and multispectral line scanner data at a national scale in China (Fu et al. 2020; Straub and Koch 2011)), the use of forest management plans and geographic information systems (Nonini and Fiala 2021; Nonini, Schillaci, and Fiala 2022), and the adoption of manual field measurements, such as line intercept sampling methods (Briedis et al. 2011; de Lima et al. 2020) and pile measurements (Long and Boston 2014).

Biomass harvesting is a practice widely adopted in northern Europe, especially in Scandinavian countries, where techniques such as "fuel-adapted" harvesting have been developed in the planning of operations with "fuels" referring to residues. In Finland, clearcutting for forest residues resulted in a decrease in the volume of large-sized deadwood, while traditional clearcutting resulted in a decrease in the volume of small-sized dead wood. However, the overall volume of deadwood did not significantly differ between the two types of clearcutting (Eräjää et al. 2010). Thinning planned for energy wood harvesting reported the same effects on stem wood growth as conventional thinning (Heikkilä et al. 2007). Moreover, slash and stump harvest monitored over a 30-year period did not have a significant impact on stand volume production, suggesting that these practices may not negatively affect forest productivity (Jurevics et al. 2018). However, different species respond differently to slash and stump harvesting, resulting in variations in productivity. For example, in boreal forests in Sweden, slash and stump harvesting led to decreased productivity in spruce-dominated stands, but at the same time increased productivity in Scots pine–dominated stands (Egnell 2016).

The main key limitations that can be retrieved from the literature investigating this relationship include

i. Quantity availability: Some studies reported residue quantities that were used during trials and tests; however, it emerged that quantity variations in biomass availability depend on a wider spectrum of factors—not only forest management practices, but also tree species planted, environmental conditions, and regional differences.
ii. Production scenario: Studies focusing on energy production and residue quantity availability are mostly concerned with fluxes of material to support existing powerplants or new ones, focusing primarily on the economic part. In this case, they may lack comprehensive assessments including not only economic feasibility but also other factors, such as environmental impacts and social implications.
iii. Land and biodiversity: More issues arise when environmental impacts and effects are not properly considered, especially when dealing with land uses and land-use changes, and potential conflicts with biodiversity conservation goals. We hence identify a lack of studies with a more comprehensive assessment of the consequences of the energetic use of residues.

Fire (n = 22)

The relationship between management of forest harvest residues and fire can be described with the term "fuel treatments," and revolves around the management of combustible materials to mitigate fire risk. Harvest residues, such as branches, tops, and other debris, can increase the fuel loads in a forest stand and elevate fire intensity and severity. Fuel treatments, which may include prescribed burning or mechanical removal of residues, aim to reduce fuel loads and modify fire behavior toward less intense fires to decrease the likelihood of catastrophic wildfires.

The full extent and impact of slash burning (i.e. pile, broadcast, slash) remain uncertain as they largely depend on site and species characteristics. In fire-prone forests, the management goal is often to influence the behavior of potential fire events by reducing the fuel load, i.e. the quantity of residues and material that can contribute to the escalation of the fire event. To achieve this goal, commonly adopted solutions include mechanical treatments (e.g. thinning, mastication, rolling, clear felling, and residue removal) and residue burning (e.g. scattered or collected in piles), or a

Table 7. Summary of impacts assessment for papers in the Fire category.

	Action	Impact	References
Impacts of mechanical treatments	Stand management		
	• Clear-cut	↓	(Palmero-Iniesta et al. 2017; Tinker and Knight 2000)
	• Thinning	↑	
	Residue treatment		
	• Residue management	↑	(Sampaio et al. 1993)
Impacts of burning treatments	Residue treatment		
	• Burning	↓↓↑	(Creech et al. 2012; Delač et al. 2021; Gibbons et al. 2000; Haskins and Gehring 2004; Hollis et al. 2011; Jang et al. 2017; Jönsson and Nihlgård 2004; Korb et al. 2004; Kranabetter and Macadam 2007)
Combined mechanical and burning	Stand management		
	• Thinning	↑	(Mason et al. 2007; Piqué and Domènech 2018; Ruiz-Peinado et al. 2013; Vega et al. 2010)
	• Salvage logging	—	
	Residue treatment		
	• Burning	↓↑	(Baeza and Roy 2008; Fettig et al. 2006; Hahn et al. 2021; McIver and Ottmar 2007, 2018; Owen et al. 2009; Walker et al. 2012; Wang et al. 2022b)
	• Residue management	↑	

The impact was classified as follows: "↑", a positive impact; "↓", a negative impact; "—", negligible or no impact.

combination of both. A summary of the impacts is reported in Table 7.

Impacts of mechanical treatments

In fire-prone forests, such as pine plantations, thinning has been studied as a means to reduce the fuel load and, at the same time, to increase fuel moisture content since retaining woody debris in decomposition has minimal long-term effects on fire behavior (Palmero-Iniesta et al. 2017). From the residue retention perspective, clearfelling generates coarser material than undisturbed sites; however, forest fire increases the presence of snags, bigger diameter logs, and longer pieces compared to the clearfelled areas (Tinker and Knight 2000). Regarding the vegetation response, in Caatinga coppice stands in Serra Talhada, Brazil, the mechanical removal of residues without burning decreased the coppice area compared to just burning, while the local vegetation response varied with increasing fire severity (Sampaio et al. 1993).

Impacts of prescribed burning

The use of low-intensity prescribed fires has emerged as a practical way of managing woody fuel load (Hollis et al. 2011). One of the most common practices to remove residues is prescribed burning; however, burning slash can also cause significant damage to residual trees and increase mortality (Gibbons et al. 2000), and can cause negative effects on the carbon storage and nutrient leaching (Jönsson and Nihlgård 2004).

When residues are grouped in piles and burned (pile-and-burn or pile burning), vegetation cover is decreased and local soil temperature, soil organic carbon, and soil nitrogen are increased. However, the effects are temporary, recovering within a year after burning (Delač et al. 2021). In some cases, these effects were observed to be positive such as for the longleaf pine (*P. palustris* Mill.) forests in the southeastern United States, where burning slash piles increases soil nutrient availability (Creech et al. 2012). By introducing techniques to buffer the burning effects, seed/soil amendments reduce the change in soil properties and promote native vegetation cover (Korb et al. 2004). In fire-adapted ecosystems, such as Northern California, USA, utilizing an air curtain burner method has been proven to have less impact on soil properties and reduce the potential for accidental wildfire ignition (Jang et al. 2017).

Impacts of mechanical treatments coupled with prescribed burning

The combination of mechanical treatments with prescribed burning can effectively reduce the amount of fuel loads, but this approach requires a tailored solution for each specific situation (Hahn et al. 2021). For example, in mixed conifer forests in Sierra Nevada, California, USA, the application of prescribed burning significantly diminished the total fuel load in the understory layer, irrespective of the presence of mechanical treatments (Walker et al. 2012). In Mediterranean Spain, brush-chipping, especially when conducted after summer, provides a better practice compared to fire for controlling *Ulex parviflorus* (L.) as it creates a hostile environmental condition for germination. This approach also has the potential to favor late-successional species that are less vulnerable to fire (Baeza and Roy 2008). Mechanical thinning and prescribed burning can decrease the risk of forest fire in Austrian pine (*Pinus nigra* J.F.Arnold) forests in northeast Spain by reducing fuel loads and increasing moisture content in the remaining vegetation (Piqué and Domènech 2018). Mechanical fuel reduction treatments can also effectively reduce bark beetle numbers and activity, with effectiveness varying depending on the treatment adopted (Fettig et al. 2006). In a dry mixed conifer forest in New Mexico, mechanical fuel treatments, such as thinning and mastication, effectively reduced fuel loads and lowered the risk of crown fires. The impact, however, varied based on the intensity and frequency of the treatments (Mason et al. 2007). In fire-prone ecosystems, mastication can be a preferable treatment due to its less impact on soil properties compared to pile burning, although there is limited information available related to its long-term effects (Owen et al. 2009).

Considering all the studies presented in this section, the key limitations in the emerging do include

i. High specialization: Studies often focus on specific forest types or regions, limiting the generalizability of their findings to other ecosystems with different ecological conditions and management practices.

ii. Short-term assessment: Many studies provide insights into short-term effects of fuel treatments on fire behavior and vegetation response, but long-term impacts remain uncertain. Longer-term monitoring is necessary to understand the durability and ecological consequences of these treatments over time.
iii. Variable methodologies: Variability in methodologies across studies makes it challenging to compare results directly and draw robust conclusions. Standardized protocols for assessing the impacts of fuel treatments could improve consistency and facilitate synthesis of findings.
iv. Limited socioeconomic considerations: While some studies address ecological aspects of fuel treatments, there is often a lack of consideration for socioeconomic factors, such as the costs, benefits, and social acceptance of different management strategies. Integrating socioeconomic perspectives could enhance the relevance and applicability of research outcomes.
v. Incomplete assessment of ecosystem services: Many of the studies presented primarily focus on fire risk reduction and vegetation response, overlooking other ecosystem services provided by forests, such as carbon sequestration, water regulation, and biodiversity conservation. A more holistic approach is needed to evaluate the trade-offs and synergies among different ecosystem services in the context of fuel treatments.

Conclusion

This review identified the general benefits and drawbacks of current harvesting residue practices and management. A novel methodical approach was introduced for the review by conducting a qualitative analysis of titles, abstracts, and keywords, providing insights into the overall trends surrounding the topic of harvesting residues. Moreover, various alternative treatments and their potential effects and impacts have been presented. The use of an AI bot during the analysis and synthesis provided a positive outcome and gave us a measure on the reliability of such tool. More to that, this application could be potentially be used for future research as a benchmark on AI-bot performances for such tasks. This work underscores the important role that forest residues play in the dynamics of forest ecosystems on a global scale. The main findings regarding residue management are summarized below.

i. Overall, it is widely acknowledged that different parts of a tree can be retraced in residues of different sizes. Finer residues, such as small branches, leaves/needles, twigs, and bark, contain large quantities of macro- and micronutrients, including nitrogen, whereas carbon is mainly stored in coarser residues.
ii. The retention of both fine and coarse residues enhances biodiversity promoting stand regeneration and providing habitats for fauna of different sizes.
iii. Retaining residues is crucial for carbon and nutrient cycling and storage. Leaving residues on site provides additional sources for replenishing C and N stocks, and decreases the risk of erosion and soil compaction, while retaining moisture at the ground level.
iv. The choice of residue treatment is key when it comes to establishing a new cohort in plantation forests, where the retention of material, integrated with other treatments, provides the best outcomes for seedling establishment and growth.
v. In fire-prone forests, uncontrolled volumes of residues may increase wildfire risks due to increased fuel loads. In such cases, prescribed burning of slash piles or scarification can be valuable options.
vi. Regarding the harvesting systems, logging activities have a considerable impact on both the quantity and quality of residues. CTL and SOH leave behind larger quantities of finer and mid-size residues compared to FT harvesting.
vii. The impact of stand management treatments is strictly linked to the choice of harvesting system adopted, influencing both quantity and quality of harvesting residues.

This review provides a general understating of the role of forest residues and highlights current management options adopted around the world. All in all, future research should address the more controversial findings highlighted by this work, also incorporating climate change considerations into residue management strategies, and how adaptive management approaches can aim to mitigate the impacts of climate-induced disturbances on forest ecosystems. The focus should be put on site-specific investigations to elucidate optimal residue management strategies tailored to different ecological contexts, considering stand characteristics, soil type, and tree species. In particular, there is a need for comparable studies with information collected following standardized protocols in order to compare different scenarios, locations, and strategies. Moreover, there is a need for comprehensive assessments of the efficacy and ecological consequences of various residue management scenarios, evaluating the long-term impacts on biodiversity, carbon and nutrient cycling, soil erosion, and moisture retention across diverse forest ecosystems. Finally, research efforts should focus on evaluating the effects of both machinery and harvesting systems on the spatial distribution of residues within forest landscapes. Comparative studies can provide insights into the relative efficiency and environmental implications of ground-based versus cable-based systems, as well as the varying residue outputs associated with different logging systems and strategies.

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Author contributions

Alberto Udali (Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing—original draft, Writing—review & editing), Woodam Chung (Formal analysis, Validation, Visualization, Writing—review & editing), Bruce Talbot (Formal analysis, Validation, Writing—review & editing), and Stefano Grigolato (Data curation, Funding acquisition, Project administration, Supervision, Visualization, Writing—review & editing)

Supplementary data

Supplementary data are available at *Forestry* online.

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Data availability

The datasets supporting the conclusions of this article are included in the article as tables and figures, or supplementary information available under request.

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