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Impacts caused by the traffic of ground-based forest harvesting machinery: State of the art and future guidelines for Chile

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ABSTRACT

The most frequently reported impacts of timber harvesting operations are on the soil and are mainly concentrated along skid trails and other areas of high traffic. Research addressing the impacts of ground-based harvesting machinery varies widely and is predominantly composed of case studies, which makes its application to other environmental contexts difficult. Considering the importance of the Chilean forest sector, the diversity of sites, and operational conditions in the country, as well as the predominant existence of plantations managed as short-rotation forest crops by clearcutting, it is paramount to identify the state of the art in Chile and knowledge gaps. To this end, environmental impacts and associated best management practice recommendations were identified based on 252 studies from 31 countries through a systematic search of articles in reference databases. The results highlight the under-studied geographical areas and soil types worldwide. The main disturbance reported were related to soil physical properties, followed by disturbance to the flora structure and composition, chemical properties, hydraulics, and soil biological properties. Seven general recommendations were identified and discussed regarding best management practices. Common recommendations include preventive measures to reduce soil impacts. In the case of studies conducted in Chile, only one indexed article (<0.01 %) was found, which raised the need to expand the search to national databases where five additional articles were found. This review is consistent with international study results. However, there is a recognized lack of knowledge regarding forest soils, types of disturbance, and the environmental impacts of modern harvesting machinery. Additionally, gaps in research related to skid trail planning alternatives, soil monitoring, and recovery times have been identified. Research needs related to these knowledge gaps have been proposed.

1. Introduction

Reducing the environmental impacts of ground-based timber harvesting machinery remains one of the main challenges of the forest sector, as inappropriate planning and execution of harvesting operations have the potential to negatively affect soil, water quality, vegetation composition, and even fauna, consequently damaging site productivity and ecosystem function (Cambi et al., 2015; Picchio et al., 2020; Nazari et al., 2021; Nazari et al., 2023). Despite the biotic and abiotic aspects of the site, the most frequently reported impacts of timber harvesting operations are on the soil properties, which are mainly concentrated along skid trails and other areas of high traffic. These impacts include soil compaction, rutting, and displacement, which decrease infiltration, increase surface runoff, and over time can lead to erosion (Adams and Froehlich, 1981; Rab, 1996; Kolka and Smidt, 2004), affecting nutrient availability and biological activity, ultimately leading to a loss of soil quality (Zenner et al., 2007; Zenner and Berger, 2008). Recent systematic reviews and metanalysis also found negative effects on species biodiversity (Latterini et al., 2023a), litter decomposition (Latterini et al., 2023b) and fine roots (Latterini et al., 2023c).

In Chile, forests cover an area of 17.7 million hectares, of which 2.3 million hectares correspond to exotic plantations (about 80 % of *Pinus radiata* (D. Don) and *Eucalyptus* spp.), which supply the forest industry (MINAGRI, 2021), one of the country's largest productive sectors that in 2021 represented 1.7 % of the total national GDP (INFOR, 2022). Annually, approximately 90,000 ha of forest plantations are harvested

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mainly from 33° to 42° S, established on sites with a wide range of soil types (parent material and pedogenetic processes) and climatic conditions with precipitation fluctuating between 500 and 2200 mm annually and intra-annual changes represented by dry periods fluctuating between 0 and 8 months (Schlatter and Gerding, 1995). Approximately 60 % of these forest plantations are located on terrain with slopes below 35 %, where ground-based timber harvesting systems are applied. The skidding machinery commonly used in these systems includes forwarders and skidders equipped with a grapple or winch (Gayoso and Gayoso, 2009).

The environmental impacts of ground-based timber harvesting are a concern for the Chilean forest sector, which mainly focuses on producing timber and fiber from short-rotation forest plantations. A series of recommendations and best management practices (BMPs) have been identified and required by forest legislation (CONAF, 2017; CONAF, 2023) and certification organizations (i.e. FSC and PEFC) as an integral part of forest management. These certification and legal requirements include avoiding the traffic of machinery through stream protection zones, watercourses, and fragile soils, and the recommendation to reduce the extent of areas impacted by the skidding machinery, designing skid trails along contour lines, and implementing diversion structures to reduce the erosive potential of surface runoff. These measures are based on scientific knowledge primarily derived from international studies. However, the results of studies addressing the impacts of ground-based harvesting machinery vary widely. They are dependent on site characteristics (climate, vegetation, average tree size, topography, and soils), machinery type, and operating conditions (i.e., harvesting method, cable vs grapple, wheeled vs tracked), which makes their application to other site conditions and operating settings difficult (Cambi et al., 2015; Picchio et al., 2020). This is especially important in Chile where forest plantations have been established in a range of climatic, edaphic and topographic conditions and managed as short-rotation forest crops by clearcutting. It is paramount to identify the state of the art in Chile and knowledge gaps, under the premise that, to provide appropriate management solutions, it is necessary to understand the relationships between the site and operation characteristics and the magnitude and distribution of the impacts (Gayoso and Iroumé, 1995; Donoso, 2009; Balocchi et al., 2023).

In this context, the objectives of this study are to i) identify the environmental impacts caused by ground-based harvesting machinery reported in indexed scientific journals from 1990 to 2024, ii) identify the preventive, corrective, and mitigation recommendations derived from these studies to reduce the environmental impacts and (iii) establish knowledge gaps in Chile and identify crucial future research guidelines.

2. Methods

2.1. Search of indexed scientific journal articles

A systematic search of articles in the Web of Science (WOS), Scopus, and Scientific Electronic Library Online (SciELO) databases was conducted using combinations of the words: 'skid trail' OR 'skidder' OR 'forwarder' OR 'forest harvesting' OR 'traffic intensity' OR 'harvesting impacts', AND 'forest disturbance' OR 'soil disturbance' OR 'soil compaction' OR 'soil recovery' OR 'forestry best management practices' OR 'Chile', classified as keywords or added in the title or abstract, for articles published in English or Spanish between years 1990 and 2024. The start of this period was selected because it corresponds to the beginning of a significant increase in the mechanization of timber harvesting systems in Chile. In all three databases, words or phrases were selected after several iterations to consider the most representative results of impacts caused by the traffic of skidders or forwarders, while ignoring others caused by other harvesting activities such as felling or processing, and other operations such as road construction or mechanized site preparation. The article titles and abstracts were carefully reviewed to ensure that the database contained only articles reporting the environmental impacts of skidding or forwarding activities. Finally, from the validated database, we extracted for each article information about the country of origin, year, disturbance type, variables observed and or measures, soil type, water content of the soil at the time of harvest, and the main recommendations related to best or acceptable management practices.

2.2. Analysis of indexed scientific journal articles

The articles in the final database were classified according to the type of disturbance reported, soil type, soil water content at the time of harvesting, and the impact type of forest machinery traffic observed. Impacts were classified as disturbance to the physical, chemical, biological (soil fauna), and hydraulic properties of the soil, as well as to the vegetation structure or composition (flora) specifically related to unwanted modifications (damage). Likewise, soil types were grouped according to order based on the taxonomic classification of the United States Department of Agriculture (USDA, Soil Survey Staff, 1999). Some soils were reclassified from the World Reference Base (WRB) or using correlations from national classification systems (e.g. Embrapa Solos, 2018, Isbell and NCST, 2021). Soil water content was classified according to the status specified in each paper as wet, dry, or both (included in each article through a chrono sequence). Finally, based on the recommendations or conclusions of the articles, recommendations for best management practices (BMP) were identified and selected according to the implementation stage as preventive, corrective, or mitigative.

To ensure that our analysis captured all existing knowledge in Chile, we expanded the search for scientific articles and research reports available in the digital library of the Forest Institute of Chile (INFOR), which is dependent on the Department of Agriculture. For this search, we used the words (in Spanish) 'mechanized skidding' OR 'environmental impacts' OR 'timber harvesting', OR 'soils', in the search topics of the platform documents published during the same period (between 1990 and 2024).

3. Results

3.1. Indexed scientific journal articles

We found 614 articles, 72 of which came exclusively from WOS, 175 from Scopus, and 19 from SciELO, and 348 articles were indexed on all three search platforms. After careful screening, 252 papers were identified as directly evaluating the environmental impacts of skidding or forwarding. Most of these articles were published between 2015 and 2024 (155 or 61.5 %), with an average of 15.5 articles published annually (Fig. 1a). These articles came from 31 countries (Fig. 2), mainly from Asia (77), Europe (73), and North America (61) (Fig. 1b). In the case of South America, we found 27 articles (10.7 %), and over half of which (55.5 %) have been published after 2017.

The countries where studies were most frequently conducted were Iran (62), mainly concentrated in the last decade (54–87 %), followed by the United States (38), Canada (22), Brazil (22), and Germany (21), with studies published mainly after 2015–2024 (Fig. 2). Only one article (< 0.01 %), by Gayoso and Iroumé (1991) was found in Chile.

Of the 252 screened articles identified, 216 (86 %) reported some soil type information (orders or reference groups) sufficient that allowed soils to be classified with certainty under the USDA order (Fig. 3a). Soil orders where the impacts of timber harvesting have been studied most frequently were Alfisols (68), Inceptisols (47), and Ultisols (33). On the other hand, soil orders that have received little attention are Aridisols (1), on sites with little to no tree cover, as well as Cambisols (1), Leptosols (1), Gleysols (4), Ferrasols (4), Stagnosols (4), Vertisols (1) and Andisols (5), the last two of which are rare soil orders at the world scale (Binkley and Fisher, 2013). Regarding the soil moisture content at harvest, only 106 (42 %) studies reported moisture content classified as

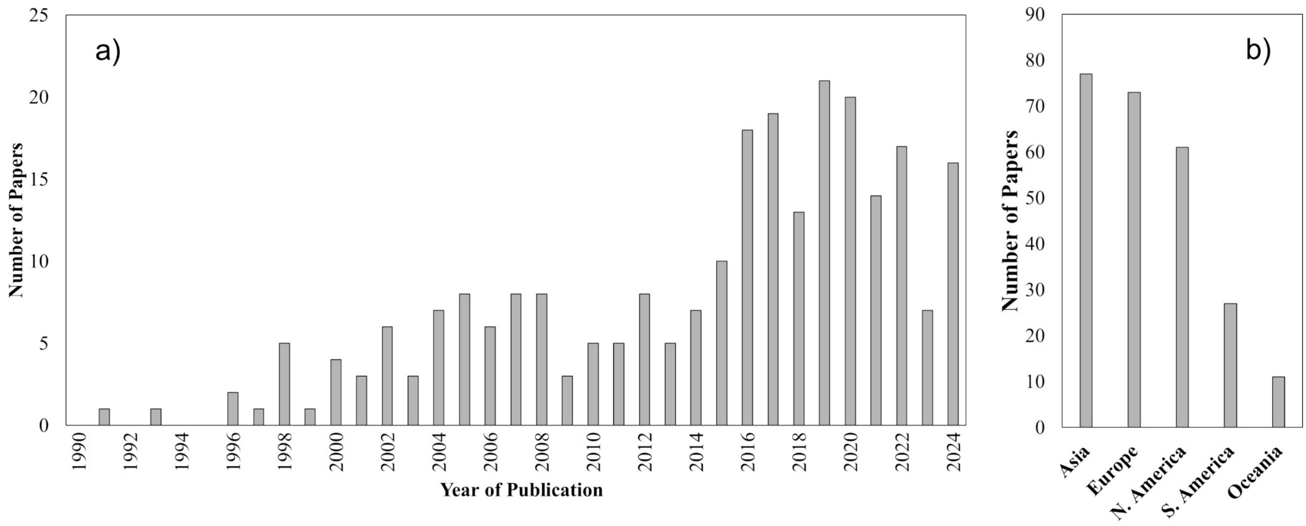

Fig. 1. Number of papers published by year (a) and region of the world (b).

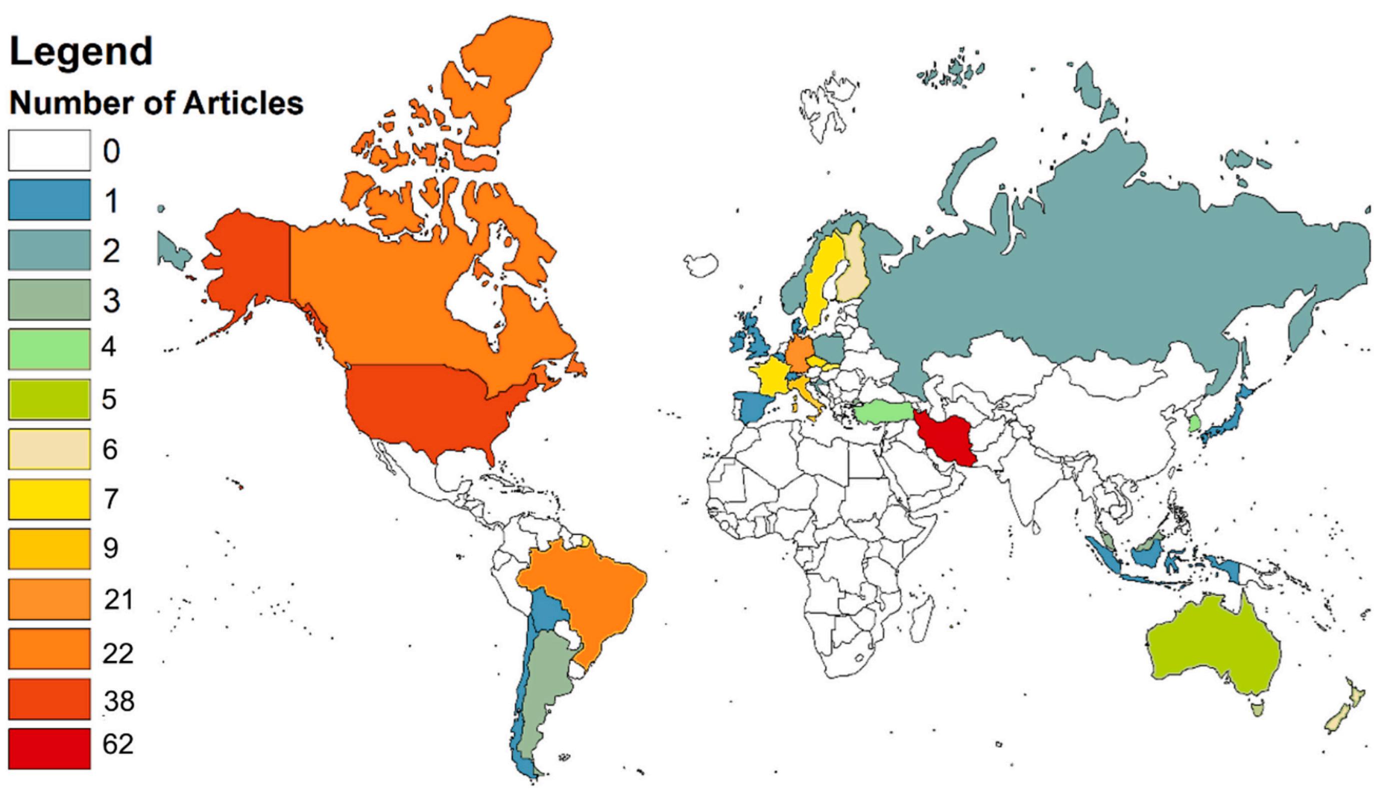

Fig. 2. Number of studies conducted per country between 1990 and 2024.

dry, wet, or both, and studies on soils classified as wet were slightly more frequent (Fig. 3b). Lastly, regardless of soil type and moisture content, the main disturbance caused by the harvesting equipment were related to the physical properties (197), vegetation structure and composition (61), chemical properties (60), hydraulic properties (51), and biological properties of the soil (21).

3.2. Impacts reported in indexed journals articles

The main impacts of timber harvesting machinery traffic were caused to the soil and vegetation. The most frequent impacts were reported as changes in soil physical properties such as bulk density (64 % of the 252 articles) and porosity (33 %), and proxies of these properties including penetration resistance (27 %), soil rutting or displacement (25 %), and shear resistance (5 %) (Table 1). Other frequently reported disturbance were those caused to the vegetation structure or composition (26 %), changes in chemical properties (17 %), gas fluxes (8 %), and other water-related aspects of the soil such as water retention (7 %), infiltration (9), and runoff (8 %). The least frequent impacts studied were those related to the biotic components of the soil, such as microbial and enzymatic properties (4 %) and fauna (3 %) (Table 1). Studies on the physical properties, proxies, and water-related aspects of soil have shown a clear change, either increasing or decreasing, in which case all changes negatively affect soil quality (Table 1). However, studies measuring changes in chemical properties, vegetation structure or composition, and the biotic components of the soil are inconsistent and

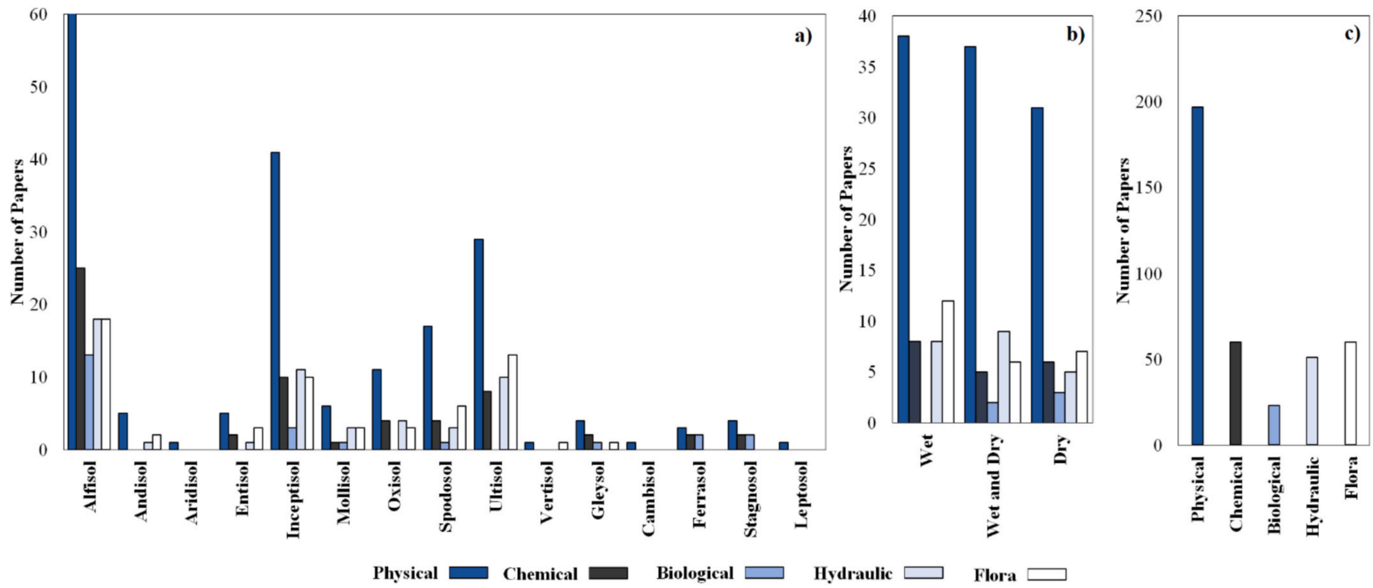

Fig. 3. Number of indexed articles according to soil order (a), soil moisture status (b), and type of disturbance (c).

Table 1
Environmental impacts caused by the traffic of forest harvesting machinery.

Indicator variable		Number of articles	Change reported*	Impact
Bulk density		161	+	Negative
Rutting/soil displacement		61	+	Negative
Porosity	Total porosity	83	−	Negative
	Macro porosity		−	
	Microporosity		+	
Penetration resistance		69	+	Negative
Shear resistance		12	+	Negative
Surface humidity/water retention		17	+	Variable
Gas fluxes	O_2 concentration	19	−	Negative
	CO_2 concentration		+	
	CH_4 emissions		+	
	N_2O emissions		+	
Chemical properties	C	42	−, =	Negative, neutral
	N		−, =	
Microbial/enzymatic properties		9	−, =, +	Variable
Fauna (earthworms, nematodes, microarthropods)		10	−, =, +	Variable
Hydraulic conductivity/infiltration		23	−	Negative
Runoff/erosion		21	+	Negative
Vegetation structure or composition		64	−, =, +	Variable

[*] "+" refers to an increase of the indicator variable, "-" refers to a decrease of the indicator variable, and "=" refers to no change of the indicator variable.

report an increase, decrease, or neutral change in the associated indicator variables.

3.3. Management recommendations

We identified seven general management recommendations that can, in terms of time of application, be classified as preventive, corrective, or mitigative (Table 2), all focusing on soil conservation for vegetation growth. The most frequent preventive measures focus on soil impacts, with the specific aim of reducing the magnitude and extent of those impacts.

The most frequent preventive recommendation is to concentrate the traffic of machines along planned skid trails based on environmental aspects to reduce the length of the skid trail network (Table 2), assuming

Table 2
Common recommendations acknowledged in the identified indexed journal articles.

Category	Recommendation	Example references
Preventive	– Adequately plan skid trail layouts considering environmental and economic factors and design permanent skid trails to minimize the extent of the disturbance (p.e. consider traffic restrictions zones and locate skid trails layouts along the contour lines).	Pinard et al., 2000, Williamson and Neilsen, 2000, Zenner et al., 2007, Ampoorter et al., 2010, DeArmond et al., 2023.
	– Select forest harvesting systems based on current soil and terrain characteristics.	Heninger et al., 2002, Eliasson and Wästerlund, 2007, Labelle and Jaeger, 2011.
	– Schedule harvesting operations when soil moisture conditions are favorable such as dry or frozen and avoid high soil moisture seasons when soil is saturated or waterlogged.	Startsev and McNabb, 2000, McNabb et al., 2001, Stone, 2002, Cambi et al., 2016, DeArmond et al., 2024.
	– Limit skidding and forwarding operations to terrains with low to moderate slopes (p.e. ≤ 35 %).	Najafi et al., 2009, Sohrabi et al., 2019, Jourgholami et al., 2021.
Corrective	– Actively monitor harvesting operations focusing on inspecting impacts along skid trail. Limit machine or stop machine traffic if predefined impact thresholds are exceeded such as rutting depth.	Stone, 2002, Jourgholami et al., 2014.
Mitigative	– Apply closure treatments along skid trails such as water diversion, placing residues, or seeding to reduce erosion potential on exposed mineral soil.	Croke et al., 2001, Wear et al., 2013, Dangle et al., 2019, Labelle et al., 2022, Latterini et al., 2024a.
	– Apply soil recovery treatments such as subsoiling or tilling for decompaction. Reforest as soon as possible to provide vegetation cover and reduce mineral soil exposure.	Fründ and Averdiek, 2016, Lang et al., 2016, Neaves III et al., 2017, Labelle et al., 2022, Latterini et al., 2024a.

that machine traffic generates most of the impacts during the first few machine passes. This involves considering traffic restriction zones and preferring skid trails along the contour lines. Additionally, economic factors were considered, as the skid trails used by harvesting equipment directly influence the economics of harvesting operations through their impact on skidding distances and cycle times. Other preventive recommendations include the implementation of harvesting operations based on site-specific information. This includes selecting harvesting systems based on soil and terrain characteristics at harvest, which involves knowing the potential impacts of different harvesting machinery to modify the type of machinery used or the harvest intensity to avoid extensive clear-cuts to mimic natural disturbance patterns. Another important recommendation is to schedule harvesting operations when soil moisture conditions are favorable, avoiding saturated and waterlogged soils (Table 2).

The last preventive recommendation is to limit ground-based operations to terrains with moderate to low slopes (i.e. < 35 %) (Table 2), because rutting and soil displacement tend to increase with slope due to increased ground pressure on the lower-elevation tires and lower traction. However, it is important to note that the boundary is quite difficult to establish because there are various ranges of suggested maximum slope for ground-based timber harvesting systems, varying from 20 % to 35 %.

Corrective recommendations include actively monitoring activities during harvesting to verify compliance with the harvest plan and making changes as necessary, with a focus on impacts along skid trails to restrict traffic if predefined impact thresholds, such as rutting depth, are exceeded (Table 2).

Regarding mitigation measures, two recommendations were made to reduce post-harvest soil degradation (Table 2). One recommendation is the application of surface water diversion treatments to reduce the erosion potential of runoff, and the placement of forest residues and seeding along skid trails to reduce exposed mineral soils. The second is the use of soil restoration treatments such as subsoiling or tilling to decompact high-traffic areas and reforest as soon as possible to provide vegetative cover.

3.4. Impacts reported in Chile

The search results on the local platform yielded five additional articles to the single article found in the indexed journal databases (Table 3). These studies were conducted between 1991 and 1999 and addressed the perturbations of the physical, chemical, and hydraulic properties in Andisols (four articles), Ultisols (four articles), and Alfisols (two articles), in some cases considering the same local soil series (or study area).

Gayoso and Iroumé (1991) reported the effect of skidder traffic intensity (1, 2, 3, 5, and 10 passes) and slope (10 and 20 %) on the physical and hydraulic properties of an Ultisol located in Valdivia, Los Ríos region. Most compaction occurred during the first three machine passes, associated with a decrease in soil macroporosity and an increase in bulk density due to the low soil bearing capacity at the time of harvest (84 and 66 % moisture at 0–10 and 11–20 cm depth, respectively). Additionally, there is a significant decrease in hydraulic conductivity after a single pass. In trails with a 20 % slope, the impacts on physical and hydraulic properties for all different numbers of machine passes and depths were significantly higher than those observed in trails with a 10 % slope.

For an Andisol in Loncoche, La Araucanía region, Ellies et al. (1993a), Ellies et al. (1993b), and Ellies (1995) reported a loss of total porosity, a decrease in macroporosity, an increase in microporosity, and an increase in soil-bearing capacity due to soil compaction on forest plantations after one and two rotations. The changes in pore distribution were assumed to be caused by the harvesting operations.

Gayoso and Iroumé (1993) evaluated skidder and oxen skidding operations on two Ultisols and one Alfisol in south-central Chile (37° - 40° south latitude) and found an increase in bulk density along skid trails (up to 1.85 times compared with undisturbed areas), increased shear resistance, and decreased permeability. These changes were associated with reduced macroporosity and increased soil cohesion (loss of structure). They also found that the relative loss of porosity increases logarithmically with traffic intensity and is higher in soils with high moisture content.

Ellies (1999), for Andisol, Ultisol and Alfisol in the regions of Los Lagos (Lago Rupanco) and Biobío (Collipulli and Yumbel), found an increase in penetration depth of vertical forces (flotation) produced by skidder traffic with increasing soil moisture, ultimately resulting in a reduction of more than 50 % in macroporosity for the Ultisol and Alfisol under wet (autumn) conditions. They also reported that compaction caused by machine traffic increased the soil-bearing capacity and cohesion.

Table 3
Summary of the studies found in Chile about soil impacts caused by skidding machinery during harvesting operations.

Indicator variable	Impact	Soil type (local soil series)*	Soil moisture condition at the time of harvest	Reference
Bulk density, total porosity, and hydraulic conductivity	Negative	Ultisol (Correltúe)	Wet	Gayoso and Iroumé (1991)
Pore distribution	Negative	Andisol (Malihue)	Without information	Ellies et al. (1993a)
Pore distribution, consolidation, and organic matter content	Negative	Andisol (Malihue)	Without information	Ellies et al. (1993b)
Bulk density, cohesion, shear resistance, pore distribution, and permeability	Negative	Ultisol (Correltúe, Nahuelbuta) Alfisol (San Esteban)	Wet and dry	Gayoso and Iroumé (1993)
Pore distribution, penetration resistance, torsional strength, shear resistance, consolidation, organic matter content, and aggregate stability	Negative	Andisol (Malihue)	Without information	Ellies (1995)
Bulk density, pore distribution, shear resistance, and bearing capacity	Negative	Andisol (Udivitrand) Ultisol (Palehumult) Alfisol (Rhodoxeralf)	Wet and dry	Ellies (1999)

* : Local soil series in Chile.

4. Discussion

4.1. Database and environmental impacts

Numerous studies have addressed the impacts of ground-based harvesting machinery from 1990 to 2024. In the last decade, the results reflect growing concerns about the environmental impacts of this heavy machinery (Fig. 1a). However, these studies are concentrated in a few regions of the world (Fig. 1b, Fig. 2) and mainly in only five countries (Iran, United States, Canada, Germany, and Brazil; 66 %), which generally represent site- and operation-specific conditions. This restricts the extrapolation of the findings to other sites, forests, and operation conditions, such as those in Chile or other countries with an important forest sector contribution. Additionally, only a few studies have been conducted in the global south, despite the importance of the forestry sector in South America (Brazil, Argentina, Uruguay, and Chile) and Oceania (New Zealand, South Africa, and Australia) (FAO, 2022).

Few studies have been conducted on Vertisols, Entisols, and Andisols (Fig. 3a), of which the latter are of great concern because of their characteristics and susceptibility to adverse effects (Parker, 2007; Crawford et al., 2021). Most studies that evaluate soil impacts focus on soil physical properties, as they are sensitive to machine traffic and easier to quantify, directly related to the productivity of a forest, and closely related to visual effects such as rutting and compaction after machine traffic. Studies focusing on hydraulic, biological, and chemical soil properties, which are more difficult to evaluate, are less numerous. Additionally, some of the indicator variables related to these less studied properties (e.g. microbial/enzymatic properties, C, N, and tree structure or composition) increased, decreased, or remained neutral because of machinery traffic, reflecting the need for further evaluations to better understand the driving factors of these impacts. However, recent studies (e.g. Kiumarsi et al., 2024) and new meta-analyses indicate more clearly negative impacts across these variables (Latterini et al., 2024b).

4.2. Best management practices and recommendations

The most frequent measure recommended in the identified studies is planning skid trails to concentrate machine traffic along a few main skid trails to limit the extension of the impacts (Table 2). A justification is based on the findings of different studies that show that most soil disturbance occur during the first few machine passes (Gayoso and Iroumé, 1991; McNabb et al., 2001; Han et al., 2006), with subsequent passes generating additional disturbance at a reduced rate, following an asymptotic relationship (McNabb et al., 2001; Solgi et al., 2017). In other words, forest machine traffic has a limited additional impact on soils that have already undergone compaction, because of the increased soil-bearing capacity derived from altered pore systems (Williamson and Neilsen, 2000). Additionally, the planning of skid trails should avoid stream crossing areas and fragile soils. It's recommended to prefer skid trails along contour lines to reduce the water runoff potential to produce sediment.

Regarding the preventive recommendation for selecting harvesting systems and methods according to the soil condition at the time of harvest, four soil characteristics are the most important (Table 2). First, soil moisture content because the higher the soil moisture content, the lower the frictional forces between the soil particles, the lower the cohesion, and therefore the lower the bearing capacity, leading to soil compaction, rutting, and displacement (Ellies, 1999; Williamson and Neilsen, 2000; McNabb et al., 2001; Ampoorter et al., 2010). The second soil characteristic is texture, due to its relationship with the soil water regime. Soils with a higher clay content are generally more susceptible to compaction than those with a coarse texture due to their higher water retention (Ampoorter et al., 2012; Kolka et al., 2012; Slesak et al., 2017). However, fine-textured soils reach their maximum cohesion between particles under very low moisture conditions, sometimes even representing a higher bearing capacity than coarse-textured soils (Ampoorter et al., 2012; Martins et al., 2018). Soil structure is also relevant because it influences soil air and water regimes (e.g., porosity, moisture, and soil-bearing capacity). This stability depends on the soil aggregate characteristics (degree of aggregation and type of structure), and thus on the organic matter content, as it relates to the wetting and dispersing capacity of the aggregates. Soils with high organic matter content have greater resistance of aggregates to wetting and dispersion by water due to their cementing capacity (Ellies et al., 1993a, 1993b; Ellies, 1995). Lastly, terrain slope is important because it affects the load distribution of the undercarriage, increasing the weight of the downhill axle (Neuenschwander, 2001). Machine movement slows with terrain inclination and loses traction resulting in slippage, which generates soil displacement and deeper rutting (Gayoso and Iroumé, 1991; Solgi et al., 2017; Sadeghi et al., 2022).

Regarding the machine's characteristics, its weight and type of undercarriage are also crucial as they affect its weight distribution and ground pressure. Generally, as tracked machines distribute weight over a larger area than wheeled machines, they exert lower vertical forces, thus having higher flotation, and due to the larger number of treads in contact with the ground, they exert higher horizontal forces, which translates to better traction (Gayoso and Gayoso, 2009; Neuenschwander, 2001). Therefore, to increase flotation and traction, and thus reduce the magnitude of the associated soil disturbance, wheeled machines are made wider or doubled and often equipped with chains or bands (Jansson and Johansson, 1998; Nery et al., 2007; Solgi et al., 2020). The type of machine, either skidder or forwarder, also affects the soil disturbance. Typically, skidders that partially drag loads of several tons (2–5 tons) generate a larger impacted area, soil displacement, and mineral soil exposure than forwarders that transport the load completely suspended. However, this can lead to high ground pressure and increased compaction, for which forest debris is typically placed along skid trails, forming a layer that acts as a cushion of debris that reduces ground pressure (Parker, 2007; Labelle and Jaeger, 2012). However, the effectiveness of woody debris in reducing disturbance depends on the debris characteristics (type and density), traffic intensity, and soil characteristics (McDonald and Seixas, 1997; Hutchings et al., 2002; Han et al., 2006; Akay et al., 2007). The effectiveness of the woody debris layer in providing soil support decreases as the number of machine passes increases (Akay et al., 2007).

Concerning the corrective measure of monitoring forest operations (Table 2), visual monitoring of environmental impacts is important to identify disturbance during harvesting and potentially halt activities when clear thresholds are exceeded. For example, Page-Dumroese et al. (2009) explicitly defined the soil disturbance classes used by the U.S. Forest Service (Crawford et al., 2021) based on visual inspection of skid trails and evidence of soil displacement, mixed soil horizons, and mineral soil exposure. Skid trails with rutting deeper than 10 cm and loss of the soil organic horizon with evidence of partially or fully exposed subsoil were considered in the highest disturbance class. In Chile by law, a maximum altered surface area of 18 % per hectare is established, which includes skid trails with rutting depths of more than 15 cm or exposed mineral soil, in addition to other areas occupied by structures (CONAF, 2023). Gayoso and Alarcón (1999) suggested stopping operations when rutting exceeded 20 cm in depth over a continuous section of 15 m. However, operationally this proposed metric is strict and forest companies have adopted a threshold of 30 cm of rutting over 30 m of continuous skid trails to halt operations. More recently, CONAF (2017) recommends (not mandatory) a minimum distance of 60 m between skid trails for mechanized operations.

Lastly, mitigation measures (Table 2) refer to the deactivation of skid trails to prevent impacts after harvesting by reducing the potential for surface runoff to cause erosion (Wear et al., 2013; Parkhurst et al., 2018; Jourgholami et al., 2020). Often these measures include installing water-diversion structures, placing readily available forest residues, or seeding. In forest plantations where clearcuts are applied, site preparation activities are applied instead of skid trail deactivation. These include drainage creation at sites with excess moisture to encourage rooting, and soil preparation through scarifying or subsoiling to address soil strength and aeration porosity constraints (Aust et al., 1998; Lang et al., 2016; Neaves III et al., 2017).

4.3. Knowledge gaps and future research needs in Chile

Based on the search criteria, both international and limited national studies indicate that ground-based machine traffic causes environmental impacts, particularly on the physical, chemical, and hydraulic soil properties. Furthermore, soil conditions, including moisture content, texture, and structure, as well as operational conditions like the type of machine and traffic level collectively determine the intensity of impacts. Nevertheless, further research is needed to determine the types of environmental disturbance and magnitude of soil impacts associated with different soil types and operational conditions. Additionally, there is a need to evaluate soil recovery times and alternatives for planning and monitoring soil impacts (Cambi et al., 2015; DeArmond et al., 2021; DeArmond et al., 2023; Kiumarsi et al., 2024). Existing studies in Chile are outdated, especially those considering modern harvesting technology. This is troublesome considering that currently approximately 60 % of the forest plantations are harvested using ground-based machinery and with the current introduction of tethered systems ground-based systems are expected to cover almost 80 % of harvesting operations (Pincheira, 2024).

4.3.1. Soils with forest plantations

Studies in Chile were conducted on three soil orders (Andisols, Ultisols, and Alfisols) (Table 3) representing specific conditions of susceptibility to disturbance. Within the distribution of forest plantations in Chile, Aridisols and Spodosols have yet to be described (Thiers et al., 2014), and Entisols, Inceptisols, Mollisols, and Vertisols have not been studied in the context of impacts of ground-based harvesting machinery.

For practical reasons, soils in Chile are also classified based on their material of origin and pedogenetic processes. Six soil types cover the forest plantations distribution: granitic, sandy, red clay, marine sediments, metamorphic, and modern volcanic ashes. The identified studies were conducted on modern volcanic ash (6), granitic (2), metamorphic (1) and red clayey (1) soils. There is an urgent need to update the identification and quantification of soil impacts on all these soil types considering the traffic intensity of modern harvesting technology, but also to focus efforts on sandy soils and marine sediments, especially considering the significant productive importance of the latter which is a hotspot of the forest industry sector (Olmedo et al., 2020).

Soil moisture content at harvest was vaguely established in only three of the six studies conducted in Chile (Table 3). As it strongly affects soil-bearing capacity it is imperative to conduct studies to establish a relationship between moisture content and the magnitude of soil impacts and identify thresholds for each soil type, considering the country's diverse climatic conditions and that forest companies conduct harvesting operations in all four seasons of the year. Typically, forest companies have extensive soil and climatic data that cover large areas. These data are proprietary and are seldom shared with the scientific community. Creating collaborations among academia, the private sector, and governmental entities holds significant promise for leveraging these data to formulate policies that prioritize the sustainable utilization of forests and natural resources (McIntyre and Schultz, 2020).

4.3.2. Impacts on edaphic properties

Concerning the types of disturbance, limited national research has focused on the physical properties of soils (Table 3), which evidences the need to research the impacts of ground-based harvesting on other important aspects such as the biological and chemical properties of soils (Table 3). For example, air and gas fluxes and C and N content variation along skid trails could be highly sensitive to machine traffic. For instance, Ampoorter et al. (2010) observed an increase in CO_2 concentration after one machine pass across different Alfisols and Spodosols in Belgium, while the penetration resistance and bulk density did not show clear trends. More recently, Warlo et al. (2022) concluded that changes in gas fluxes (CH_4 and N_2O) may be a more appropriate indicator of soil structural parameters than the physical properties obtained from destructive soil samples, due to the impossibility of the latter to be repeated at the same location.

Current environmental assessments of forest management on water quality include the production of sediment from forest roads while ignoring skid trails, which are denser and might even be closer to streams (Schuller et al., 2021). Thus, it is necessary to establish medium- to long-term studies to monitor sediment production from skid trails and to evaluate the efficiency of alternative mitigation measures to reduce sediment production.

4.3.3. Alternative for planning skid trails

Operational harvest planning is the key to avoiding severe environmental impacts. Currently, the layout of skid trails is performed manually in the field considering the site-specific topography and vegetation conditions. Although manual designs can reduce soil impacts, it is impractical to evaluate the numerous possible alternatives and optimize skid trails simultaneously considering the characteristics of the harvesting system and traffic restrictions (e.g. protection zones and microrelief). A few studies, not included in the article search, have addressed the optimization of skid trail networks using different methodologies applied to hypothetical or small-scale cases, without real and operational applications. Additionally, because of its complexity, they simplified the problem by considering only the skidding or forwarding cost while ignoring environmental aspects (e.g. Flisberg et al., 2007; Contreras and Chung, 2011; Søvde et al., 2013; Ezzati et al., 2015). Some notable approaches include the work of Halleux and Greene (2003), who developed an automated procedure that generates skid trails based on estimates of skidding costs without considering soil impacts. Contreras et al. (2016) developed a procedure to optimally design skid trail networks to reduce skidding costs and soil disturbance, by considering the cost of soil recovery as an economic indicator of soil impacts. A more recent study (Flisberg et al., 2021), developed a decision-making tool to automate the design of skid trails for cut-to-length harvesting systems that minimize forwarding distances while avoiding steep slopes and areas with soils with higher rutting potential owing to moisture conditions.

In Chile, Gayoso (1996) proposed a method to evaluate the environmental impacts generated by harvesting operations in *P. radiata* plantations considering environmental costs such as subsoiling to mitigate compaction and the cost of excess, non-mitigable compaction. Gayoso and Muñoz (1997) estimated an index for classifying the level of susceptibility of forest soils to degradation considering the risks of soil compaction, removal, erosion, and landslides. However, there are currently no operational tools available to solve the problem of optimal skid trail design that simultaneously minimizes soil impacts and skidding costs, which is a paramount need for forest companies that own forests and contracting companies that perform harvesting operations.

4.3.4. Soil monitoring

Post-harvest soil monitoring is required to assess the impacts of ground-based harvesting machinery and to evaluate soil recovery. The reviewed studies indicate that not all consequences are negative for soil and site productivity (Table 1). However, forest operations require clear thresholds to determine when environmental impacts are significant to justify halting operations and prevent severe impacts. For this, a suite of studies should be established to assess impacts as a function of machine traffic for different soil moisture contents, soil types, and harvesting equipment, and to develop post-harvest soil monitoring protocols that clearly define types of disturbance and acceptable levels. The assessment of changes in soil properties requires indicators that reflect changes in soil functionality. In Chile, forestry studies have focused on the assessment of its productive function (soil fertility), considering the capacity of the soil for plant development and yield production, based on rooting space, water regime, air regime, heat regime, and nutrient regime (Schlatter et al., 2003; Thiers et al., 2014; Schlatter and Gerding, 2024). Selecting a standard set of soil quality indicators can be complex because they vary among forest ecosystems and management objectives. However, it is essential to define monitoring indices applicable to all forest plantations and native forests that can be implemented operationally considering the ease of collecting information and its value (Thiers et al., 2012).

A commonly used proxy for assessing soil impacts is the area affected and the magnitude of rutting and soil displacement. Operationally, this is estimated in the field by sampling along transects or plots and counting the presence or absence of disturbance (p.e. Tavankar et al., 2017, Gier et al., 2018). Recently, the area impacted has been quantified directly using global positioning receivers (GPR), which also allows the retrieval of the area used by skid trails. Additionally, several international studies have used remote sensing technologies such as high-resolution imagery, unmanned aerial vehicles (UAVs), and LIDAR technology for rutting and soil displacement assessment (Haas et al., 2016; Nevalainen et al., 2017; Salmivaara et al., 2018; Ferencík et al., 2022). At the national level, there is no record of studies using these technologies to monitor harvesting machinery or soil impacts, indicating a clear need for future research. For instance, it is common knowledge that large forestry companies in Chile use GPRs mounted on harvesting machinery to monitor traffic, which can be used to quantify the area impacted and the traffic intensity. This also shows a worrisome trend in which the industry might be ahead of academia because of the proprietary nature of this information, which prevents advancing research in this area. Collaboration between the private and public sectors with the academia is thus much needed.

4.3.5. Soil recovery

For each soil type with forestry use in the country, it is necessary to determine the recovery times of the edaphic properties after harvesting. In general, soil recovery is related to site conditions, especially the water regime, texture, and biological activity of the soil, as well as the magnitude of impacts, which vary with depth in the soil profile (Page-Dumroese et al., 2006; Cambi et al., 2015). In a recent study, DeArmond et al. (2021) determined from a review of 121 articles that the recovery of soil physical properties naturally varies from a few years to several decades, primarily according to the type of forest assessed (biomes), traffic intensity, and soil texture. Long-term studies are required to identify and understand the factors that determine the soil recovery. An important effort is the North American Long-Term Soil Productivity study (Powers et al., 2005), which has evaluated the impact of clear-cutting, soil compaction, and organic matter removal on soil recovery times and site productivity in major forest types in North America over decades, with site-specific results (Page-Dumroese, 2020).

Efforts can be made to reduce soil recovery time, such as soil preparation activities in the establishment of intensively managed plantations, which is a common activity in the country that, if performed correctly, can improve soil physical properties related to rooting, air, and water capacity (Ramantswana et al., 2020). However, errors in the interpretation and application of soil preparation techniques can result in neutral or negative impacts on soil and site productivity (Albaugh et al., 2004; Rubilar et al., 2013). Despite the knowledge of the effect of soil preparation activities on some forest plantation growth in Chile (e.i., Rubilar et al., 2023), their effects on the recovery time and stability of soil properties associated with skid trails are unknown. This is particularly important because of the 2,3 million ha of forest plantations harvested using clear-cuts every ~22 years for *P. radiata* or ~ 12 years for *Eucalyptus* sp., and if soil cannot recover before the next rotation, soil quality might decline over time.

5. Conclusions

The findings of the collective research reviewed show a steadily increasing interest in reporting the impacts caused by the traffic of harvesting machinery, but almost two-thirds of the research body is concentrated in the last decade. The main disturbance is related to alterations of soil physical properties, followed by disturbance to flora structure and composition, chemical properties, hydraulics, and soil biological properties. This disturbance typically results in adverse effects on soil physical and hydraulic properties, with varying outcomes observed in chemical and biological properties, and vegetation structure and composition. The research is concentrated on a few soil types and geographic regions, highlighting the need to expand the research interest to other conditions, especially those with an active forest industry.

It is important to consider individual site conditions to reduce soil impacts. However, seven general and broadly applicable recommendations were identified and incorporated into best management practices. Common recommendations were preventive measures to reduce soil impacts including concentrating machine traffic along planned skid trails and selecting harvesting systems based on current soil characteristics. Corrective measures include actively monitoring harvesting operations to avoid exceeding predefined impact thresholds such as rutting depth. Mitigative measures consider the deactivation of skid trails to reduce the potential for surface runoff to cause erosion.

In Chile, where the forest industry plays a crucial role in the country's economy, only one indexed article was found, which raised the need to expand the search to national databases, where five additional articles were found. The national research is consistent with international studies regarding the generally negative impacts of the traffic of ground-based harvesting machinery on soil properties. However, it is discontinued, outdated, and does not apply to modern harvesting machinery. Although national studies mention the importance of soil moisture content, terrain slope, and traffic intensity on the magnitude of impacts, questions remain about the type of environmental impacts and soil disturbance for different soil types and operating conditions.

Several crucial research gaps were identified for Chile, which instead of being addressed individually, would be more appropriate to establish long-term environmental impact research sites where different aspects such as soil, water, vegetation, and fauna can be monitored due to harvesting operations and other forest management treatments. Considering the importance of the forest industry and the sustainable use of forest resources in Chile, this urgent need calls for a dedicated research program from government agencies such as the National Agency for Research and Development.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marco Contreras reports financial support was provided by National Agency for Research and Development. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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