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How and How Much, Do Harvesting Activities Affect Forest Soil, Regeneration and Stands?

Rodolfo Picchio¹ · Piotr S. Mederski² · Farzam Tavankar³

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Abstract

Purpose of Review Lowering the impact of forest utilisation on the forest environment is a part of the improvement in sustainable forest management. As part of forest utilisation, timber harvesting can also cause environmental implications. The main impact of forest operations is on the soil, on regeneration and on the residual stand. The aim of the present review was to identify the state of the art in forest utilisation, identifying how and how much forest operations affect forest soil, regeneration and the remaining stand. Particular attention was paid to the level of impact and potential to limit this.

Recent Findings There are a large number of publications tackling forest harvesting, but most of them do not give a comprehensive framework and they mainly focus on one or very few aspects of forest damage. In order to improve general knowledge of the impact of forest operations, it was proposed that the scope of recent findings should be examined and a compilation of the available results from different regions should be presented in one paper.

Summary It was found that the least impactful machine-based forest operations were harvester–forwarder technologies, while a larger scale of damage could be expected from ground-based extraction systems (skidders) and cable yarders. Animal power, if applicable, tended to be very neutral to the forest environment. A decrease in damage is possible by optimising skid trail and strip road planning, careful completion of forest operations and training for operators. The existence of legal documents controlling post-harvesting stand damage are rare and have been implemented in only two countries; there is no post-harvesting control on soil damage and natural regeneration.

Keywords Forest operations · Thinning · Selection cutting · Soil damage · Stand damage

Introduction

One of the main and essential aims of the last 20 years within the forestry sector was to improve sustainable forest management (SFM) [1]. SFM includes the ecological aspects of forest operations, and it aims to develop new methods and technologies for sustainable use of forest resources and to minimise

any negative impact on the environment [2]. Focusing on forest harvesting, it is important to consider high productivity (economic aspects), a low negative impact on the environment (environmental aspects) and safe working conditions for forest operators (ergonomic and social aspects) [3••]. Forest logging is an impactful operation which could lead to possible implications in forest ecosystem. In particular, in recent years, forest researchers have focused on the impact of forest operations in relation to the soil, the regeneration dynamics and the stand conditions.

It is important to underline that soil is highly sensitive to improper logging activities [4], and the soil environment could suffer substantially over a long period of time thereby affecting forest productivity and ecosystem efficiency [5]. Forest soil impacts with a higher intensity in terms of area are mainly linked to ground-based extraction systems, such as skidding and traditional cable yarding; however, growing harvester and forwarder use, especially in Europe [6], has also impact on soil compaction. With this in mind, one of the most

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important ecological issues for the forest sector is a minimisation of the ground disturbance caused by forest operations [7]. If not properly implemented, forest operations with extraction based on skidders or large forwarders could lead to high soil compaction [4], and later to soil erosion and rutting, particularly evident along skid trails and strip roads.

The impact on forest regeneration is more complex to evaluate directly. Some studies reported that soil compaction due to the passing of machinery often leads to an inhibition of potential tree regeneration [8, 9]. On the other hand, in other studies the improved recruitment of seedlings and saplings was observed in areas where soil had been scarified or modified by logging activities [10, 11]. So, this particular aspect of forest operation sustainability is very difficult to analyse unequivocally in the short period of time after an operation.

The impact on the residual stand may decrease the quality of residual trees but also increase tree mortality due to insect and disease infestation [11] and fungal decay [12] as well as lead to stem deformity and significant losses in final crop volume and value [13]. Furthermore, excessive damage to residual trees during logging operations may change aesthetic value and directly influence other ecosystem services, including recreational ones.

Taking into consideration the abovementioned dangers, the methods of felling, processing, bunching and extraction should be planned on a larger scale and for a longer period of time, with consideration to environmental, economic and social contexts [14]. In recent years, much scientific research has been focused on assessing the impact of logging in relation to sustainability, assessing forest ecosystem resilience and suggesting best practice.

In light of the large but scattered number of scientific publications on this topic, this paper is an attempt to bring together the in-depth knowledge and insights of experts within an integrated and comprehensive framework using research collated over the last decade with special attention to the last 5 years. In particular, the aim of this paper was to find out how contemporary studies and good practices contribute to the mitigation of environmental impact due to forest operations, such as soil damage and injuries to natural regeneration and the remaining stand.

Materials and Methods

Literature Research

One of the basic techniques to search for particular documents in a complex database is the use of Boolean Operators. The Boolean search method is a symbolic logic system that creates relationships between expressions and words. The use of Boolean search has the aim of analysing all studies in a specific research field. The research of papers for this review was

performed using the databases of Science Direct, ISI Web of Knowledge and Google Scholar. Using the search string “Forest operations impacts” and related synonyms expressions four specific categories, returned, in total, over 944,000 findings, while over 72,000 findings appeared once the search was restricted to research during the last 5 years (Fig. 1).

However, many items identified in the search were not completely related to the addressed topic. Eventually about 90 papers published in the last 5 years were selected and analysed with the focus on the evaluation of forest operations and the results of their impact on the environment, i.e. the soil, regeneration and the remaining stand.

Results and Discussion

Harvesting-Soil Interaction

Soil plays a crucial role in forest ecosystems by transmitting nutrients and water, providing energy flows that are linked to forest productivity and sustain biodiversity [15].

Features of Forest Soil After Harvesting

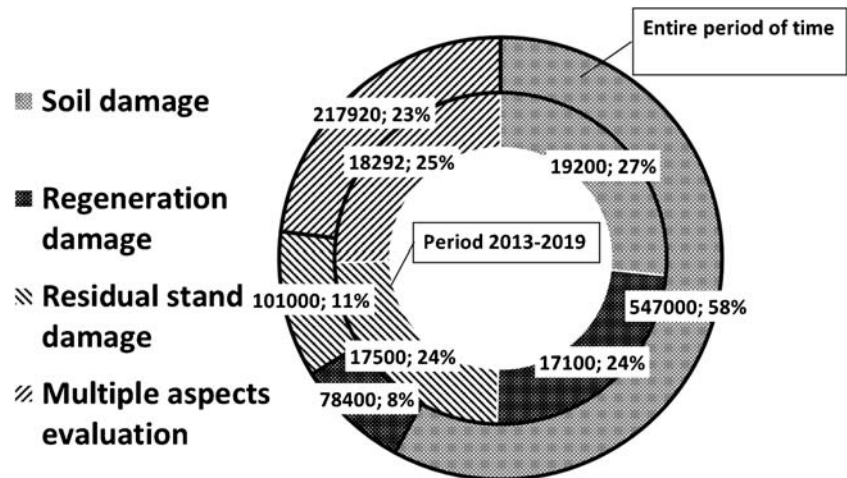
In terms of the visual features of the soil after a forest operation and the condition of the canopy cover, these can be included in one of the four following types: (I) undisturbed soil, canopy cover not removed (NDS-NCR), e.g. normal control samples; (II) undisturbed soil, canopy cover removed (NDS-CR), e.g. logging gaps without winching corridors; (III) disturbed soil, not canopy cover removed (DS-NCR), e.g. winching corridors; and (IV) disturbed soil, canopy cover removed (DS-CR), e.g. disturbed skid trails, landing sites and processing sites.

How

The physical, chemical and biological properties of the forest soil change as a result of harvesting operations, and this is commonly referred to as soil disturbance [4, 16–19]. Chemical and biological changes occur in the soil after physical modification. Therefore, changes in the physical properties of the soil are the most prominent indicator of soil disturbance following the use of logging equipment [4, 20]. Detrimental soil disturbance associated with ground-based extraction often includes compaction, rutting, lateral soil displacement, topsoil mixing and the formation of puddles.

A large number of factors influence the extent and severity of soil compaction. As found by many authors, overall harvesting operations can lead to a reduction in soil porosity [14, 19–23], increased soil erosion [20–24] and a decrease in root penetration and length expansion [19].

Fig. 1 Schematic representation of bibliographic research, detailed for the four specific thematic groups (soil damage; regeneration damage; residual stand damage; multiple aspects evaluation) and contextualised to the long period of time and to the period between 2013 and 2019



Soil compaction can lead to reduced water infiltration and hydraulic conductivity, which contributes to increased waterlogging on flat terrain and soil runoff with erosion on slopes. Soil compaction can reduce the access of plant roots and microorganisms to water, oxygen and nutrients. Long-lasting damage to the soil system can negatively affect forest productivity and ecosystem functionality [5]. One way to estimate the severity of logging damage to the forest soil is to measure soil bulk density before treatment and compare it with its critical level after harvesting operations [25, 26].

Picchio et al. [19] reported higher soil penetration resistance 10 years after skidding. An increase in the bulk density of soil should not always be regarded as equivalent to a detectable decrease in tree growth. Changes in soil bulk density that have led to some decline in the biological and vegetative development of beech and maple seedlings have been observed when increased by 0.15 to 0.43 g cm⁻³ [19]. Depending on soil type and tree species, the number of changes in soil compaction that will result in reduced plant growth varies. In this context, specific surveys are necessary to assess the real occurrence of the negative effects of bulk density increment on tree growth.

An important factor differentiating soil changes after harvesting is the impact of different machinery. Allman et al. [27] compared the influence of different logging machines on soil compaction and reported that all wheeled machines caused the same amount of soil compaction in the ruts, despite differences in tires, machine weight, etc. Cambi et al. [28] studied the effect of bogie tracks on the physical properties of the soil during forwarding operations in a coniferous stand in north-eastern Italy. The authors reported a clear difference in the physical parameters of the soil before and after operations. Eroğlu et al. [29] studied the effects of four timber logging techniques (cable yarder, skidder, manpower and chute system) on some physical and chemical properties of the soil in Turkey's forests. It was found that logging by skidder can have a clear influence on soil permeability, bulk density and

soil water balance, and that skidding can reduce the content of organic matter and nutrient levels in the soil.

Lang et al. [30] studied the influence of mechanical site preparation treatments on the physical properties of disturbed soils in harvested wet lands. Their results showed that macroporosity had not recovered to the pre-harvest levels for any site preparation treatments except Mole-Plowed; bulk density and total porosity recovered to near pre-harvest levels for all treatment combinations, but saturated hydraulic conductivity rates remained lower than the pre-harvest values.

Summarising, forest operations usually lead to changes in the soil's physical, chemical and biological characteristics. One of the most important factors influencing soil impact intensity is the level of mechanisation, as well as machine weight and type of operation (i.e. skidding or forwarding). Soil compaction can be reversed; however it may take more than 10 years for full rehabilitation [31].

How Much

The extent and severity of soil disturbance during harvesting operations depends on several factors that can be divided into three groups:

1. Stand conditions: extracted timber volume [28, 32], soil type and texture [33–35], soil moisture content [25], soil's organic matter content, site topography [34, 35], stand density and canopy extension [34, 35];
2. Yard logistics: harvesting system, advanced level of logging operation planning, type of machines, logging method [28, 32], machine and load mass, tire pressure, vibrations transmitted by vehicles [20], intensity of machine traffic [32], weather conditions during skidding operation, training, experience and expertise of operators as well as planning and worker proficiency [36];
3. Forest road network characteristics: density of roads and skid trails, slope gradient of skid trail [20].

Expansion of soil damage by logging depends on the type of technology used [4, 17]. More pressure, slipping and a lower speed can dramatically increase soil disturbance on a steep slope trail. Venanzi et al. [37] demonstrated that physical, chemical and biological features of the soil can be greatly impacted by harvesting operations and consequently, eventually soil mesofauna could be changed. In particular, heavy ground-based logging equipment can cause severe and long-lasting damage of the soil system, which can negatively affect forest productivity and ecosystem function [5, 16, 38]. The results of various studies of the impact of mechanised harvesting on forest soil show that changes to the soil can be very different, from low to very high, including values that exceed 100% (Table 1).

In addition, at a low level of mechanisation, Jourgholami and Majnounian [39] reported that mule logging had a statistically significant effect on soil bulk density along mule trails before and after extracting. Soil bulk density increased

significantly as animal passes increased in number; however, the degree and level of compaction did not differ with increasing trail slope. In contrast, Badraghi et al. [53] evaluated soil disturbance and compaction caused by mule extraction and reported that only 1% of the harvested area was disturbed, and soil bulk density increased only by 0.3%.

Limiting and Preventing Disturbance

One goal of forest managers in harvesting should be to minimise the impact of vehicles on the soil, the negative effects of which can be significant and long lasting, although often unrecognised or neglected [4]. The ongoing trend to constantly increase the size, power and load of machines makes it even more imperative to plan logging logistics in order to limit soil disturbance and stand damage [11]. In the available studies, suggestions to reduce soil damage due to forest operations can be grouped into the following:

Table 1 Magnitude of soil changes as published by selected authors

Reference	Year	Reference number	Investigated parameters	Magnitude of soil changes (A–B–C–D) ¹
Labelle and Kammermeier	2019	[33]	Soil bulk density	A
Picchio et al.	2016	[14]	Penetration resistance–shear resistance	C–B
Jourgholami and Mainounian	2013	[39]	Soil bulk density	A
Allman et al.	2015	[27]	CO ₂ concentration	D
Jaafari et al.	2014	[40]	Soil bulk density–organic carbon–nitrogen–phosphorus–potassium–hydrogen	B–C–C–A–A–C
Kleibl et al.	2014	[41]	Soil bulk density–penetration resistance–deflection–porosity–CO ₂ concentration	A–C–C–A–B
Allman et al.	2015	[25]	CO ₂ concentration	D
Hosseini et al.	2015	[42]	Electrical conductivity–organic carbon–moisture–porosity–soil bulk density	A–A–A–B–B
Solgi et al.	2015	[20]	Soil bulk density	B
Zhou et al.	2015	[43]	Phosphorus–potassium	A–A
Cambi et al.	2016	[28]	Soil bulk density–penetration resistance–porosity–QBS-ar index ²	B–B–A–A
Naghdi et al.	2016	[22]	bulk density–porosity–moisture–forest floor biomass–soil OC–N–P–K–pH	B–B–B–C–B–C–B–B–B
Naghdi et al.	2016	[44]	Soil bulk density	B
Ozturk	2016	[45]	Penetration resistance	C
Proto et al.	2016	[46]	Soil bulk density	C
Abdi et al.	2017	[47]	Soil bulk density	B
Cudzik et al.	2017	[48]	Penetration resistance	D
Jourgholami et al.	2017	[49]	Erosion reduction with straw mulch application–erosion reduction with sawdust application	C–C
Macri et al.	2017	[50]	Penetration resistance–soil bulk density–porosity–water content	D–B–A–C
Malvar et al.	2017	[51]	Soil bulk density–porosity	A–A
Tavankar et al.	2017	[18]	Soil bulk density	A
Sealey and Van Rees	2019	[52]	Soil bulk density	A

¹ Magnitude of soil changes: A: low 0–25%; B: medium 25–50%; C: high 50–100%; D: very high > 100%

² QBS-ar index: soil biological quality index referred to micro-arthropod communities

1. Machine traffic should be carried out (if possible) during dry and favourable weather conditions [27, 44, 54–56], and it is important to reduce the number of load passes.
2. The proper design of forest roads can play an important role in reducing soil disturbance [18, 55–59], and it is important to reduce the trail slope gradient.
3. Both training and supervision can be efficient in soil impact mitigation [12, 14].
4. Employing ameliorative site preparation could contribute to initial survival and an increase in early growth on harvested stands with wet soil conditions [16, 30].
5. Applications of straw and sawdust mulch following skidding operations can reduce surface runoff and sediment on skid trails [16, 49].
6. Traditional animal power with a low impact on the soil can be used for timber extraction in steep terrain conditions [39].

Harvesting-Tree Regeneration Interaction

Timber harvesting represents also a key factor in the ecological management of stands, changing (in negative or positive way) stand structure and species diversity [13, 60]. Availability to sunlight, reduction in plant competition and scarified soils are needed for tree regeneration, and these favourable conditions can be created by harvesting operations [10, 61•]. Proper harvesting operations not only control the amount of sunlight that reaches the forest floor but also make the soil and site conditions ideal for the successful natural regeneration of trees [61•]. Forest managers applying close-to-nature silviculture plan harvesting systems to control the available light on the forest floor in order to obtain regeneration species diversity. In addition to the positive impact of harvesting, mechanical damage to young trees is often an inevitable side effect. With this in mind, good forestry practice should consider ways to mitigate these negative effects.

How

Effect on Seedling Growth The felling of trees and the opening of the forest canopy increases the intensity of light reaching the forest floor, and the establishment and growth of a tree's regeneration is positively affected [13]. Disturbances that open small canopy gaps create environmental heterogeneity, particularly the amount of light and water reaching the forest understory, and thereby provide a range of regeneration niches for trees and other plants [60]. In addition, scratches on the surface of forest soil due to skidding create favourable conditions for seed germination and further sapling growth [10]. However, in some research it was found that the germination rate had a

strong negative correlation with an increase in soil bulk density [22–24, 62]. Moreover, germination rates and growth could be significantly reduced by the number of passes and the trail slope gradient [19, 22, 23, 55]. The height of seedlings was also found to be lower on machine operating trails than in undisturbed areas [63]. The effects of soil compaction may create particularly challenging conditions for seedling survival during drought periods, because seedlings with short roots may be unable to access water at deeper soil levels [44, 55].

Mechanical Damage Forest regeneration can be affected by mechanical damage during harvesting [18]. The extent and severity of damage to forest regeneration can be influenced by several factors, from which the logging system and harvesting intensity seem to be the most influential (Table 2).

In forest with a natural regeneration system, after shelter-wood and selection cuttings, damage to saplings is common and usually inevitable. When timber harvesting has advanced planning and the developed forest operation is applied, a reduction in damage to regeneration may be more feasible. Damaged regeneration by tree felling operations is usually in the form of stem breakage, while the winching operation usually causes uprooting [18]. When trees are growing, stem flexibility decreases, the probability of uprooting reduces while the probability of stem breakage increases [18]. The amount of regeneration damage in the winching stage is usually higher than in the felling and skidding stages. This was also confirmed by Picchio et al. [63], where bunching (during winching) was the main cause of damage to regeneration during cable skidder logging, and the amount of regeneration damage on steep slopes was higher than on gentle slopes.

The amount of damage to regeneration can decrease when workers have more experience [61•]. Soil scarification can increase the success of natural regeneration [10], but at the same time soil compaction may reduce the establishment of regeneration [44] and growth of regeneration [23]. Compacted soil layers due to forest machine traffic are the most common problem affecting seedling regeneration after forest harvesting [23, 432, 44]. García-Orenes et al. [68] reported that salvage logging may damage the bank of seedlings and affect plant regeneration after fire, reducing plant density. Salvage logging can also decrease the amount of natural tree regeneration [24, 69]. Fernández and Vega [70] found no detrimental effect of a salvage logging treatment compared with natural regeneration. These contradictory results could be due to factors such as the type of soil, when and how the salvage logging treatment is carried out and meteorological conditions which can be decisive.

Table 2 Affective factors in level of damage to regeneration by harvesting operation

Reference	Reference number	Harvest intensity	Ground slope	Logging system	Planning level	Machine type	Machine traffic	Logging season
Picchio et al. 2019	[57]		+					
Sealey & Van Rees 2019	[52]							+
Solgi et al. 2019	[23]						+	
Picchio et al. 2018	[11]			+		+		
Badraghi et al. 2018	[53]			+				
Premer and Froese 2018	[64]			+				
Naghdi et al. 2016	[22]						+	
Gavinet et al. 2015	[65]	+						
Tavankar et al. 2015	[13]	+	+					
Schweitzer and Dey 2013	[66]				+			
Schweitzer and Dey, 2013	[66]	+						
Picchio et al. 2016	[14]			+	+	+		
Stańczykiewicz et al. 2015	[67]			+		+		

How Much

The share of regeneration that can be damaged during different logging systems can vary from several percent to more than 60% (Fig. 2) [67]. The mean frequency of damage on seedlings, small saplings and large saplings were 8.8%, 12.8% and 19.5%, respectively, in skidder extraction in mixed beech stands [18]. A lower level of damage was observed after cable-skidding and ranged from 4.9 to 7.1% [18]. Stańczykiewicz et al. [74] studied the damage of regeneration using two systems: (1) a tower cable system combined with farm tractor and (2) a skidder in a mature spruce stand. The damage of regeneration using the tower cable system (23.9%) was lower than using the skidder system (61.3%). The tower cable system mostly destroyed regeneration, while during skidder logging, it is usually stem and side-branches that can be broken. Most damage to regeneration using the tower cable system occurred on the shortest regeneration (up to 0.5 m from the ground), while skidder logging usually affected the regeneration of medium height (0.5–4.0 m).

Limiting and Preventing Damage to Regeneration

Damage to regeneration can be limited by introduction of the following:

1. Identifying and Marking fragments of regenerated stands for protection and avoiding winching through these stands; planing of skid trails and lay out landings should be carried out before harvesting operations begin.

2. Focusing on protection of the residual stand rather than on the trees being removed.
3. Considering the felling season, there is usually less damage during the winter months.
4. Matching machine/equipment type, size and deployment to stand and site conditions [19].
5. Limiting or concentrating machine activity on skid trails and access corridors.
6. Increasing awareness of the consequences of mechanical injuries to trees and forest stands.
7. The use of the snatch block could positively improve the winching operation.
8. Alternatively, when possible and when financially acceptable, different forms of extraction should be used, for example, cable cranes or traction-winch-supported forwarders [74].
9. A detailed planning strategy will reduce damage to a level which is acceptable and predictable [12].
10. For a post-harvesting assessment of a logging operation, obtaining an accurate measure of residual stand damage is recommended [12, 18].
11. A post-harvest inventory of soil and stand damage, and prioritisation of contractors that have a good level of training, should be carried out for reduced impact logging (RIL) [19].

Harvesting-Stand Interaction

Forest operations influence the stand condition, which can be measured by taking into account several factors, mainly

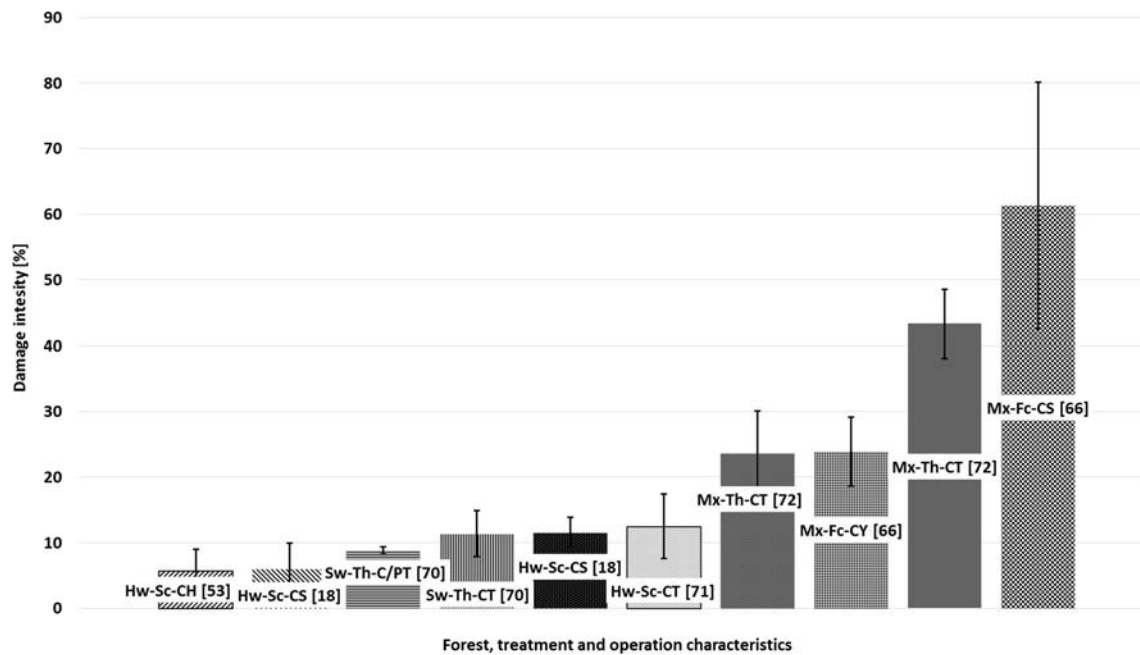


Fig. 2 Damage intensity of regeneration in different forest types after silvicultural treatments provided by various forest operations. Results presented as average values \pm standard deviation. Abbreviations used on bars: Hw-Sc-CH [53]: hardwood forest, selection cutting with chainsaw and horse skidding, published in [53], damage 6% \pm 2.3%; Hw-Sc-CS [18]: hardwood forest, selection cutting with chainsaw and skidder, published in [18], damage 6% \pm 4.1%; Sw-Th-C/PT [71]: softwood forest (pine forest), thinning with chainsaw and processor with tractor skidding, published in [71], damage 9% \pm 6.6%; Sw-Th-CT [71]: softwood forests (pine forest), thinning with chainsaw and tractor skidding, published in [71], damage 11% \pm 7.9%; Hw-Sc-CS [18]: hardwood forest, selection cutting with chainsaw and skidder,

published in [18], damage 12% \pm 0.6%; Hw-Sc-CT [72]: hardwood forest, selection cutting with chainsaw and tractor skidding, published in [72], damage 13% \pm 4.9%; Mx-Th-CT [73]: mixed forest, thinning with chainsaw and tractor skidding (with snatch block), published in [73], damage 24% \pm 6.5%; Mx-Fc-CY [67]: mixed forest (spruce-beech forest), final cutting with chainsaw and cable yarder [67], damage 24% \pm 6.8%; Mx-Th-CT [73]: mixed forest (pine and other hardwood species), thinning with chainsaw and tractor skidding without snatch block, published in [73], damage 43% \pm 5.2%; Mx-Fc-CS [67]: mixed forest (spruce-beech forest), shelterwood cutting with chainsaw and skidder [67], damage 61% \pm 18.8%

environmental, social and economic [3••], as well as ergonomic factors and those linked to product quality [75].

It may be considered that the level of damage depends on the machine operator's skills; however, there are certain objective reasons that can cause a higher probability of damage. The level of damage caused to residual trees during forest operations has been described by several authors and many factors influencing damage level have been indicated. As a summary of these factors from different findings, Siren et al. [76] quote in their publication that the level of damage depends on the forest characteristics, such as the amount of timber removed during harvesting, stand density and basal area. In addition, well designed access to the forest can limit the probability of damage, such as skid-trail spacing or road density [12]. Extracting timber on steeper slopes usually causes more damage [19, 77, 78].

It was also found that tree injuries depend on the season, and can be higher in summer [79], as well as affected by stand structure: in uneven-aged stands, damage can be more frequent, especially among younger trees [76]. Mechanised harvesting tends to cause less damage than using a chainsaw for felling and more damaged trees are observed near strip roads

[80, 81]. The harvesting system definitely influences the level of damage: the long wood system (LWS) is usually associated with a higher probability of damage compared with the short wood system (SWS) [82].

Wounds created due to bark and cambium removal can heal; however, bark pockets or stone pockets are created, defects difficult to detect many years after wounding, especially if they occurred on a young tree. Newly grown wood tissue can cover the wounded area, but the disjunction between the old and the new tissue can create ring shake. Generally, wounds negatively impact diameter growth which may slow down by 8–13% [12, 83]. The healing rate is faster on younger trees if the wound is higher on a tree and at a lower elevation [18]; a slower healing process was observed on bigger wounds as well as on southern slopes [18].

In addition to discontinuity in the wood, sometimes irregular stem forms, local grain deviations and colour variations (not necessarily pathological) can be observed. However, injured trees can have a high risk of pathogen infections following harvesting damage, since open wounds with missing bark and cambium can be susceptible to fungi. Bark inclusions reduce the mechanical strength and the aesthetic appeal of

artefacts; therefore, they are not accepted in timber for packaging or for flooring. Wounded trees are affected negatively, they produce lower-quality timber [84] and a lower diameter increment can be observed [12, 83].

An analysis of the presented findings shows that the most important and principle injuries to the remaining stand are bark and cambium removal from trees. Most of the damage is observed close to the skid trails. Trees with damage will produce lower quality timber and are vulnerable to fungi and rot development.

How

Damage to the remaining stand can be observed after thinning, selective cutting or another partial tree removal from a stand [76]. Damage is generally understood as bark and cambium removal with partial wood tissue disturbance, also a broken tree. It is considered that damage can occur due to felling, processing or timber extraction [76]; however, it was also confirmed that rolling rocks in hilly areas can be a reason for damage to remaining trees [85]. Additionally, another cause of damage which is as frequent as injuries generated by harvesting, can be animal browsing which affects ca. 3–4% of wounded trees in the stand, or twice as many in spruce stands [86].

During harvester–forwarder operations, it is usually the felling and pulling of trees by the harvester boom which injures the remaining trees [76]. In motor manual operations with a chainsaw in LWS, it is usually skidding rather than felling which creates more damage [12, 84]. If winching and skidding are analysed as two separate operations, it can be seen that skidding causes more damage to the remaining stand [78].

How Much

In practice, thinning or selective cutting operations are rather associated with some level of damage to the remaining stand, although it is occasionally possible to complete the extraction of short logs using animal power without causing damage [53]. However, in order to keep damage at an acceptable level, legal requirements or limitations have been implemented in some countries to control damage to the trees. In Finland, for example, if the percentage of trees with damage is over 15%, it exceeds the limit of the Forest Act [76]. In Poland, the usual acceptable level of damage to the remaining stand after thinning is 5%. Usually, there are financial consequences when a higher share of trees is injured.

Short Wood System vs Long Wood System

Less intensive damage is usually observed in CTL in thinning, and on average only 7–8% trees can be affected, with no

particular difference between older (70–75 y.o.) and younger stands (30–35 y.o.) or species: oak or spruce [87]. Cudzik et al. [48] confirmed a lower level of damage, 4–6% in thinned stands, where CTL was used, and 9–12% for chainsaw felling with skidding in the late thinning of pine stands.

This was also mentioned by Siren et al. [76], who compared studies from Slovenia from the last decade, where CTL caused 13–15% and 17–19% when motor-manual technology was used. A similar level of damage (14–17%) was observed after skidding in an even-aged stand of Corsican pine [73]. An interesting feature of this study was that, 10 years after harvesting/skidding, more damage was revealed (17%), which was explained by the fact that some trees may be hit but have no bark removal, and the consequences of this (dead cambium) may become visible after many years. Further studies, after 20 years, revealed nearly 18% of damage and that increase was explained by the mortality of some trees [11]. This study also confirmed that skidding caused more damage than felling, and the same was confirmed by Tavankar et al. [88] (16.3% and 5.2% by skidding and felling, respectively).

To reduce the level of damage while skidding, the short wood system (SWS) may be applied. In studies carried out by Jourgholami [89], there were 44% fewer damaged trees when SWS was used during skidding. There were also ca. twice as many trees with damage when LWS was applied compared with SWS in close proximity to the skid trails (up to 3 m). This study, however, does not present the productivity when SWS was used.

Nevertheless, there was a substantial difference when LWS was used with skidding as extraction, which left 18% of trees with damage and more than double (45%) the number of injured trees when large and long logs from a much older stand, i.e. 110 y.o. oak were skidded [87]. The same authors observed that a higher thinning (or shelterwood cutting) intensity can cause a higher level of damage. More injured trees were also observed closer to the strip or skid roads [87]. When tracked machines were used more damage to the roots was observed, although studies were carried out in spruce stands, and these trees have roots which are only partially under the surface of the soil [87].

Sirén et al. [76] also provided an interesting method for damage estimation, which considered monitoring the number of trees with damage during the whole life of the stand. According to these authors, modelling showed that during a 160-year rotation period and after 10 thinnings, the total number of damaged trees continuously grew and reached 90% at the end of the rotation. Sirén et al. [76] also mentioned that in old stands, a higher share of damaged trees (64–70%) can be recorded.

Furthermore, in the study by Sirén et al. [76] in uneven-aged stands, the percentage of damaged trees (according to the classification of the Forest Act) was 13.8%. Usually in

selection cuttings it is very difficult to reach low damage levels typical for even-aged stands.

Full Tree System

The full tree system (FTS), in which felled trees with branches are extracted, can also leave a substantial share of the trees with damage. In a study carried out in Italy, there were 35–50% of the trees with damage after the skidding or yarding of whole trees using various methods. The use of snatch blocks when skidding and semi-automatic carriage when yarding were effective in limiting the damage level, while snatch blocks also turned out to be effective in limiting damage without a loss in productivity [17]. A high level of damage was also observed when a feller–buncher was used in Spain, where up to 50% of the remaining trees in coppice stands had some damage [90]. A lower harvesting intensity could cause a lower level of damage in FTS, i.e. up to 22% (in tropical forest conditions) [91]. However, in that study, less than one tree per hectare was harvested, albeit of large DBH sizes ranging from 60 to 216 cm [91].

Animal Power

A very low level of damage can be observed when animal power is used. Animal extraction was completed without any damage [53] when short wood was extracted by carrying, or very low, ca. 3% when animal skidding on the ground was provided.

Limiting Stand Damage

Taking into account the studied literature, there are few proposals for limiting stand damage. Basically, many authors suggest careful harvesting and skidding with particular attention to areas close to skid roads. However, a suitable design of skid roads can limit the level of damage. There is also the more objective possibility of using CTL technology and animal force, which tend to cause very low levels of damage to up to 5% of the remaining trees in the stand (Fig. 3). A high level of damage is mainly observed during skidding, when long wood is extracted or a whole tree system is applied (Fig. 3). These systems require particular attention when timber extracting is in operation.

Conclusions

Felling and extracting of timber from forests has an inevitable impact on the environment. This impact is either in the form of soil disturbance, regeneration or stand damage.

Soil Damage

Soil damage seems to be the most difficult to avoid. Any machine (or animal power) has impact on the soil, especially at the stage of timber extraction. Soil disturbance includes a change in the physical properties, followed by modifications in the chemical and biological properties. Common methods used to estimate soil damage severity include the measurement of bulk density or penetration resistance which is compared with critical values, when possible. For example, regarding bulk density, critical values are limiting factors for root growth, depending on the type of soil, and they vary from 1.4 Mg m⁻³ for clay soils to 1.8 Mg m⁻³ for sand and loamy sand soils. The organic carbon or CO₂ concentration and QBS-ar index are parameters which also appear in the latest research widening the knowledge of soil reactions to forest operations.

Damage expansion generally depends on the method of forest operation and the machines used, mainly their weight, load and number of passes. Weather conditions, tyre variations and size are also essential in limiting rutting and general soil erosion. Good forest roads and skid trail (strip road) networks, as well as their quality, can be essential in limiting soil damage. Nevertheless, damage and erosion on slopes with greater gradients are difficult to control. However, erosion control can be achieved when brushwood, straw or chips/sawdust mulch are applied on skid roads during and after extracting. In any cases of changes in soil properties, it is worth noticing whether soil regeneration takes place, and if not, a reclamation process can be put in place to return the soil to the pre-harvest state.

Regeneration Damage

Forest operations can be very severe for forest regeneration. However, it is worth mentioning that harvested trees open the canopy and initiate soil scarification which contributes to future tree growth. On the other hand, germination, young tree growth and root development can be negatively affected after forest operations, where an increase in bulk density was observed after high traffic intensity or on steeper slopes.

Ground-based extraction-transport systems, where timber has direct contact with the soil, usually cause more damage to regeneration than other systems such as forwarding or aerial transport systems.

Limiting damage in natural regeneration is difficult as young trees grow at a higher density. Using forwarders and sky yarders should limit injury, as well as the planning of skid roads and winching corridors before felling and extracting.

Stand Damage

The presented results have shown that it is possible to restrict the level of damage to the remaining stand at a low level by using mechanised CTL forest operations. In harvester–

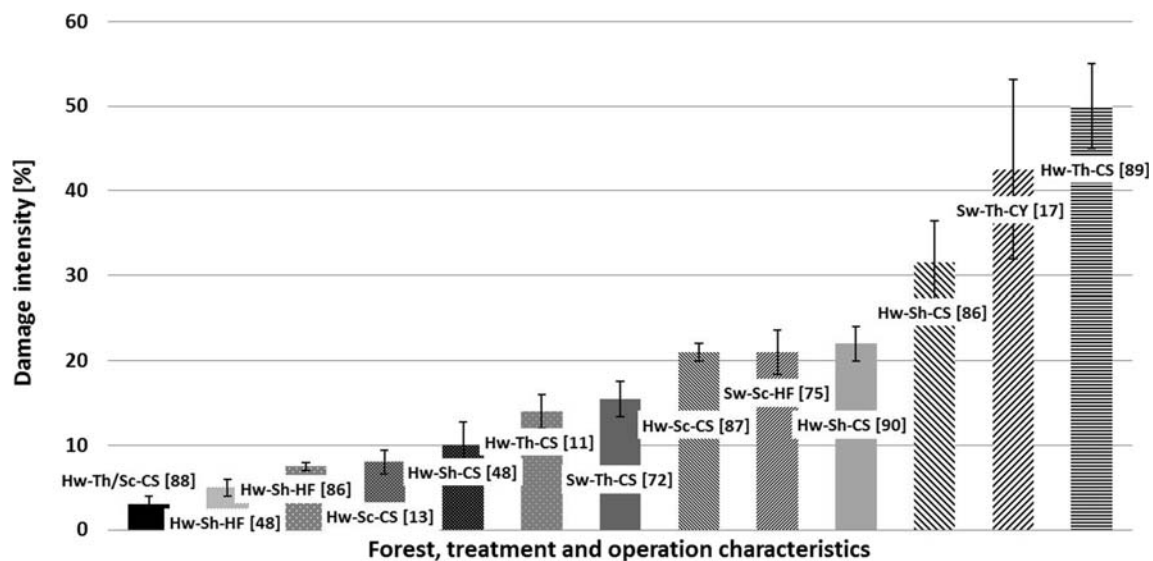


Fig. 3 Damage intensity to remaining stand in different forest types after silvicultural treatments provided by various forest operations. Results presented as average values \pm standard deviation. Abbreviations used on bars: Hw-Th-Sc-CS [89]: hardwood forest, thinning or selection cutting with chainsaw and skidder, published in [89], damage $3\% \pm 1.0\%$; Hw-Sh-HF [48]: hardwood forest, shelterwood cutting with harvester and forwarder, published in [48], damage $5\% \pm 1.1\%$; Hw-Sh-HF [87]: hardwood forest, shelterwood cutting by harvester and forwarder, published in [87], damage $8\% \pm 1.0\%$; Hw-Sc-CS [13]: hardwood forest, selection cutting with chainsaw and skidder, published in [13], damage $10\% \pm 2.8\%$; Hw-Sh-CS [48]: hardwood forest, shelterwood cutting with chainsaw and skidder, published in [48], damage $14\% \pm 2.0\%$; Hw-Th-CS [11]: hardwood forest, thinning with chainsaw and skidder, published in [11], damage $16\% \pm 2.1\%$; Sw-Th-CS [72]: softwood forest (pine), thinning with chainsaw and skidder, published in [72], damage $21\% \pm 1.0\%$; Hw-Sc-CS [87]: hardwood forest, shelterwood cutting with chainsaw and skidder, published in [87], damage $21\% \pm 2.6\%$; Sw-Sc-HF [75]: softwood forest, selection cutting with harvester and forwarder, published in [75], damage $22\% \pm 2.0\%$; Hw-Sh-CS [90]: hardwood forest, shelterwood cutting with chainsaw and skidder, published in [90], damage $32\% \pm 4.9\%$; Hw-Sh-CS [86]: hardwood forest, shelterwood cutting with chainsaw and skidder, published in [86], damage $43\% \pm 10.6\%$; Sw-Th-CY [17]: softwood forest, thinning treatment by chainsaw and cable yarder, published in [17], damage $50\% \pm 5.0\%$; Hw-Th-CS [89]: hardwood forest, thinning or selection cutting with chainsaw and skidder, published in [89], damage $50\% \pm 5.0\%$.

forwarder-based thinnings, damage should be at level of over several percent of the remaining trees, although it can occasionally reach ca. 20%. This level, however, should be treated as exceptional. A higher share of injured trees can be observed when skidding is used, and it can vary from ca. 10 to 20% in the long wood system. However, this may double when full trees are extracted. When yarding is used, the expected damage can also vary from 35 to 50%.

Post-Harvesting Assessment

According to the studied literature, there are local prerequisites that may be helpful in limiting damage to the remaining stand. Taking into account best practice, there are two European countries that have legal prerequisites to control stand damage: in Poland, no more than 5% of the remaining trees should have injuries. If the percentage is higher, financial penalties may be imposed on the entrepreneurs carrying out forest operations. In Finland, legal regulations accept damage no higher than 15%. The literature analysis presented shows that there is no control on the amount of soil damage as well as natural regeneration.

CS [73]: softwood forest (pine), thinning with chainsaw and skidder, published in [73], damage $16\% \pm 2.1\%$; Hw-Sc-CS [88]: hardwood forest, selection cutting with chainsaw and skidder, published in [88], damage $21\% \pm 1.0\%$; Sw-Sc-HF [76]: softwood forest, selection cutting with harvester and forwarder, published in [76], damage $21\% \pm 2.6\%$; Hw-Sh-CS [91]: hardwood forest, shelterwood cutting with chainsaw and skidder, published in [91], damage $22\% \pm 2.0\%$; Hw-Sh-CS [87]: hardwood forest, shelterwood cutting with chainsaw and skidder, published in [87], damage $32\% \pm 4.9\%$; Sw-Th-CY [17]: softwood forest, thinning treatment by chainsaw and cable yarder, published in [17], damage $50\% \pm 5.0\%$; Hw-Th-CS [90]: hardwood forest, thinning treatment by chainsaw and skidder, published in [90], damage $50\% \pm 5.0\%$.

The area of soil damage can be controlled naturally by the design and establishment of permanent skid trails (for skidders) or strip roads (for forwarders). However, in both cases, there is still the possibility of additional damage due to unskilled operators. The same can be observed in natural regeneration. Therefore, the setting of maximal limits, as in the case of stand damage, should further limit soil disturbance and injuries to natural regeneration.

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Compliance with Ethical Standards

Conflict of Interest Rodolfo Picchio, Piotr S. Mederski and Farzam Tavankar declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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