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REVIEW ARTICLE

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A Meta-analysis of the effects of ground-based extraction technologies on fine roots in forest soils

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Abstract

Fine roots are an important component of forest soil as they play a key role in fundamental processes like plant nutrition and water supply. As with all the features of forest soil, the compaction related to the forest operations and, in particular, to the wood extraction via ground-based technologies could lead to a significant impact on the presence of fine roots in the soil affected by the passage of the machines. Considering the lack of a review, we used a meta-analytic approach to synthesise effect sizes of ground-based extraction technologies affecting the presence of fine roots in the soil, using a multivariate mixed-effects meta-analytic model. The obtained results revealed that the presence of fine roots in the soil affected by the passage of the machines was significantly reduced by both skidding ($g = -1.23$, 95%CI -1.87, -0.60) and forwarding ($g = -1.37$, 95%CI -2.01, -0.74). Due to the higher soil compaction caused by forwarding, this method had a marginally but statistically significant greater impact than skidding. We further confirmed the hypothesis that soil compaction and the presence of fine roots were strongly correlated, with the latter being greatly reduced in compacted soils characterised by higher bulk density. What is more, even more than 20 years after a harvesting intervention, the presence of fine roots was significantly lower in both strip roads (forwarding) and skid trails (skidding) as compared to areas which were not impacted by the machine passage. This shows that fine roots are particularly vulnerable to forest operations. On the other hand, the majority of the trails in the database used for the meta-analysis were created in countries that favour the creation of a small number of widely used trails. Therefore, it would be scientifically valuable to do a comparative evaluation in various forestry contexts, such as in the Mediterranean area, where the development of the forest trails network is oriented on creating a large number of trails with low traffic volumes. Because machinery-induced soil compaction is the major driver of the decrease in fine roots in skid trails and strip roads, both the application of best management practices as well as of a smarter planning of the trail network to limit soil compaction are strongly recommended. Both applications are highly recommended to be used in the planning phase and in the practical implementation of logging activities.

KEYWORDS

forwarding, reduced-impact logging, skidding, soil compaction, sustainable forest management, sustainable forest operations

1 | INTRODUCTION

Fine roots (diameter less than 2 mm) are fundamental elements in each forest soil ecosystem (Freschet et al., 2021; Lorenc et al., 2018; Weemstra et al., 2020). The main role of fine roots is related to tree nutrition, as these have the function to uptake water and nutrients from the surrounding soil (Huang et al., 2022; Jagodziński & Kałucka, 2011; Matulewski et al., 2022). Fine root production accounts for about 33% of the global annual net primary production, although fine root biomass generally represents less than 10% of the total forest biomass (Cao et al., 2020; Jagodziński et al., 2014; Karki et al., 2022). Furthermore, fine roots contribute to about one-third of the overall litter input, therefore they are also a fundamental component of the carbon and nutrient cycling among trees and forest soil (Clemmensen et al., 2013; Ding et al., 2019). In particular, it has been found that carbon and nutrients returned to the soil after fine root decomposition can be even higher than from leaves, as a consequence of the very rapid turnover of fine roots (Eldhuset et al., 2017; Freschet et al., 2013; Głuszek et al., 2015).

As it happens for any component of the forest soil (Karami et al., 2023; Latterini, Venanzi, et al., 2023; Mohieddinne et al., 2022), the features and presence of fine roots can also be considerably affected by forest management activities and particularly by ground-based forest operations, mostly as a consequence of machinery-induced soil compaction (Högberg & Wester, 1998; Jourgholami, Feghhi, Tavankar, et al., 2021; Malo & Messier, 2011; Proto et al., 2016). Rooting is indeed ensured only in soils where a constant supply of water, nutrients and gas exchange is maintained (Flores Fernández, Rubin, et al., 2019; Schäffer et al., 2009) and previous research highlighted how the compacted soil after the passage of heavy machinery limits rooting capacity (Mariotti et al., 2020) and alters gas fluxes (Vantellingen et al., 2022).

Several studies highlighted that the presence of fine roots in the soil affected by the passage of the heavy machinery typically applied in forest operations is substantially decreased in comparison to the undisturbed soil (DeArmond et al., 2022; Malo & Messier, 2011; Schäffer, 2022). On the other hand, some research showed a no significant difference in fine root density between the skid trails and the soil not affected by the passage of the machinery (Stutz et al., 2017). Furthermore, scientific literature in the topic reports high variability concerning the issue of the recovery time needed after the harvesting intervention. Indeed, Schäffer (2022) reported that a recovery trend was observed after 10 years in the major part of the investigated research sites, while DeArmond et al. (2022) indicated that even after 27 years, the fine roots presence in the compacted soil is still much lower than in the undisturbed one, confirming the findings from Warlo et al. (2022) which detected a statistically significant lower presence of fine roots in the skid trails 10 years after the harvesting operations.

Given the abovementioned variability reported in the previous studies and the important role of fine roots within the forest soil system, it is imperative that more information is collected for a deeper understanding in the effects of disturbance (Meyer et al., 2014; Sugai et al., 2020; Watson & Kelsey, 2006). It is also worthy of acknowledging that few studies deal with this topic in comparison to the amount of studies conducted on other forest soil features (Schäffer, 2022). What is more, there is no review on this topic in the current literature.

It is expected that soil compaction can lead to a decrease in the presence of fine roots, therefore a quantification of the effects of machinery-induced compaction and a clear identification of the main driver of this process will be valuable. Thus, a systematic literature review may fail to deepen our knowledge in such topic and therefore we decided to apply a meta-analytic approach to investigate the effects of ground-based harvesting technologies on the presence of fine roots in the soil. Meta-analysis is a statistical technique that is used to develop a literature review summarising the results of several studies dealing with the same topic quantitatively (Gatica et al., 2022; Ghorbani et al., 2023; Gong et al., 2021; Meaza et al., 2022). The main benefit of using meta-analysis is that the results from several studies with comparable experimental designs are statistically analysed to produce overall conclusions that would not have been evident from a single trial (Hedges et al., 1999; Lajeunesse, 2011). Furthermore, meta-analysis gives the possibility of obtaining a quantitative and objective evaluation for topics in which the literature reports substantial variability and lack of a clear trend. Therefore, this technique results in highly suitable for the investigation of the influence of ground-based forest operations on the presence of fine roots in the forest soil.

In particular, we applied a meta-analytic approach to investigate the effects of different ground-based approaches to extraction operations on fine roots. Specific objectives were to analyse the relationship between soil compaction (increase in soil bulk density) and the presence of fine roots; to assess the recovery process after forest harvesting and the effectiveness of amelioration interventions, for instance, mulching and planting fast-growing trees and to recover the ecological functions of forest soils resulting from the presence of fine roots.

2 | MATERIALS AND METHODS

2.1 | Literature search, studies inclusion criteria and database building

We conducted a systematic search of the literature references indexed within the databases of Google Scholar, Scopus and Web of Science. We used the following keywords: fine roots, skid trail, strip road, forest operations, skidder, forwarder, tractor, harvesting system, logging; adding the Boolean operators AND or OR (Figure 1).

We further used the snowball technique consisting of using a reference list of recent papers to find other appropriate references to gather additional literature sources. We used the snowball method beginning with the reference list of the papers published in 2021 and 2022. In this way, we identified four further papers. We found 87 papers that were potentially eligible after searching the scientific

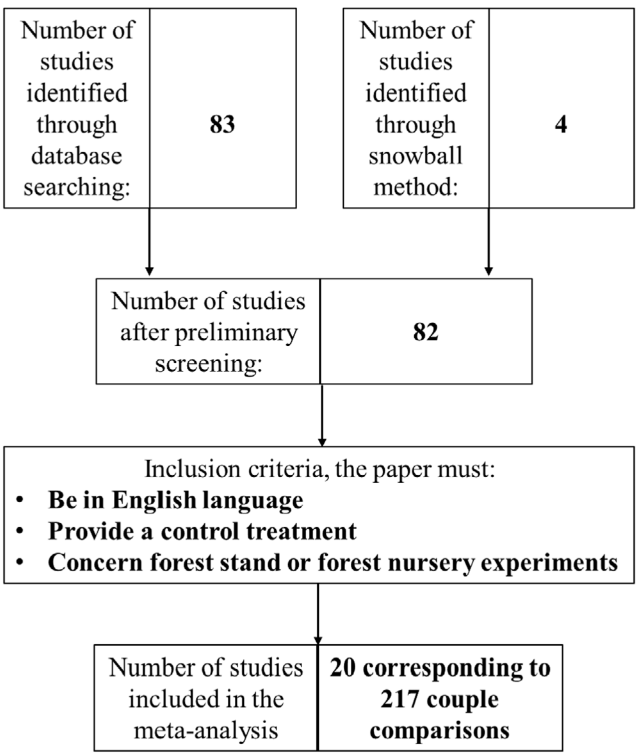

FIGURE 1 Meta-analysis chart for this study.

repositories for relevant material. Initially, we eliminated duplicate studies, then we excluded papers whose titles and abstracts did not fit with the topic. Finally, we examined the 30 remaining studies applying the following inclusion criteria: i) the study must provide a control treatment which consists of soil not affected by machine passage located close to the analysed skid trail/strip road; ii) the experiment must be set up in a forest stand, nursery studies are also included but they have to be clearly related to a forest context.

With these criteria, 19 papers (DeArmond et al., 2022; Ebeling et al., 2017; Flores Fernández, Hartmann, & von Wilpert, 2019; Flores Fernández, Rubin, et al., 2019; Högberg & Wester, 1998; Jourgholami, Feghhi, Picchio, et al., 2021; Jourgholami, Feghhi, Tavankar, et al., 2021; Jourgholami, Ghassemi, & Labelle, 2019; Jourgholami, Ramineh, et al., 2019; Malo & Messier, 2011; Meyer et al., 2014; Rygiewicz et al., 2004; Schäffer, 2022; Schäffer et al., 2009; Stutz et al., 2017; Sugai et al., 2020; Warlo et al., 2019, 2022; Watson & Kelsey, 2006) that generated 217 couple comparisons were finally included in the database for the meta-analysis (Figure 1).

As a quantitative measurement of the fine roots, we used the number of fine roots or biomass per unit soil area or volume, as different studies based on various methodological approaches. In the first version of analyses, we accounted for such a difference including measure type (number or mass of fine roots) as a random effect in the models, however, it was colinear with study ID and resulted in zero variance, therefore we excluded it from the analyses. For non-numerical values in the main text or tables but only in a graphical form, we used the WebplotDigitizer software to retrieve the numerical information. For 58 of 217 couple comparisons in the database, we did not obtain data about the dispersion measure. Thus, we assessed the relationship between the standard deviation and the average values presented in our database to fulfil this gap (Latterini, Dyderski, et al., 2023; Pigott, 1994; Wiebe et al., 2006). Due to non-linearity, we used a power model (Equation 1), after a log-transformation to better handle a wide range of values in our dataset (Equation 2):

$$SD = a \cdot M^b, \quad (1)$$

$$\log(SD) = a + b \cdot \log(M), \quad (2)$$

where SD—standard deviation, M—mean, a and b—model parameters. We fit models using the *stats::lm*() function (Table S2; Figure S1 in the Appendix).

2.2 | Meta-analysis implementation

We developed multivariate mixed-effects metanalytic linear models for the whole dataset with complete data points to investigate the effects of various categorical (sub-group meta-analysis) and continuous moderators (meta-regression) on the magnitude of fine roots alteration (Table 1).

TABLE 1 Moderators applied in the sub-group meta-analysis and meta-regression.

Moderator	Type	Levels (*n*, for categorical moderators)	Mean ± SE, range (for continuous moderators)	Notes
Extraction method	Categorical	Forwarding (157), skidding (60)		Skidding implies dragging the log/tree on the ground, while forwarding consists of carrying the log/tree on a loading deck
Amelioration	Categorical	Yes (76), No (141)		Whether any amelioration treatment has been applied (mulching, planting, liming)
Years post-harvesting	Continuous		9.7 ± 0.6, 1–42	Years
Soil depth	Categorical	0–15 cm (102), 16–30 cm (61), >31 cm (54)	21.5 ± 1.3, 0–80	Discretised into three levels to account for as random effect
Change in bulk density values	Continuous		30.0 ± 1.8, −15.8–78.1	%, available only for 57.1% of the couple comparisons. Decrease in bulk density in the skid trails or strip roads is associated only with those which experienced amelioration treatments

To estimate the effect size we used Hedges' *g*, representing an unbiased standardised mean difference (Hedges, 1981) (Equation 3):

$$g = J \cdot \left[\frac{(\overline{X_t} - \overline{X_c})}{\sigma_{pooled}} \right] \quad (3)$$

here $\overline{X_t}$ and $\overline{X_c}$ represent, respectively, the average values of fine root quantity in the experimental treatment and in the control, σ_{pooled} is the estimate of the pooled standard deviation (Rosnow & Rosenthal, 1996) and *J* represents a correction factor for small sample size (Hedges & Olkin, 2014). Positive Hedges' *g* values indicate an increase while negative indicate a decrease in fine root quantity as a consequence of the experimental treatment.

As the majority of the studies in our database contributed with more than one comparison (Cheung, 2019), we decided to account for within-study dependence using random effects in mixed-effects, covering the spatiotemporal autocorrelation and similar methodological approaches (Cheung, 2014). Thus, we used multivariate mixed-effects metanalytical linear models implemented in the metafor::rma.mv() function (Viechtbauer, 2010). We also accounted for soil depth using random effects, to obtain effect size estimates not biased by the vertical distribution of fine roots. In particular, we distinguished three depths, as the majority of fine roots is located in the upper 30 cm of soil and differences between 0–15 cm and 16–30 cm have been reported (Freschet et al., 2021; Jagodzinski et al., 2016; Varik et al., 2013). First, we checked differences in effect sizes between forwarding and skidding, as these extraction techniques can lead to different magnitudes and patterns of disturbances to forest soil, as a consequence of the different distribution of the loads during wood extraction (Marra et al., 2022; Spinelli et al., 2016). We checked it with the model with a single moderator. It is important to underline that this was a preliminary analysis carried out not considering any other influential variable (like for instance the time after harvesting), that we performed to understand if the two extraction techniques should be treated separately in the subsequent more detailed analyses.

Then, for skidding and forwarding, we separately assessed the effects of all moderators (Table 1). We checked the fitness of models using Akaike's information criterion (AIC), selecting models with the lowest AIC. We assessed possible publication bias and the variability of data using funnel plots, visualising the relationship between effect size and standard error. We used orchard plots for categorical moderators and bubble plots for continuous moderators, implemented in the orchard package (Nakagawa et al., 2021) to visualise the model outcomes.

To ensure robustness of our results, we also replicated analyses using a subset excluding studies with unclear information about sample size, to check correctness of results. In detail, we identified three studies (Flores Fernández, Hartmann, & von Wilpert, 2019; Flores Fernández, Rubin, et al., 2019; Schäffer, 2022) which were characterised by a very high sample size, as a consequence of the particular methodology applied which were based on counting fine roots rather than sampling them and weighting. In these studies, it was troublesome to clearly identify the sample size, and therefore we decided to perform the robustness analysis by repeating all the analyses by excluding these three papers from the database. The graphical results of the robustness analysis are reported in the supplementary material of the manuscript. It is worth to point out that, due to complex structure of our dataset, including multilevel heterogeneity structures, typical pathway for meta-analysis robustness assessment with 'leave one out' approach was impossible to be applied, therefore we decided to compare the results of whole and reduced datasets. Reporting results we provided three metrics of heterogeneity—QE, QM and I^2. Q is a test statistic for residuals heterogeneity, while QM—of heterogeneity explained by moderators (Viechtbauer, 2007), and is formally tested in the metafor::rma.mv() function (Viechtbauer, 2010). I^2 provides information about heterogeneity between studies in a dataset (Higgins & Thompson, 2002). We calculated I^2 for between-clusters and within-clusters heterogeneity, to assess how much of heterogeneity is attributed to differences between studies and how much—within studies (Konstantopoulos, 2011). All statistical analyses were performed using the software R version 4.2.2 (R Development Core Team, 2022).

3 | RESULTS

3.1 | Spatial distribution of the studies

The majority of analysed studies came from the temperate zone in Central Europe (Figure 2). However, each continent except for Africa, was represented at least by one study location. The topic has been profoundly investigated in Germany as well as in Iran. It is, however, evident that tropical and sub-tropical forests are underrepresented and there was also a complete lack of trials in the Mediterranean context. Furthermore, there are no evaluations of forwarding impacts on fine roots in boreal Europe.

3.2 | Effects of forest operations on fine roots

Standardised mean differences differed from −8.70 to 1.60, with an interquartile range of −1.88 to −0.32, and with an average of −1.35 ± 0.11. Meta-analysis revealed that the overall effect size was −1.31 ± 0.32 (95% CI: −1.93, −0.69), with study-related random effect SD = 1.63 and heterogeneity measure Q(df = 216) of 8252.5 ($p < 0.001$), I^2 of between-cluster heterogeneity of 0.957, within-cluster heterogeneity I^2 of 0.0243 and AIC of 4939.1. Subgroup analysis (AIC = 4928.3) revealed statistically significant effect sizes for both skidding ($g = -1.23 \pm 0.32$) and forwarding ($g = -1.37 \pm 0.32$), and a statistically significant difference between these two types. The heterogeneity measure for residuals QE(df = 215) was 7120.2 ($p < 0.001$), QM(df = 1) = 13.7 ($p < 0.001$), I^2 of between-cluster heterogeneity of 0.959, and within-cluster heterogeneity I^2 of 0.0228 (Figure 3 and Table S2). The very high between-cluster heterogeneity is explainable considering that this first analysis was a preliminary test, carried out just to investigate the overall differences between skidding and forwarding effects in order to decide if carrying out the following, more detailed, analyses in a separated way for the two extraction methods.

3.3 | Drivers of skidding effects on fine roots

A multivariate meta-analysis of skidding effect sizes revealed that all hypothesised factors were included in the final model (AIC = 131.4, AIC_0 = 228.7). In the final model, the study-related random effect was SD = 0.96, soil depth-related random effect was SD <0.01, and heterogeneity measure was QE(df = 13) = 113.1 ($p < 0.001$), QM(df = 3) = 100.4 ($p < 0.001$), I^2 of between-cluster heterogeneity of 0.850, and within-cluster heterogeneity I^2 of <0.001 (Table S3). Analysis revealed the highest importance of bulk density increment. Hedges' g decreased from −1.25 at 10% to −6.25 at 45% bulk density increment (Figure 4). We also found a statistically significant negative impact of time since harvesting. Hedges' g decreased from −2.5 at

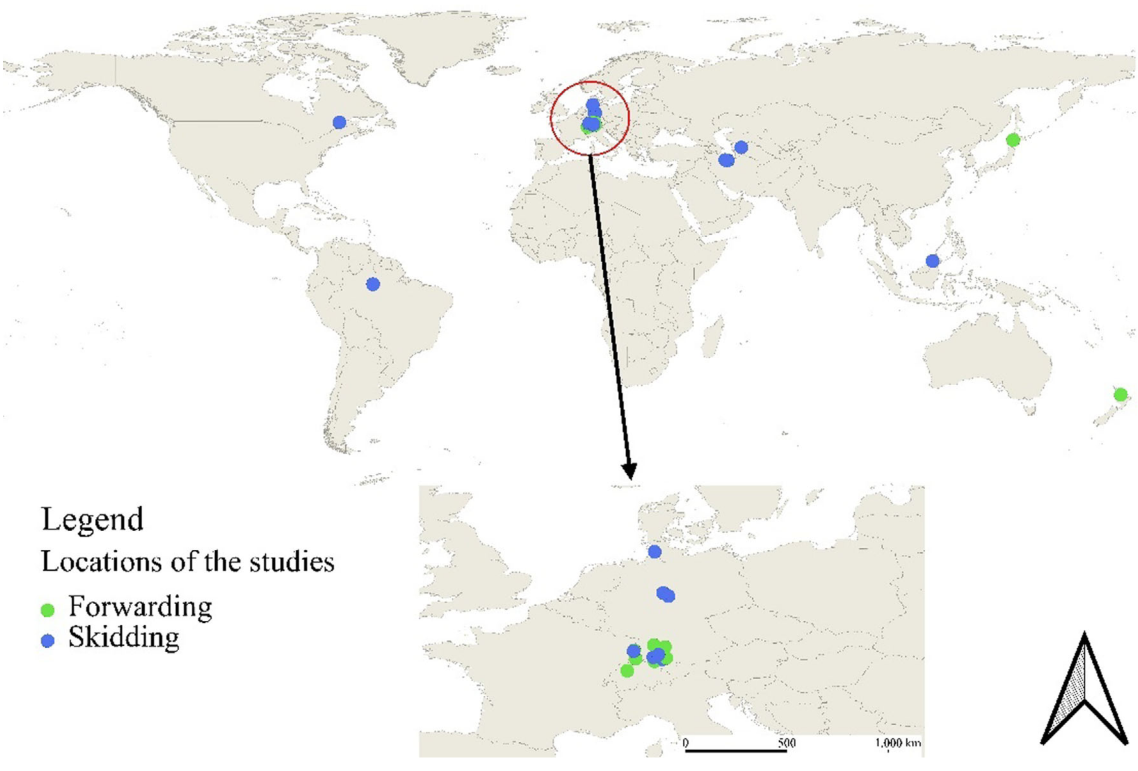

FIGURE 2 Locations of the studies included in the meta-analysis. Number of circles in the figure does not correspond to the number of studies in the database considering that some of them investigated multiple study sites. [Colour figure can be viewed at wileyonlinelibrary.com]

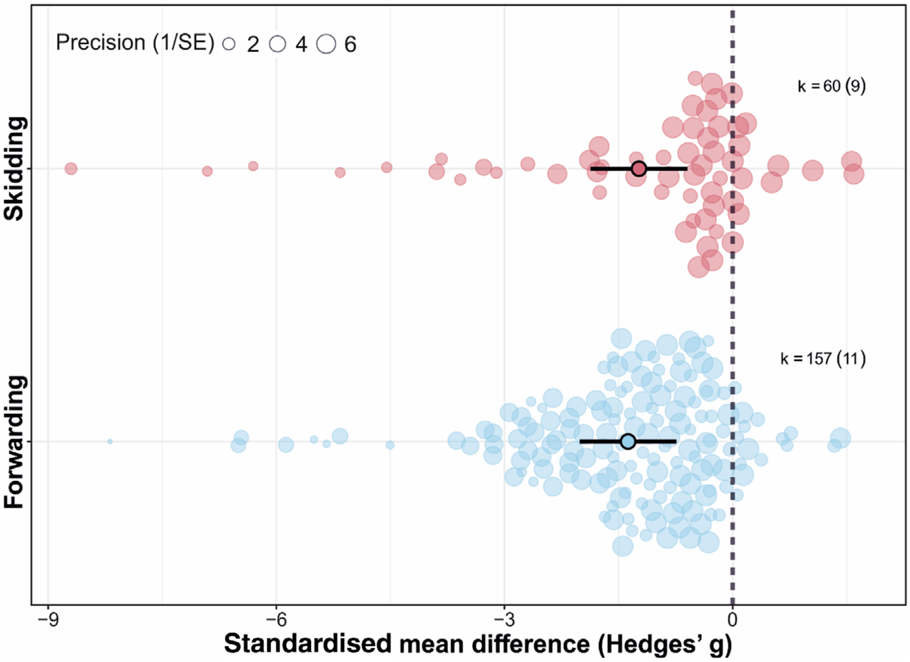

FIGURE 3 Orchard plot of standardised mean differences (Hedges' g) of studies assessing effects of forest operations on fine roots (bubbles), with effect sizes (black dots) and 95% confidence intervals (lines) estimated using multivariate meta-analysis (Table S2). K denotes the number of effect sizes per estimate with the number of related studies in brackets. [Colour figure can be viewed at wileyonlinelibrary.com]

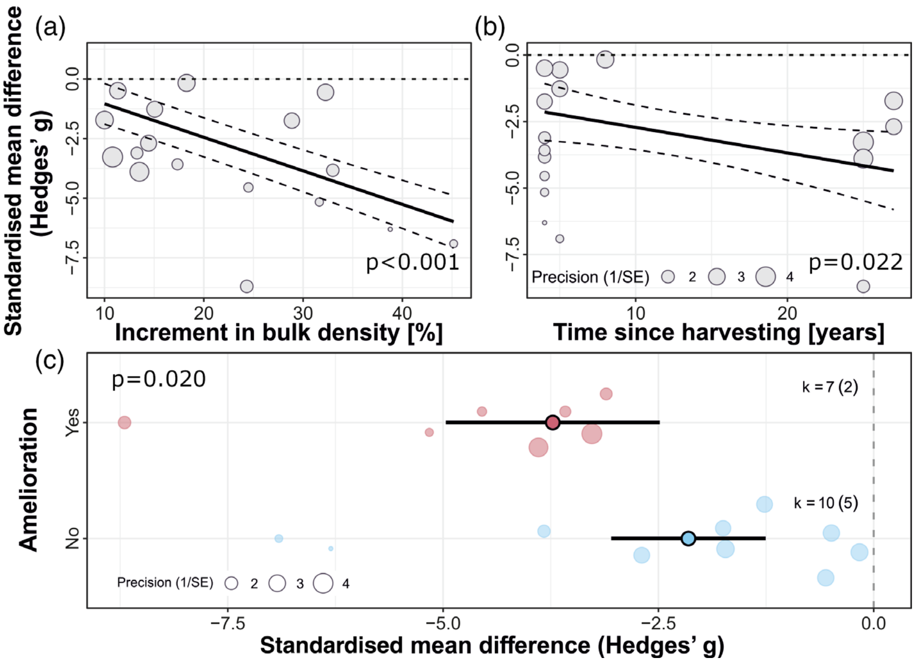

FIGURE 4 Effects of moderators driving effect sizes of skidding on fine roots: increment in bulk density (a), time since harvesting (b) and amelioration (c). Orchard plot of standardised mean differences (Hedges' g) shows differences between the two amelioration treatments in effect sizes (bubbles), with effect sizes (black dots) and 95% confidence intervals (lines) estimated using multivariate meta-analysis (Table S3). Bubble plots show the predicted response of effect size to continuous moderators, with 95% confidence intervals. [Colour figure can be viewed at wileyonlinelibrary.com]

3 years to −4 at 27 years since harvesting. Amelioration provided a statistically significant and biologically relevant decrease in effect size.

3.4 | Drivers of forwarding effects on fine roots

A multivariate meta-analysis of forwarding effect sizes revealed that all hypothesised factors were included in the final model ($AIC = 2404.1$, $AIC_0 = 2891.4$). In the final model, study-related random effect was $SD = 1.10$, soil depth-related random effect was $SD = 0.54$, and heterogeneity measure was $QE(df = 103) = 3062.3$ ($p < 0.001$), $QM(df = 3) = 491.6$ ($p < 0.001$), I^2 of between-cluster heterogeneity of 0.785, and within-cluster heterogeneity I^2 of 0.191 (Table S4). Analysis revealed the highest importance of bulk density increment. Hedges' g decreased from −0.3 at −15% to −1.5 at 70% bulk density increment (Figure 5). We also found a low and statistically insignificant negative impact of time since harvesting. It decreased from −0.3 at 2 years to −1.6 at 18 years since harvesting. Amelioration provided a statistically significant and biologically relevant increase in effect size.

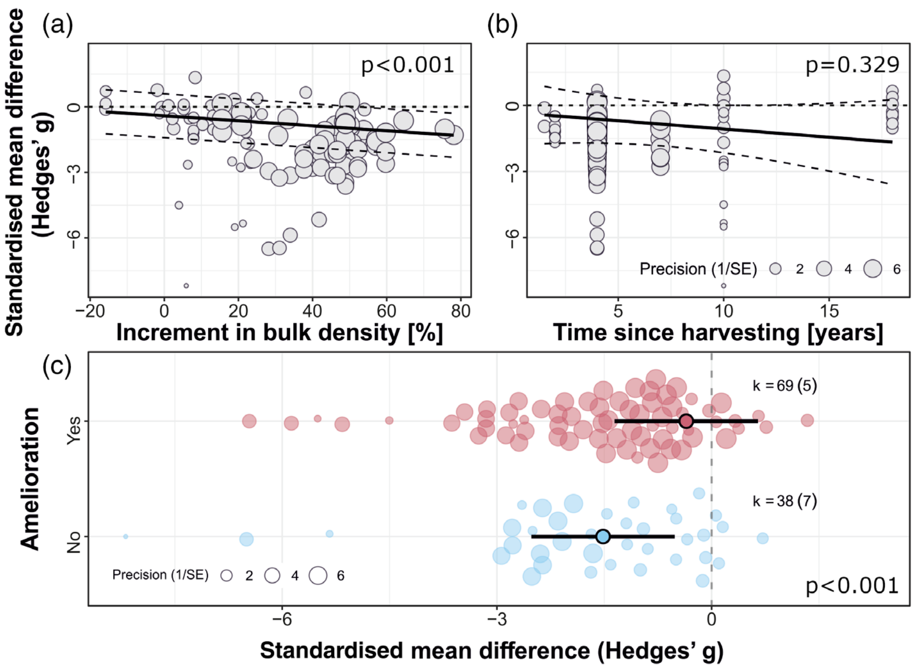

FIGURE 5 Effects of moderators driving effect sizes of forwarding on fine roots: increment in bulk density (a), time since harvesting (b), and amelioration (c). Orchard plot of standardised mean differences (Hedges' g) shows differences between amelioration treatments in effect sizes (bubbles), with effect sizes (black dots) and 95% confidence intervals (lines) estimated using multivariate meta-analysis (Table S4). Bubble plots show the predicted response of effect size to continuous moderators, with 95% confidence intervals. [Colour figure can be viewed at wileyonlinelibrary.com]

3.5 | Robustness of analyses

After excluding three papers with unclear sample size description from dataset, we repeated all analyses and we obtained similar distribution of effect sizes and standard errors of particular observations than as in case of testing the whole dataset (Figure 6). In both cases, funnel plots revealed prevailing negative effects over positive effects and high clustering of similar standard error values.

In the alternative analysis, standardised mean differences differed from −8.70 to 1.34, with an interquartile range of −1.68 to −0.32, and with an average of −1.53 ± 0.20. Meta-analysis revealed that the overall effect size was −1.35 ± 0.37 (95% CI: −2.08, −0.62), with study-related random effect SD = 1.37 and heterogeneity measure Q(df = 87) of 933.5 ($p < 0.001$), I^2 of between-cluster heterogeneity of 0.899, within-cluster heterogeneity I^2 of <0.001, and AIC of 416.9. Subgroup analysis (AIC = 410.5) revealed statistically significant effect sizes for skidding ($g = -2.08 \pm 0.46$) and a significant difference between skidding and forwarding ($g = -0.62 \pm 0.45$). The heterogeneity measure for residuals QE(df = 86) was 736.9 ($p < 0.001$) and QM(df = 1) was 5.16 ($p = 0.023$), I^2 of between-cluster heterogeneity of 0.867, and within-cluster heterogeneity I^2 of <0.001 (Figure S2 and Table S5). The results were consistent with the whole dataset analysis.

An alternative multivariate meta-analysis of skidding effect sizes revealed that all hypothesised factors were included in the final model (AIC = 131.4, AIC_0 = 228.7). In the final model, the study-related random effect was SD = 0.93, soil depth-related random effect was SD <0.01, and heterogeneity measure was QE(df = 13) = 113.1 ($p < 0.001$), QM(df = 3) = 100.4 ($p < 0.001$), I^2 of between-cluster heterogeneity of 0.850, within-cluster heterogeneity I^2 of <0.001 (Table S6). Analysis revealed the highest importance of bulk density increment. Hedges' g decreased from −1.04 at 10% to −5.98 at 45% bulk density increment (Figure S3). We also found a statistically significant negative impact of time since harvesting. Hedges' g decreased from −2.1 at 3 years to −4.3 at 27 years since harvesting. Amelioration provided a statistically significant and biologically relevant decrease in effect size. The results were consistent with the whole dataset analysis.

An alternative multivariate meta-analysis of forwarding effect sizes revealed that all hypothesised factors were included in the final model (AIC = 132.2, AIC_0 = 153.3). In the final model, study-related random effect was SD = 0.88, soil depth-related random effect was SD < 0.01, and heterogeneity measure was QE(df = 39) = 142.0 ($p < 0.001$), QM(df = 3) = 22.7 ($p < 0.001$), I^2 of between-cluster heterogeneity of 0.772, and within-cluster heterogeneity I^2 of <0.001 (Table S7). Analysis revealed no importance of bulk density increment (Figure S4). We also found a low and statistically insignificant negative impact of time since harvesting. It decreased from −0.11 at 2 years to −1.52 at 18 years since harvesting. Amelioration provided a statistically significant and biologically relevant increase in effect size. The results were similar to the whole dataset analysis, differing only in the statistical significance of bulk density increment, while effect sizes were similar.

4 | DISCUSSION

We observed a statistically significant reduction of fine root quantity for both skid trails (skidding) and strip roads (forwarding) in comparison to the forest soil not affected by the machine passage. Furthermore, a multivariate meta-analysis revealed the presence of statistically significant differences between the two extraction methods; forwarding resulted in a larger impact than skidding (Figure 3). This can be related to the higher soil compaction produced

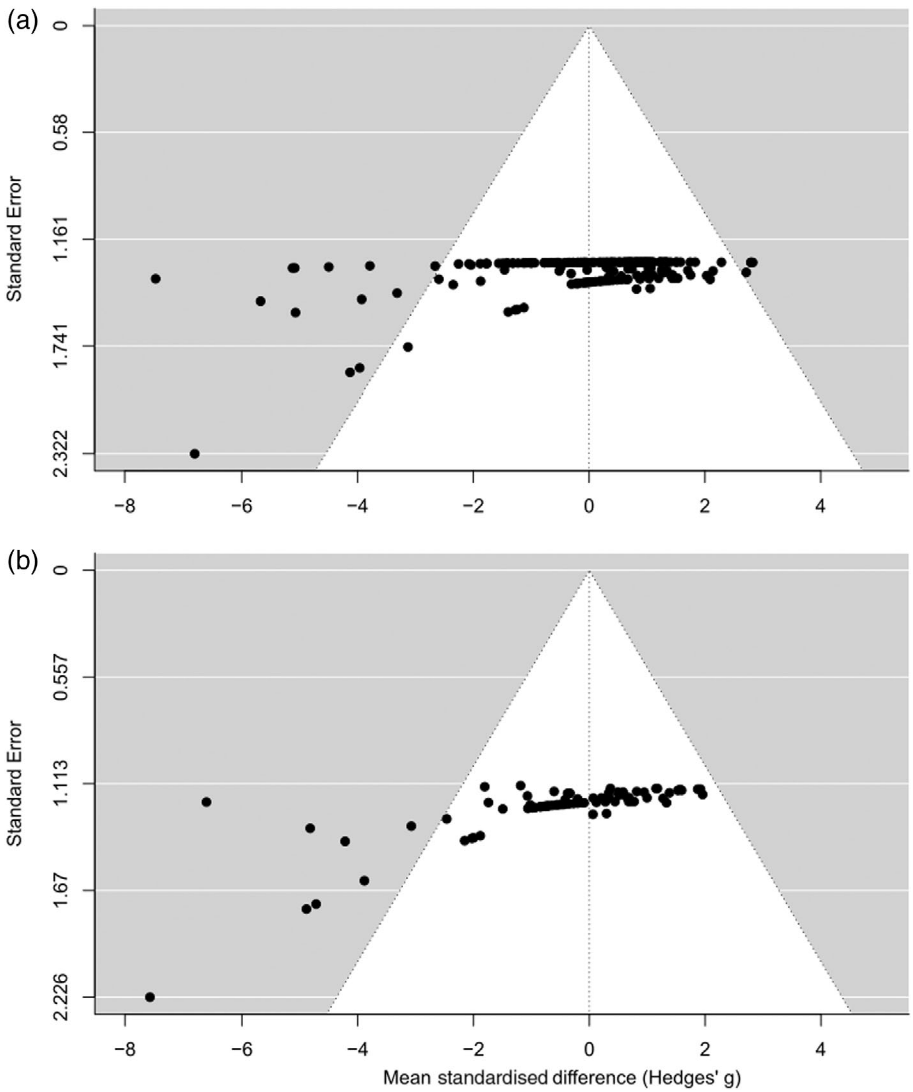

FIGURE 6 Funnel plots reveal relationships between effect sizes and standard errors in the whole dataset (a, $n = 217$) and reduced dataset (b, $n = 88$).

by forwarding (Marra et al., 2022). Within our database, the average bulk density increase was +31.3 ± 20.6% for forwarding and +22.5 ± 10.8% for skidding. However, both extraction approaches revealed a substantial decrease in the presence of fine roots, thus highlighting how mechanised ground-based forest operations can have a significant impact on this important component of the soil ecosystem.

The results of the meta-regression showed a strong relationship between machinery-induced soil compaction and decreased presence of fine roots (Figures 4 and 5). This confirms that the major alteration to the forest soil caused by forest logging activities is directly related to the passage of the machine and the consequent alteration of soil physical features (Grigorev et al., 2022; Lepilin et al., 2022; Tavankar et al., 2021). Therefore, the implementation of best management practices and smarter planning of the skid trail/strip road patterns, to reduce machinery-induced soil compaction, was confirmed to be a fundamental aspect in the implementation of proper sustainable forest operations (SFO) (Jourgholami, Ramineh, et al., 2019; Jourgholami, Feghhi, Picchio, et al., 2021; Labelle et al., 2022). Such technical adjustments deal with the proper planning of the viability pattern (Kazama et al., 2021); some direct modifications of the machine, that is, high flotation tires, use of an extra bogie axle, lower inflation pressure, use of steel flexible tracks (Cudzik et al., 2018; Haas et al., 2016; Labelle & Jaeger, 2019); and amendments to mitigate soil disturbance such as placing brash mats on the machine trail (Labelle & Jaeger, 2012; Solgi et al., 2018).

A very interesting and somehow unexpected finding of this meta-analysis was the lack of any recovery trend of fine root presence with increasing time after harvesting (Figures 4 and 5). The presence of fine roots in skid trails and strip roads remains steadily lower than in the soil which was not affected by machinery passage even more than 20 years after the harvesting activities. In contrast, for different parameters of the forest soil ecosystem, for instance, sediment yield, the morphology of the seedlings and biodiversity of microarthropods, a clear recovery trend was shown sometimes even for a short time after the intervention (Karami et al., 2023; Tavankar et al., 2022; Venanzi et al., 2019). There are various reasons for the lack of a recovery trend for fine roots. First, it is important to take into consideration that not all machine trails are similar. A recent review on the topic of skid trail recovery stated that the recovery process of different features can be complete and fast on secondary or tertiary skid trails, characterised by a low number of machine passages and subsequent lower soil compaction (DeArmond et al., 2021). In contrast, primary skid trails in which there was a high number of machine passages and stronger compaction generally show only partial and slow recovery (DeArmond et al., 2021). This applies also to fine roots. In the present database, the major part of the studies were conducted in Germany and Iran, where the approach to forest infrastructure network planning is based on the concept of implementing a few heavily used skid trails (Ebeling et al., 2017; Lotfalian et al., 2016). These trails are often used for the passage of mechanical means for other reasons, as tourism or wildfire management (Picchio et al., 2018). The effects of these types of uses on soil compaction are hard to be identified and evaluated. Therefore, it can be expected that in such studies the investigated machine trails with a high number of machine passages will show a considerable and long-lasting alteration of the fine roots. It would therefore be interesting to implement similar studies in the context of Mediterranean forests, where the machine trail pattern is generally based on implementing many dispersed lightly used trails (Picchio et al., 2020). This will allow for the different ecological contexts to be accounted for, and for the investigation of the effects of machinery-induced soil compaction on trails characterised by a lower number of machine passages. It is also possible that fine roots could be a component of the forest soils which is particularly sensitive to ground-based forest operations. It is indeed important to highlight that each trail represents the portion of the cutting block in which the disturbance to the forest ecosystem is given by the sum of the effects of the machine passage and of the applied silvicultural treatment, while in the rest of the cutting block, there are only the effects of the silvicultural treatment (Latterini, Venanzi, et al., 2023). In the context of continuous-cover forestry, it is typical that the magnitude of the intervention in terms of percentage of biomass removal, for instance, a thinning, is higher around the machine trails to favour their establishment. Summing the effects of a higher number of trees removed surrounding the trails and the compaction caused by the machines, it is possible to imagine that fine roots can be particularly impacted by ground-based harvesting methods. Another interesting future research project could also be to perform a comparison of the effects of forest operations carried out in the same areas, both in the framework of rotation and continuous-cover forestry. Although different recent studies highlighted how a major canopy opening led to a higher decrease in the presence of fine roots (Yang, Qin, et al., 2022; Yang, Wang, et al., 2022), it is also true that in final felling interventions by clear-cut there is a larger availability of logging woody residues. These can be easily applied along the skid trails or strip roads to reduce soil compaction (Ilintsev et al., 2021; Ring et al., 2021) and lower the level of disturbance to fine roots in the soil directly affected by the passage of the machinery (Figure 7).

The number of studies on the effects of amelioration interventions on the presence of fine roots in skid trails were not enough to give data supporting the type of intervention which is most effective. Conclusions can be drawn that show the effectiveness of the amelioration interventions to enhance the recovery of fine roots in the strip roads used for forwarding. No positive effects were observed on the skid trails used for skidding (Figures 4 and 5). The only amelioration intervention applied to skid trails was mulching (Jourgholami, Ghassemi, & Labelle, 2019; Jourgholami, Feghhi, Picchio, et al., 2021), while for forwarding data are mostly on alder (*Alnus glutinosa* (L.) Gaertn) planting on the trails (Flores Fernández, Hartmann, & von Wilpert, 2019; Flores Fernández, Rubin, et al., 2019). Although, as stated above, it was not possible to compare the effects of the alternative amelioration interventions due to the low number of trials, it can be expected that planting trees is more effective than mere mulching with straw or forest litter to favour the recovery of fine roots. This would explain the contrasting results of the meta-analysis

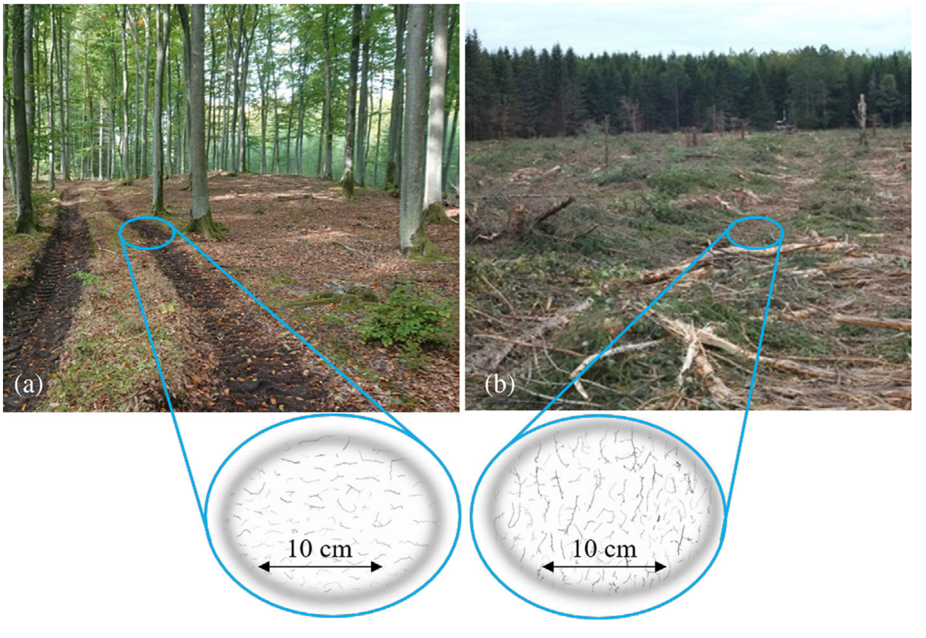

FIGURE 7 Fine roots in the skid trails can be substantially reduced (a). However, the application of logging residues and brash mats on the trails can reduce soil compaction, thus lowering the negative effects of ground-based extraction on fine roots (b). [Colour figure can be viewed at wileyonlinelibrary.com]

between the effectiveness of amelioration interventions in strip roads and skid trails.

Assessment of meta-analysis robustness revealed that even after excluding a significant part of data trends and distribution of effects sizes and precision were similar (Figures S2–S4; Tables S5–S7). We decided to exclude three studies, where methodology did not allowed for precise estimation of effective sample size, based on root-counting. These studies provided valuable insights into forest operation effects on fine roots, and wide range of moderator values. However, even exclusion of such large database did not change high heterogeneity of data, resulting from including large variability of study conditions, indicating that our results are robust. The only difference was a slightly lower effect size of bulk density increment regarding forwarding, which in the whole dataset was statistically significant, while in reduced was insignificant. However, this difference results from smaller sample size, affecting p-values (Wasserstein & Lazar, 2016).

5 | CONCLUSION AND FUTURE RESEARCH SUGGESTIONS

Bearing in mind the goal of reviewing the effects that ground-based forest harvesting methods can have on the presence of fine roots in the soil, we applied a meta-analytic approach for developing a quantitative synthesis of the effect sizes presented by the different studies on the topic. We applied a multivariate mixed-effects meta-analytic model to account for the correlation among trials implemented by the same authors and at the same soil depth. We further investigated the effects of the two main options for ground-based extraction methods, which are skidding and forwarding, the relationships between the presence of fine roots and soil compaction, and the related recovery process with increasing post-harvesting time.

Obtained findings revealed that skidding and forwarding significantly decreased the presence of fine roots in the soil affected by the passage of the machines. Forwarding was slightly, but statistically significant, more impactful than skidding, as a consequence of the higher soil compaction triggered by this extraction approach. There is indeed a strong correlation between soil compaction measured as bulk density increase, and the presence of fine roots. The analysis of the recovery process revealed that even after more than 20 years from the harvesting intervention fine roots in both strip roads and skid trails were significantly lower than in the soil not affected by the machine passage. We suggest that future research should be directed towards making a similar evaluation in different forestry contexts, such as the Mediterranean area, where the planning of the forest trails network is based on developing many trails, but with lower traffic intensity. Furthermore, it is strongly recommended to always accompany data on fine root presence with a measure of soil compaction, that is bulk density or total porosity, since this is the main driver of alterations to fine roots. Soil compaction is also a direct consequence of ground-based harvesting methods.

Finally, it would be very important to analyse the effects of machinery-induced soil compaction on some other root traits, such as diameter, length, area and volume. It can be hypothesised that fine roots growing in compacted soils can also experience some changes in their morphology (for instance lower diameter and length), however, this hypothesis should be specifically tested with dedicated research.

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CONFLICT OF INTEREST STATEMENT

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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