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Effects of Ground-Based Forest Operations on Aboveground and Belowground Growth of Seedlings: A Meta–Analysis

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Abstract

Ground-based forest operations can produce an intense level of soil disturbance and hamper the growth of seedlings. However, previous studies on the topic of seedling growth performance on the skid trail network showed high variability and non-uniform responses. Therefore, a multivariate meta-analysis was applied to investigate the effects of soil disturbance after ground-based forest operations on the aboveground and belowground growth of seedlings. We further assessed the effects of the following moderators: type of regeneration, type of stand, number of years since the forest operations, mass of the machine used, number of machine passes in the investigated skid trails, and the increased soil compaction in the skid trails. The results supported our hypothesis that ground-based forest operations had a greater effect on the growth of broadleaf species and natural regeneration. This was, however, mostly true for belowground growth, that was typically more affected than aboveground growth. We discovered that there is a recovery in seedling biomass and lenght following harvesting, but this is a long process that requires about ten to twenty years to begin. We found that the number of machine passes and the machine mass did not directly correspond to a higher level of impact, indicating that the actual disturbance drivers are more complicated interactions that occur among the machine, the way in which forest operations are carried out, and the soil properties. It was finally demonstrated that soil compaction was the primary cause of disturbance to seedling growth, primarily affecting belowground biomass and lenght. In particular, we identified a minimum threshold of a 30% increase in soil bulk density to observe statistically significant negative effects on seedling belowground growth. Soil compaction proved to be the main factor that can jeopardize the development of forest regeneration in the skid trails. This suggests that the same best management practices that are used to reduce soil compaction caused by machinery should also be used to reduce the detrimental effects of ground-based forest operations on seedling development. As future research directions, long-term studies are recommended to assess the recovery process dynamics. Moreover, more research on broadleaf, natural regeneration, and Cut-to-Length machinery is strongly suggested.

Keywords: sustainable forest management, sustainable forest operations, best management practices, soil compaction, soil displacement

1. Introduction

For millennia, wood has been an essential renewable and multipurpose resource for humankind (Çiçekler et al. 2023, Hoeben et al. 2023, Łukawski et al. 2023). However, forests do not provide only wood but also a plethora of various and complex ecosystem services (Triviño et al. 2023). As a long-term carbon sink, forests are fundamental for mitigating climate change (Evans et al. 2022, Zhang et al. 2023). Furthermore, forests represent the major terrestrial shelter for biodiversity (Asbeck et al. 2021a, 2021b), and they play a crucial role in protecting against flooding and landslides (Brander et al. 2018, Miura et al. 2015). To enable forests to provide mankind with all their ecosystem services, it is fundamental to manage forests sustainably, as highlighted by the latest European Strategies on the topics of forests, soil, and biodiversity (European Commission 2021, 2020, European Union. 2021).

On the one hand, sustainable forest management is strongly connected with the ability of forests to regenerate, naturally or artificially (Langmaier and Lapin 2020, Latterini et al. 2023b). On the other hand, the success of regeneration is related to how forest management is carried out (Bürgi and Schuler 2003, Filothei and Petros 2023, Houšková et al. 2023). This is particularly true when considering the possible alterations to the forest ecosystem, which can occur as a consequence of the practical implementation of forest management activities, through forest operations (Latterini et al. 2024b).

The application of any harvesting system, mostly ground-based ones, implies a disturbance to the forest soil related to soil compaction, soil displacement, and rutting (Hoffmann et al. 2022, Labelle et al. 2022, Borz et al. 2023, Forkuo and Borz 2023, Latterini et al. 2024c). The disturbance to the physical characteristics of the soil is however only the first direct consequence of forest operations, because the mechanical disturbance may determine alterations in biological features of the soil (Latterini et al. 2023c). For instance, a recent review highlighted that machinery-induced soil compaction can decrease the presence of fine roots in the forest soil affected by the machine passage (i.e. the skid trails network) (Latterini et al. 2024a). Another study also suggests the possibility that mechanical soil disturbance related to forest operations can lead to decrease soil organic carbon pool (Mayer et al. 2020), even if the effects of forest operations on processes such as litter decomposition should be further investigated (Latterini et al. 2023a).

One of the main disturbances related to the machinery-induced compaction after ground-based forest operations is the potential alteration of seedlings characteristics, such as biomass and lenght. On the one hand, some studies showed that the skid trails network can represent a suitable area for the regeneration of pioneer species (Brais 2001, Picchio et al. 2018). On the other hand, compacted and displaced soil can reduce the ability of seedlings to grow, resulting in reduced growth, both aboveground and belowground (Naghdi et al. 2023). A meta-analysis carried out on papers published until 2017 highlighted that soil compaction can reduce the belowground and aboveground growth of seedlings (Mariotti et al. 2020). However, Mariotti et al. (2020) also considered pot studies in environmentally controlled conditions, while a deeper knowledge of »real case studies« is needed to understand the impact of the various aspects of forest operations on the seedling response. For example, the influence of parameters such as the machine mass and the number of machine passes, as well as their correlation with soil disturbance, and the subsequent consequences on seedling aboveground and belowground growth should be investigated.

To investigate this fundamental topic for sustainable forest management, a meta-analysis of the studies was developed taking into consideration the effects of machinery-induced soil disturbance on the growth of seedlings. We further tried to understand how ecological factors like the type of stands, and engineering factors such as the harvesting system implementation, can explain the variability that characterizes the literature in this topic. The meta-analytic approach is highly suitable for addressing these issues, considering that, compared to a systematic literature review, it allows for a quantification of the effect size, thus giving to the reader a quantitative estimation of the studied phenomena (Janiszewska-Latterini and Pizzi 2023, Nazari et al. 2023). The main benefit of using meta-analysis is that it allows for the statistical analysis of results from a collection of studies with similar experimental designs, to produce generalized conclusions (Hedges et al. 1999, Lajeunesse 2011).

The aim of applying the meta-analytic approach was to test in detail the following research hypotheses:

⇒ being roots the plant organ directly affected by the machinery-induced soil compaction, the disturbance of ground-based forest operations has more impact on belowground growth than on aboveground growth of seedlings

⇒ considering that seedlings of coniferous species are mostly light-demanding, pioneer, and fast-growing, and that in artificial regeneration many negative factors affecting the establishment and growth of seedlings are reduced through species selection, compliance with planting distance, and possibly tillage practices, our second hypotheses is that the negative effects of ground-based forest operations on the biomass of coniferous seedlings and artificial regeneration are less than those of broadleaf species and natural regeneration

⇒ higher number of machine passes, higher machine mass and higher increase in soil bulk density lead to stronger impacts on seedling features. However, there is a clear recovery trend with increasing time after harvesting.

Finally, we defined the threshold recovery time after intervention and the magnitude of soil compaction that is needed to have a negative effect on the aboveground and belowground growth of seedlings.

2. Materials and Methods

2.1 Building Meta–Analysis Database

We performed a systematic literature search at the end of November 2023 using the databases Web of Science, Scopus, and Google Scholar. The following keywords were used: seedlings, forest operations, logging, skidder, forwarder, tractor, wood extraction, animal logging, soil compaction, skid, trail, strip road, root biomass, root length, belowground biomass, belowground growth, aboveground biomass, aboveground growth, stem length, stem biomass. The Boolean operators AND or OR were used to link the keywords and perform the literature search (Fig. 1). No time or geographical restrictions were applied, so our database included studies from all over the world and published since 1950.

The snowball system was further applied to identify other literature sources. This system consists of checking the reference list of the papers already in the database to find further suitable references. Three additional literature studies were identified using this method. The literature search identified 139 potentially suitable papers. We performed a first screening by reading the title and abstract of the papers and by removing the duplicates, and after this step there were 60 possibly suitable papers. Subsequently, the following inclusion criteria was applied to build the final database:

⇒ the paper must report a control treatment consisting of the values of seedlings growing outside the soil disturbed by the machine passage

⇒ the research must be carried out in a natural environment, thus excluding pot trials.

By applying these criteria for inclusion, the final database consisted of 21 papers (Ares et al. 2005, Bigelow et al. 2018, Brais 2001, Froehlich 1976, Holub et al. 2013, Jamshidi et al. 2018, Jourgholami et al. 2020, Kranabetter et al. 2017, 2006, Lyczak et al. 2021, Naghdi et al. 2023, 2016, Neaves et al. 2017, Norris et al. 2014, Picchio et al. 2019, Simcock et al. 2006, Solgi et al. 2019a, Tan et al. 2015, Tavankar et al. 2021, Treasure et al. 2019, Youngberg 1959) leading to 293 paired comparisons (Fig. 1).

2.2 Data Preparation

All analyses were conducted using R version 4.3.2 (R Development Core Team, 2023). No information was found about standard deviations for 39 of 213 observations of aboveground characteristics (biomass and length) and 20 of 80 for belowground characteristics (biomass and length). For that reason, we decided

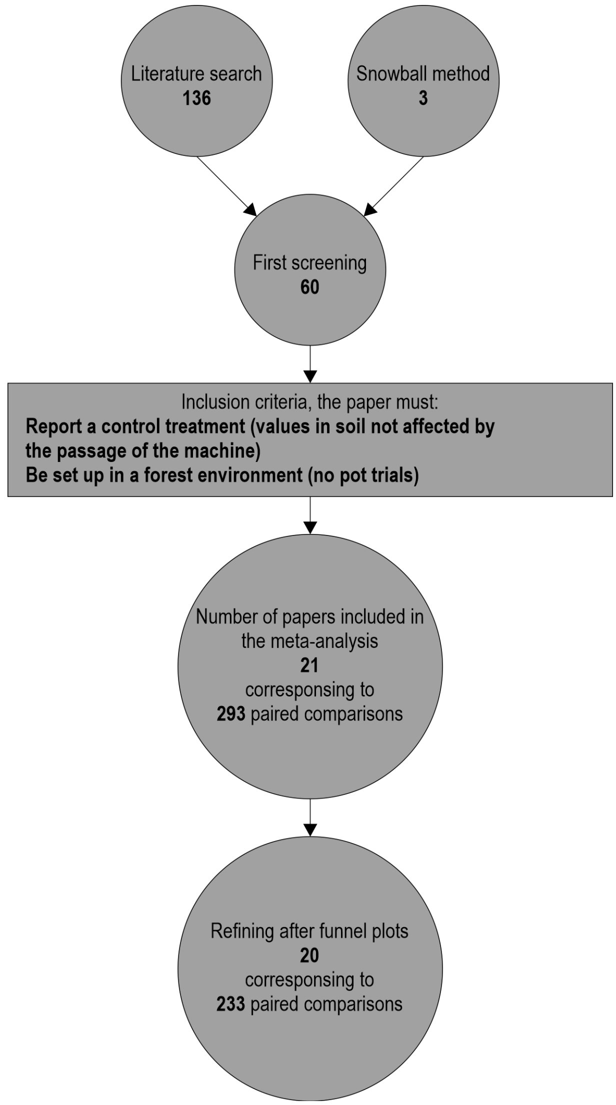

Fig.1 Meta-analysis chart

to impute missing standard deviations using an approach suggested by Higgins and Green (2011), by imputing values based on non-linear regression, similar to our previous study (Latterini et al. 2023a). We developed separate models for each characteristic, and we checked whether such an approach provides reliable estimates for missing mean values. The relationship between mean and SD was assessed using power models (Eqn. 1):

$$SD = aM^{b} \tag{1}$$

Where:

SD standard deviation

M mean, *a* and *b* – model parameters.

The models were fit using the stats::*nls()* function (Table A1).

The following moderators were considered: the type of regeneration (natural regeneration vs artificial (planted) regeneration), the type of forest stand (coniferous vs broadleaf), the number of years passed from the harvesting intervention to the data collection, the number of machine passes in the trails, the mass of the machine establishing the trails and the level of soil compaction in the trails. This last was measured as percentage difference in soil bulk density between the trails and the soil not affected by the machine passage (control). It should be highlighted that, as it usually happens in meta-analysis based on a limited dataset, it is difficult to have in the dataset all the possible combinations among the various moderators. Our database contains data regarding only artificial regeneration for coniferous seedlings. Moreover, there is only one study dealing with belowground growth of coniferous seedlings. These possible limitations were addressed as follows. Having only one study dealing with belowground growth of coniferous seedlings, this moderator was excluded from the sub-group meta-analysis dealing with the belowground biomass and lenght of the seedlings. Concerning the lack of data about natural regeneration of coniferous seedlings, we checked if this fact could hamper our modelling approach, by implying collinearity between the moderators type of stand and type of regeneration. We therefore ensured a lack of collinearity among moderators by assessing the variance inflation factors (VIF), which resulted lower than 5 for all the moderators. In this way it was proved that all the moderators could be used in the development of meta-analytic models, without biasing the results as a consequence of excessive collinearity.

The completeness of moderators (proportion of observations in whole dataset per moderator; Table 1) were assessed and then missing values for moderators were imputed using random forest-based imputation model, the case-wise estimated missing values based on all remaining moderators, implemented in the missForest package (Stekhoven and Bühlmann 2012). This procedure allows for the use of data where some information is missing. This prediction was strengthened by including all predictors in the random forest-based imputation. The normalized mean root squared error of imputation for the aboveground dataset was 0.477 and for belowground of 0.352. The completeness of each moderator (Table 1) for information about data reliability was reported.

The effect size was estimated using Hedges' *g*, representing an unbiased standardized mean difference (Hedges 1981) (Eqn. 2):

$$g = J * \left[\frac{\bar{X}_t - \bar{X}_c}{\sigma_{pooled}} \right] \quad (2)$$

Where:

$\bar{X}_t$ and $\bar{X}_c$ represent the average values of seedling features in the experimental treatment and in the control, respectively

σ_{pooled} is the estimate of the pooled standard deviation (Rosnow and Rosenthal 1996)

J represents a correction factor for small sample size (Hedges and Olkin 2014).

Table 1 Moderators applied in meta-analyses for aboveground (ag) and belowground (bg) datasets. Numbers in Levels column indicate number of observations per each level of categorical moderators

Moderator	Type	Levels *n*, for categorical moderators	Mean±*SE* range for continuous moderators	Notes
Measured variable	Categorical	Ag: biomass (26), diameter (51), height (100) Bg: biomass (25), length (31)	–	Measured characteristic of seedlings, used as a random intercept in models
Regeneration	Categorical	Natural (ag=32, bg=20) Artificial (ab=145, bg=36)	–	Type of regeneration
Forest type	Categorical	Coniferous (ag=117, bg=12) Broadleaf (ag=60, bg=44)	–	Dominant tree species
Time since harvest	Continuous	–	Ag: 7.1±0.5, 0.5–31 Bg: 6.4±1.1, 0.5–30	Years
Number of machine passes	Continuous	–	Ag: 12.6±1.5, 1–100 Bg: 18.3±2.6, 3–72	Number of machine passes, 22 missing observations for ag and 8 for bg
Mass of machine	Continuous	–	Ag: 14.4±0.5, 3–40 Bg: 11.5±0.3, 10.0–15.5	Mass of machine, t, 11 missing observations for ag
Difference in bulk density	Continuous	–	Ag: 23.4±1.9, –12.3–98 Bg: 37.7±3.2, 9.0–98	Expressed as % change in treatment, related to the control, 10 missing observations for ag and 8 for bg

Positive Hedges' *g* values indicate an increase while negative ones indicate a decrease in seedling features as a consequence of the experimental treatment. After calculations of the standardized mean differences (SMDs), funnel plots were inspected to assess the distributions of obtained variables and check for potential publication bias. Funnel plots show dispersion of data in two dimensions: effect size (SMD, on *X* axis) and precision (SE, on *Y* axis). These plots allow to conclude publication bias (asymmetry of point cloud towards positive or negative results, as well as very precise studies with low standard error and not precise ones with high standard error) or outliers. We found that SMDs calculated from (Naghdi et al. 2023) were highly left-skewed and provided unreliably low values (up to –106; Fig. A1). Such outliers seem to be somehow biased and would blur the overall estimate of effects as influential outliers, therefore they were excluded. For that reason, that study was excluded from analyses (*n*=36 for aboveground and *n*=24 from belowground), resulting in total *n*=177 for aboveground and *n*=56 for belowground datasets (Fig. 2). The observations in our datasets were rather symmetrical both along the *X* (positive vs negative effect sizes) and *Y* (precise vs not precise studies) axes, thus excluding a substantial effect of publication bias on our results.

2.3 Data Analyses

We developed multivariate mixed-effects meta-analytic 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 effects on seedlings (Table 1). Forest type was not included in belowground characteristics as coniferous forests were represented by only one study. For overall effect size estimations, we developed meta-analytical mixed-effects models with no moderators. This served to test the hypothesis that the overall effect of forest operations differ from zero, i.e. to test whether forest operations have any effect of seedlings. We used the specific paper number (study ID) and measured variables (length or biomass) as random effects, covering the dependence connected with methodological similarities and site-specificity. This also accounted for within-study dependence, which is especially important as the majority of the studies in our database contributed more than one comparison (Cheung 2019). For model development, we used the metafor::rma.mv() function (Viechtbauer 2010). To select the final meta-analytical mixed-effects models, we calculated Akaike's Information Criterion (AIC), and then we simplified the models until AIC could not be further reduced. As final models, we used those with the lowest AIC. AIC aims to increase the amount of explained variability (expressed by log-likelihood function) and simultaneously to decrease the number of used variables. Therefore, the final model can also include variables with low effect size and high *p*-values, if only these variables increase overall model fitness.

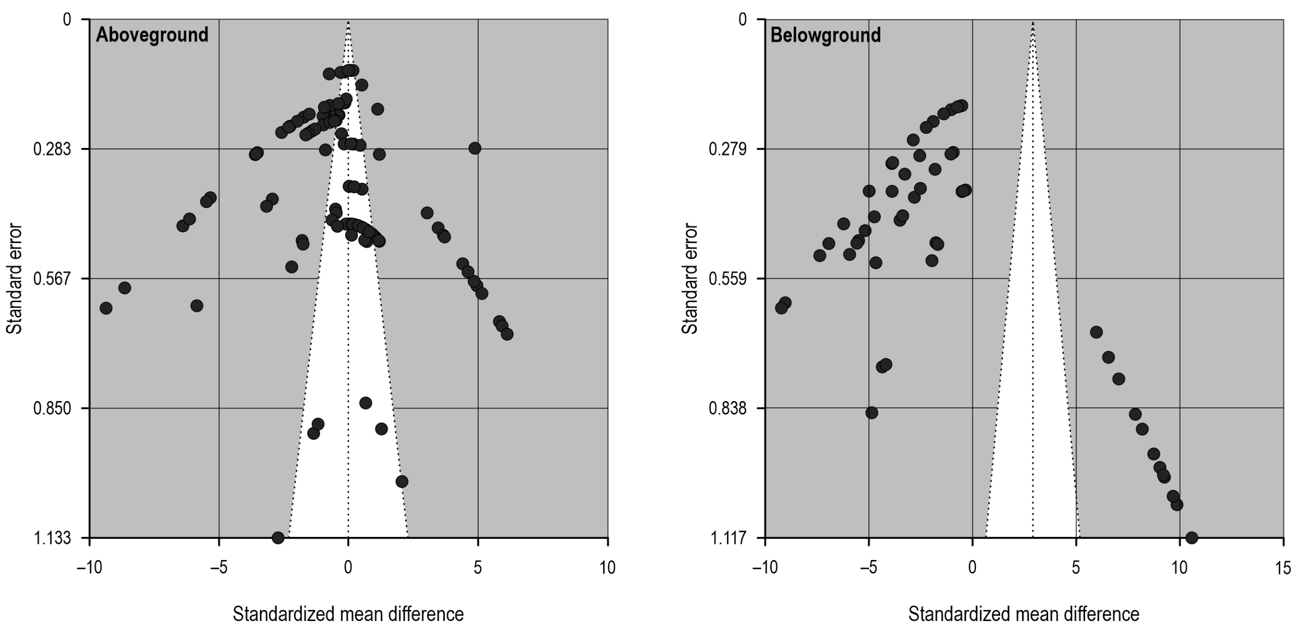

Fig. 2 Funnel plots revealing relationships between effect sizes (expressed by standardized mean difference) and precision of each estimate (expressed by standard errors) in aboveground (*n*=177) and belowground dataset (*n*=56). Dispersion of data indicates level of estimate precision for particular effect size values, while symmetry of points indicates including both positive and negative results in the literature

Three metrics of heterogeneity were reported: QE, QM, and I2. QE is a test statistic for residuals heterogeneity, QM – is the heterogeneity explained by moderators (Viechtbauer 2007), formally tested in the metafor:rma.mv() function (Viechtbauer 2010), while I^2 provides information about heterogeneity between studies in a dataset (Higgins and Thompson 2002). We calculated I^2 for between-clusters and within-clusters heterogeneity (Konstantopoulos 2011), to assess the level of heterogeneity attributed to differences between studies and within studies. Orchard plots were provided to visualize the impacts of particular predictors for categorical moderators, and bubble plots were used for continuous moderators, implemented in the orchard package (Nakagawa et al. 2021). All these plots represent marginal responses of effect sizes to predictors, i.e. mean predicted values, assuming all other predictors at a constant (mean) level, and excluding random effects. Thus, these lines represent global trends, separated from the influence of random effects structures (dependence within studied characteristics and within the same study).

3. Results

3.1 Geographic Representation

Although the number of studies is in line with other meta-analyses in forest ecology (Koricheva and Gurevitch 2014), studies were undertaken in only four countries, including Canada (six studies for aboveground and no studies for belowground), Iran (seven and seven), New Zealand (one and zero), and the USA (seven and one). The full datasets dealing with aboveground and belowground seedling growth can be found in Table A2 and A3 in the supplementary materials. No paper dealing with harvester/forwarder system was found, and the papers in the database mostly dealt with skidder extraction or excavator-based harvesting.

3.2 Overall effect sizes

For aboveground seedlings biomass and lenght standardized mean differences ranged from –9.36 to 6.12, with an interquartile range of –0.43 to 0.73, and with an average of 0.01±0.16. Meta-analysis revealed that the overall effect size was –0.02±0.31 (95% *CI*: –0.62, 0.58), with study-related random effect standard deviation (*SD*) equal to 1.33, within variable standard deviation of 0.13, and heterogeneity measure Q (df=176) of 4211.5 (p<0.001), I^2 of between-cluster heterogeneity was 0.951, and within-cluster heterogeneity I^2 was 0.010 (Table 3, Fig. 3a). For belowground seedlings biomass and lenght standardized mean differences ranged from –9.21 to 10.57, with an interquartile range of –4.22 to –0.45, and with an average of –0.78±0.71. Meta-analysis revealed that the overall effect size was –0.67±1.51 (95% *CI*: –3.64, 2.92), with study-related random effect *SD*=4.00, within variable *SD*<0.001, and heterogeneity measure Q (df=55) of 3073.0 (p<0.001), I^2 of between-cluster heterogeneity was 0.992, and within-cluster heterogeneity I^2 was <0.001 (Table 2, Fig. 3b). This indicates high heterogeneity and no effect of forest operations on seedlings within both datasets. It means that the overall effect size of forest operations did not differ from zero. As this was a preliminary analysis carried out with the overall datasets without considering any moderator, this high between-study heterogeneity was obviously expected.

3.3 Drivers of Forest Operations Effects on Aboveground Characteristics

A multivariate meta-analysis of forest operations effects on aboveground seedlings biomass and lenght revealed that all hypothesized factors were included in the final model (AIC=1025.4, AIC0=2086.5). In the final model, the study-related random effect had a standard deviation of 3.58, seedling characteristic-related random effect had a standard deviation of 0.38, and the heterogeneity measure was QE (df=170)=3202.9 (p<0.001), QM (df=6)=1076.5 (p<0.001), I^2 of between-cluster heterogeneity was 0.983, and within-cluster heterogeneity I^2 was 0.011 (Table 3). An increase in time since harvest increased the effect sizes from –2.70 at half year since harvest to 4.95 at 30 years since harvest (Fig. 4a). However, the estimate of long-term studies can be biased due to a low representation in the dataset. The effects of machine mass and number of machine passes were statistically and biologically insignificant (Fig. 4b–c). Although the effect of machine mass was strong and increasing, the final result

Table 2 A multivariate meta-analysis of ground-based forest operations effect on seedlings aboveground (n = 177) and belowground (n = 56) characteristics

Dataset	Estimate	*SE*	*z*	*p*	95% *CI*		Study random effect *SD* (τ2)
Aboveground	–0.0204	0.3083	–0.0661	0.9473	–0.6247	0.584	1.329
Belowground	–0.6719	1.5139	–0.4438	0.6572	–3.6391	2.2953	4.002

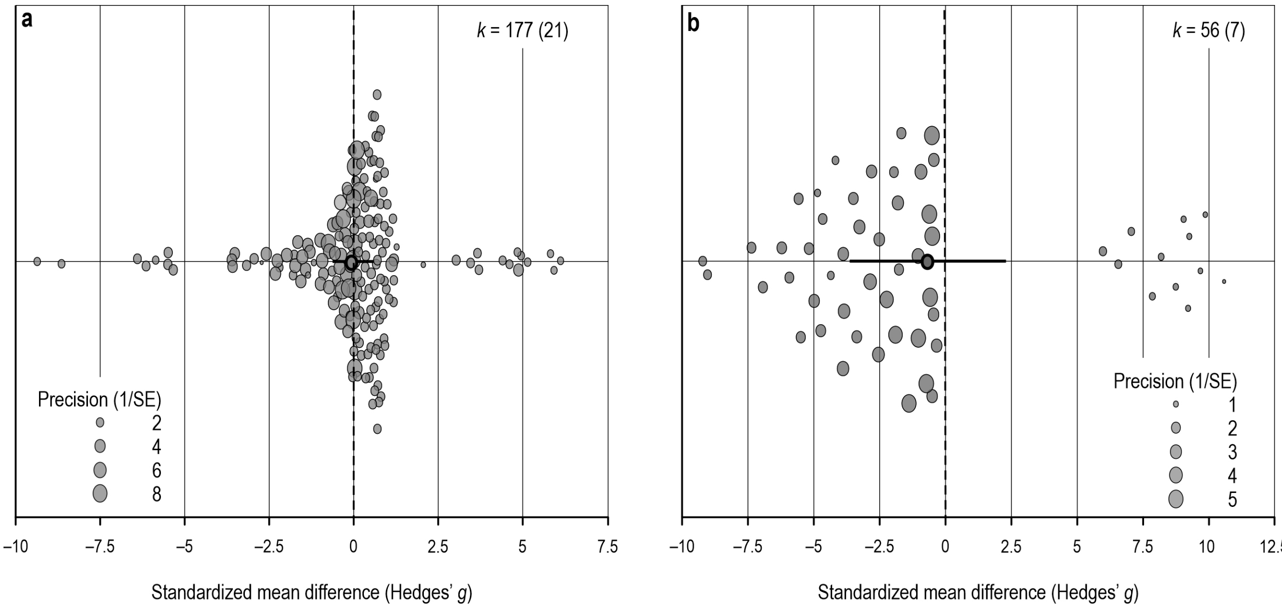

Fig. 3 Orchard plot of standardized mean differences (Hedges' *g*) of studies assessing effects of forest operations (bubbles) on seedlings aboveground (a) and belowground (b) characteristics, with effect sizes (black dots) and 95% confidence intervals (lines) estimated using multivariate meta-analysis (Table 2). *k* denotes the number of effect sizes per estimate with the number of related studies in brackets

was biased by a small representation of the heaviest machines. An increase in the difference in bulk density related to the control decreased Hedges' g from –0.60 at –10% to –1.76 at 90% bulk density increment (Fig. 4d). The effects of forest and regeneration types were both statistically and biologically insignificant (Fig. 4e–f).

3.4 Drivers of Forest Operations Effects on Belowground Characteristics

A multivariate meta-analysis of forest operations effects on belowground seedlings characteristics revealed that all hypothesized factors were included in the final model (AIC=234.5, AIC0=1280.2). In the final model, the study-related random effect had a standard deviation of 2.18, seedling characteristic-related random effect had *SD*=<0.01, and the heterogeneity measure was QE (*df*=50)=935.5 (*p*<0.001), QM (*df*=5)=1048.2 (*p*<0.001), I^2 of between-cluster heterogeneity was 0.974, and within-cluster heterogeneity I^2 was <0.001 (Table 4). An increase in time since harvest increased the effect sizes from –2.34 at half year since harvest to 7.16 at 30 years since harvest (Fig. 5a). However, the estimate of long-term studies was represented by a low number of observations. The positive effect of machine passes number was statistically significant but based on a small number of cases for larger values of that predictor (Fig. 5b). In contrast, the effect of machine mass was strong: estimated effect size for 10 t machines was of –2.99 and for 15 t of 5.46 (Fig. 5c). An increase in bulk density difference from 10% to 98% increased Hedges' g from 0.95 to –3.33, reaching 0.0 at

Table 3 A multivariate meta-analysis of moderators effect on seedlings aboveground characteristics (*n*=177). For categorical moderators the reference level (with no additional term in formula) of regeneration is »artificial« and for forest type – »broadleaf«

Moderator	Estimate	*SE*	*z*	*p*	95% *CI*	
Intercept	–5.242	1.657	–3.164	0.002	–8.489	–1.995
Regeneration = natural	0.529	2.27	–0.233	0.816	–4.978	3.92
Forest type = coniferous	0.044	0.394	0.113	0.910	–0.727	0.816
Number of machine passes	0.009	0.007	1.224	0.221	–0.005	0.023
Machine mass	0.192	0.084	2.295	0.022	0.028	0.357
Time since harvest	0.257	0.008	30.765	<.0001	0.241	0.274
Difference in bulk density	–0.011	0.003	–4.461	<.0001	–0.016	–0.006

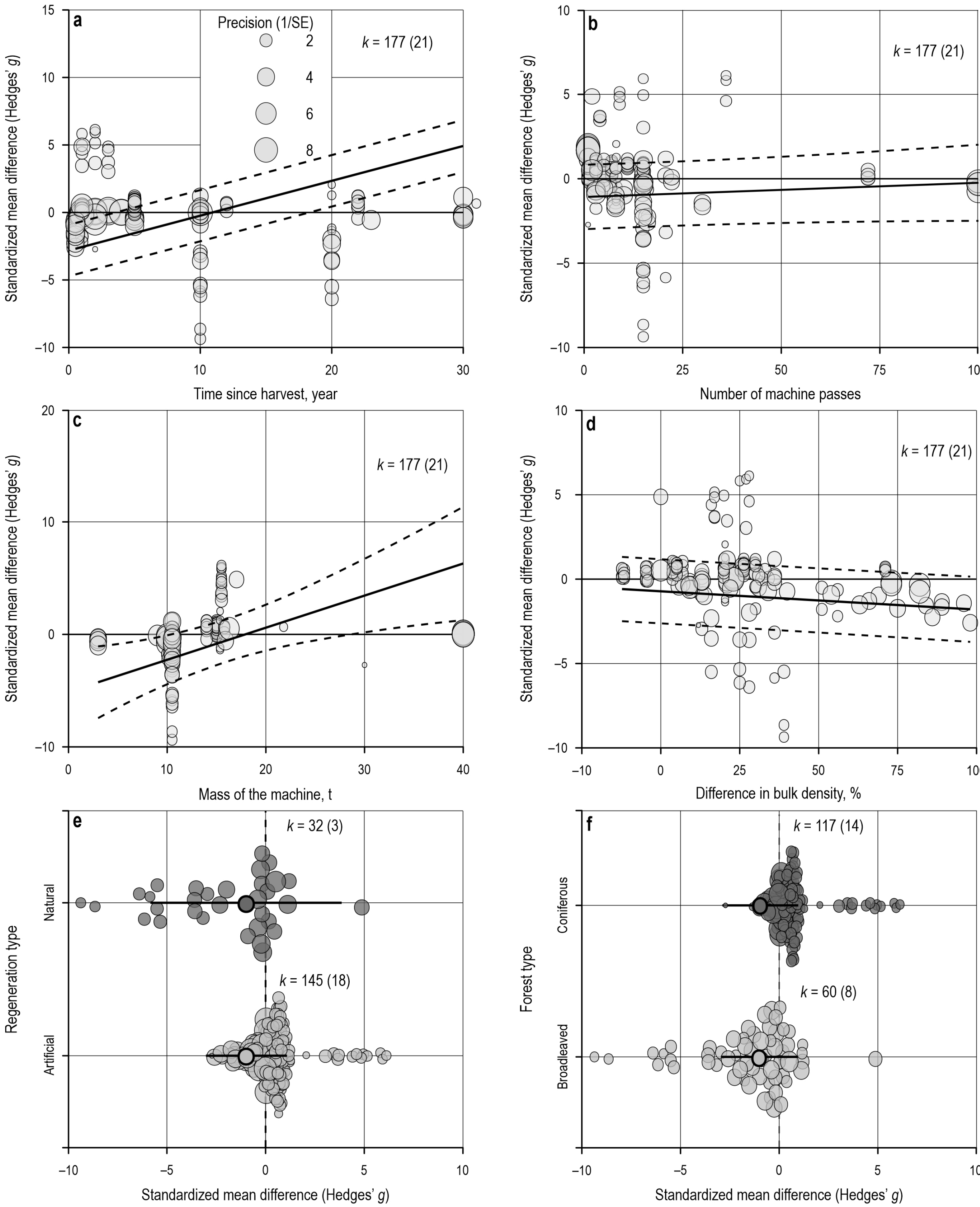

Fig. 4 Effects of moderators driving effect on seedlings aboveground biomass and length: time since harvesting (a), number of machine passes (b), mass of machine (c), difference in bulk density, related to the control (d), regeneration type (e), and forest type (f). Bubble plots (a–d) show the predicted response of effect size (solid line) to continuous moderators, with 95% confidence intervals (dashed lines). Orchard plots (e–f) of standardized mean differences (Hedges' *g*) show differences between categorical moderators in effect sizes (bubbles), with effect sizes (black dots) and 95% confidence intervals (lines). For model details see Table 3. *k* denotes the number of effect sizes per estimate with the number of related studies in brackets

Table 4 A multivariate meta-analysis of moderators effect on seedlings belowground biomass and lenght ($n=56$). For categorical moderator regeneration the intercept is »artificial«

Moderator	Estimate	*SE*	*z*	*p*	95% *CI*	
Intercept	–18.173	5.54	–3.281	0.001	–29.031	–7.316
Regeneration = natural	–7.023	1.893	–3.71	0.000	–10.733	–3.313
Number of machine passes	0.029	0.014	2.089	0.037	0.002	0.055
Machine mass	1.689	0.478	3.537	0.000	0.753	2.626
Time since harvest	0.322	0.013	25.616	<.0001	0.298	0.347
Difference in bulk density	–0.048	0.005	–9.98	<.0001	–0.058	–0.039

29% bulk density difference (Fig. 5d). Artificial regeneration had a positive effect size (estimate 2.08, 95% *CI*: 0.15, 4.01), while natural regeneration – a negative (estimate –4.94, 95% *CI*: –8.13, –1.75; Fig. 5e).

4. Discussion

The results only partially confirmed the main research hypotheses. No significant overall effect of forest operations on seedlings aboveground and belowground features was found. Instead, the analysis revealed the high heterogeneity in the database, indicating the need to account for factors related to the heterogeneity. However, concerning belowground effects (Table 2 and Fig. 3b), it is possible to clearly identify two clusters of effect size, one negative and one positive. As can be seen in Table A3 in the supplementary material, the positive effect sizes all belong to coniferous species. This suggests that soil disturbance can hamper the belowground growth of broadleaf seedlings, while the effect on coniferous species is less evident, and sometimes even positive. However, it should also be highlighted that all the coniferous seedlings in our database were planted, and this also could have an influence on the results. From these aspects it is possible to state that the soil disturbance related to the machine passage is not a mere compaction, but also a certain degree of soil displacement and mixing (Latterini et al. 2024b, Marra et al. 2022), which can favour pioneer species such as conifers (Brais 2001). However, it was not possible to verify this assertion by the meta-analysis, considering that only one paper in our database considered the effects of soil disturbance on belowground growth of coniferous seedlings, leading to the exclusion of this moderator from the sub-group meta-analysis. The trend is confirmed also for aboveground features, even though, in this case too, the effect size was not significant (Table 3 and Fig. 4f). Effect sizes for conifers were indeed generally positive, while for broadleaf species they were generally negative.

Focusing on the effects of the regeneration type (natural vs artificial), no significant effect of this moderator on aboveground features was detectred (Table 3 and Fig. 4e), while instead the effect was significant for belowground biomass and lenght (Table 4 and Fig. 5e). In particular, effect size for natural regeneration was significantly negative, while it was slightly significantly positive for artificial regeneration, even though in this case there were several negative effect sizes. These results imply that soil disturbance induced by the machine passage causes more negative effects on natural regeneration by creating obstacles to the proper belowground development of the seedlings. In the case of artificial regeneration the soil preparation activities, even if conducted locally, can limit the negative consequences of machinery-induced soil disturbance. The effect is however evident only when dealing with belowground growth, considering that aboveground growth was not affected by the type of regeneration.

The meta-regressions concerning time since harvesting reported a positive trend of the regression line with increasing time (Table 3 and Fig. 4a; Table 4 and Fig. 5a), thus suggesting the ability of the forest soil to recover after the machinery-induced disturbance (DeArmond et al. 2021), leading to a decreased effect on both aboveground and belowground seedling growth with increasing time since the forest operations moment. However, the localization of the effect sizes in the bubble plots in Fig. 4a and Fig. 5a suggests a more complex dynamics. The most negative effect sizes refer to a period of 10 years after harvesting, while from 20 years after harvesting the effect sizes start to get closer to the 0 line for both aboveground (Fig. 4a) and belowground features (Fig. 5a). It seems that the proper shape of the regression should not be a line but a unimodal trend with a minimum at 10–20 years after logging. Although the distribution of points in the graphs suggest different type of relationship, our meta-analysis included random effects related to the study and studied seedling biomass and lenght,

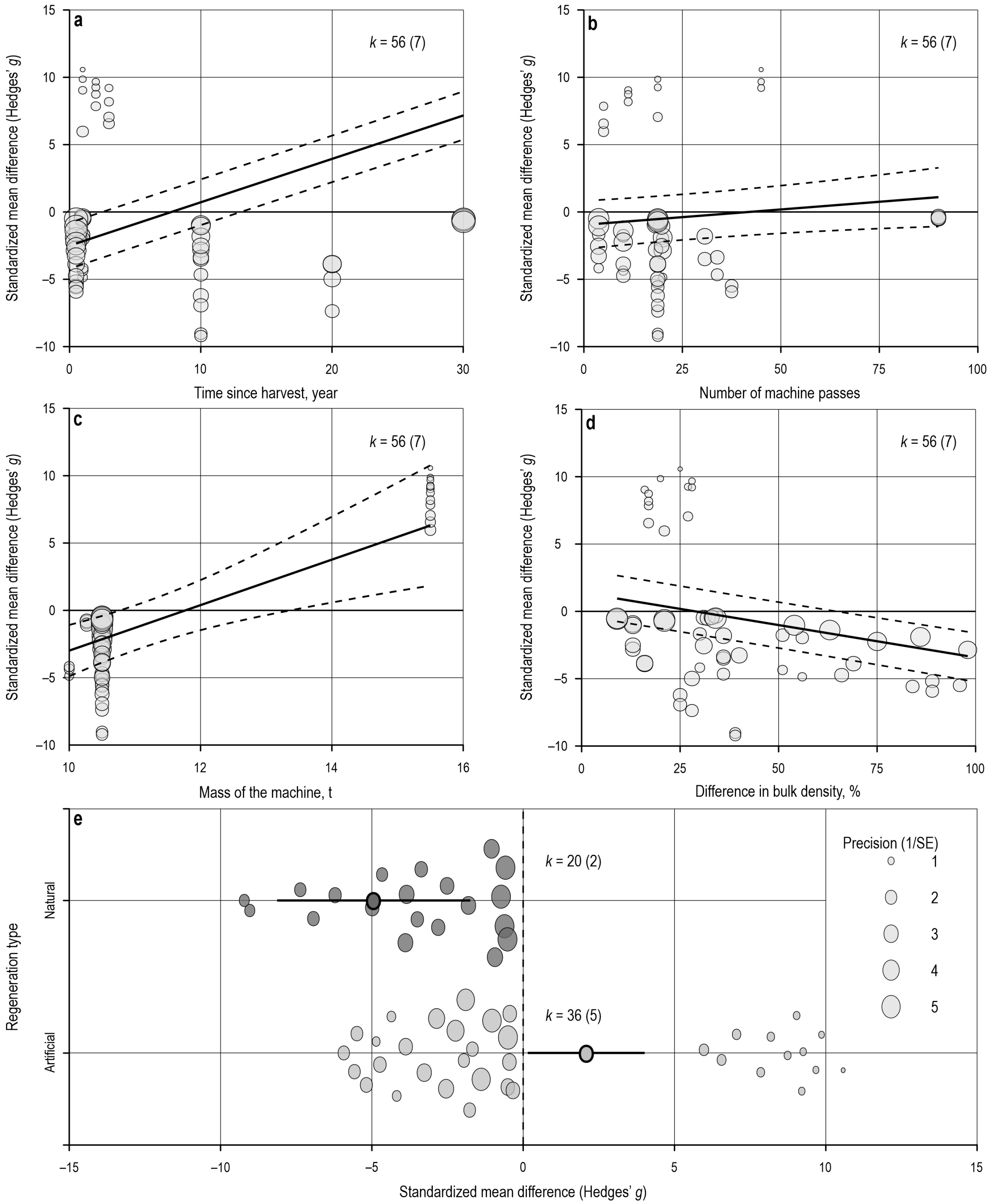

Fig. 5 Effects of moderators driving effect on seedlings belowground biomass and length: time since harvesting (a), number of machine passes (b), machine mass (c), difference in bulk density related to the control (d), and regeneration type (e). Bubble plots (a–d) show the predicted response of effect size (solid line) to continuous moderators, with 95% confidence intervals (dashed lines). Orchard plots (e–f) of standardized mean differences (Hedges' g) show differences between categorical moderators in effect sizes (bubbles), with effect sizes (black dots) and 95% confidence intervals (lines). For model details see Table 4. *k* denotes the number of effect sizes per estimate with the number of related studies in brackets

treated as random intercepts. Therefore, our model captured these variability and the predicted line is a response of the global population (excluding random effects), showing the general trend. However, this is a mere graphical interpretation, unable to be confirmed by the current meta-analytic method, based on linear regressions. Using a quadratic term in such analysis would require more data for better handling uncertainties related to dispersion of data points and effects magnitude. We therefore suggest conducting more long-term studies to effectively understand the time threshold needed to recover the seedlings biomass and lenght after ground-based forest operations.

An increasing number of machine passes was a significant moderator for belowground growth (Table 4 and Fig. 5b), while the effects on aboveground growth were negligible (Table 4 and Fig. 4b). In fact, the significant effect on belowground growth can be considered as a typical case of statistical significance but biological insignificance, which is driven by the low number of studies reporting a high number of machine passes. The bubble plot in Fig. 5b revealed that the strongest negative effect was observed after 15–20 passes. This would suggest that this is the threshold above which the effects of this moderator are not further increasing. However, within this range of predictor, the highest values of effect sizes were observed. This is a very complex topic, depending on a plethora of characteristics, starting from the soil texture (Solgi et al. 2019b), and therefore should be further investigated in different experimental conditions.

Surprisingly, the mass of the machine had a positive impact on both aboveground (Table 3 and Fig. 4c) and belowground growth (Table 4 and Fig. 5c). Therefore, the analyses revealed that positive effect sizes are related to heavier machines, in contrast with what was hypothesized. Moreover, the bubble plots in Fig. 4c and Fig. 5c show how the most negative effect sizes refer to a machine of about 10 Mg mass, mostly old models of wheeled skidders. The fact that medium-mass machines cause the highest amount of damage to the soil has been highlighted in a recent study by Nazari et al. (2021), particularly regarding changes in soil bulk density after forest operations. Also, another study by Latterini et al. 2023c confirmed the same, concerning soil compaction related to forest operations in the Mediterranean context. Higher impacts to different soil features when using medium-size machines can be related to the fact that this machinery is generally not purpose-built for forestry, as it is common in the Mediterranean area where the most applied extraction systems are forestry-fitted farm tractors (Cataldo et al. 2020, Magagnotti et al. 2012). In Bulgaria forestry-fitted farm tractors represent 60% of the skidding fleet, while in Italy their share reaches even 90% (Spinelli et al. 2021). In Romania as well and generally in Eastern Europe this extraction system is largely the most applied (Mederski et al. 2021, Spinelli et al. 2021). Machines designed specifically for forestry, such as forwarders or new generation skidders, despite having higher mass, have a series of technical adjustments, for instance wider tires, bogie tracks, auxiliary axles, rubber-tracked bogie axles, and larger tires, which are helpful to reduce soil disturbances (Fjeld and Østby-Berntsen 2020, Labelle and Jaeger 2019, Starke et al. 2020, Borz et al. 2021). Furthermore, the heaviest machines (40 t) in our database were tracked shovels, and it is well-known that crawler equipment causes less soil disturbance than wheeled machines (Ala-Ilomäki et al. 2021, Gelin and Björheden 2020). Therefore, our results rather suggest that the higher impact on seedling features is related more to the technical characteristics of the machines used for ground-based forest operations than to their mere mass. However, it is worth highlighting that in our database studies dealing with heavy machines were very limited, and there were no studies at all on modern Cut-to-Length systems (harvester+forwarder).

The last continuous moderator, namely the increase in bulk density in the skid trails in comparison to the undisturbed soil, was the most important driver for both aboveground and belowground growth of seedlings. For both aboveground (Table 3 and Fig. 4d) and belowground features (Table 4 and Fig. 5d), the slope of the regression line was negative, highlighting increasing negative effects on seedling growth with increasing soil compaction. The effect was very strong for belowground growth, while more limited (although significant) for aboveground. Soil compaction was therefore confirmed to be the most important consequence of ground-based forest operations, and the factor with the highest influence on the overall functioning of the forest soil ecosystem (Latterini et al. 2024a). From the bubble plot in Fig. 5d it is also possible to estimate the threshold of increase in soil bulk density that causes a significant effect on belowground features of the seedlings (point in which the regression line meets the 0 line). The meta-analytic model indicates a threshold of about 30% increase in soil compaction to have a significant decrease in belowground growth of seedlings (Fig. 5d). Due to excessive variability in the database, it is not possible to identify an analogous threshold for aboveground growth (Fig. 4d).

This finding implies two very important consequences at the level of future research and practical implications. First, as the increase in soil bulk density is strongly related to decreased belowground growth of seedlings, we recommend that every study on the topic of seedling growth alteration after ground-based forest operations should report the increase in soil bulk density in the skid trails (at the time of measuring seedling features) along with the characteristics of the seedlings. Secondly, being soil compaction the major driver of decreased belowground growth of seedlings, it can be asserted that all those best management practices aimed to decrease the level of compaction and rutting, for instance, positioning mats on the trails or planning the trail networks, accounting for the soil sensitivity, can be effective in reducing soil compaction and the detrimental effects of ground-based forest operations on forest regeneration (Hoffmann et al. 2022,

Table 5 Conclusive summary of the study

Research Hypothesis	Moderator	Main Findings	Future Research
I Disturbance of ground-based forest operations is stronger on belowground growth than on aboveground growth of seedlings	None - full database analysis	General trends confirm the hypothesis but no statistical significance could be achieved due to large database variability	Future studies should not only focus on one part of the seedling (above or below) but analyze both and look for correlations between the two growth levels
II Negative effect of ground-based forest operations is stronger on broadleaf species and natural regeneration than in coniferous species and artificial regeneration	Regeneration type	Hypothesis is confirmed concerning belHowground growth, with decreased growth of natural seedlings in skid trails; results on aboveground growth are more heterogeneous and not significant	Future research should investigate more thoroughly the effects of ground-based logging disturbance on natural regeneration of broadleaf species
	Forest type	Hypothesis partially confirmed. Dataset for belowground growth did not report enough studies to carry out a sub-group analysis for this moderator, however effect sizes for broadleaf species are negative while positive for conifers. The trend for aboveground growth is similar but characterized by higher variability	
III Higher number of machine passes, higher machine mass and higher increase in soil bulk density lead to stronger impacts on the features of seedlings; on the other hand there is a clear recovery trend with increasing time after harvesting	Years after harvesting	From the statistical point of view the results confirm the hypothesis for both aboveground and belowground growth. However, the distribution of the effect size suggests a more complex dynamics which is difficult to be explained with a linear regression. There seems to be a negative trend until 10–20 years after the logging intervention, followed by a recovery of seedling growth	More long-term studies are needed to better understand the recovery process after disturbance
	Number of machine passes	Hypothesis rejected. Results revealed biologically insignificant effects for both aboveground and belowground growth. However, most negative effect sizes for belowground growth were observed between 15 and 20 machine passes, suggesting that this could be the threshold for the highest impact	Effect of the moderator to be tested in multiple contexts considering the complexity of the interaction between machine, operational framework and soil
	Machine mass	Hypothesis rejected. Results revealed biologically insignificant effects for both aboveground and belowground growth	Effect of the moderator to be tested in multiple contexts considering the complexity of the interaction between machine, operational framework and soil. Studies on Cut-to-Length machines such as forwarders are particularly recommended
	Increase in soil bulk density	Hypothesis confirmed. Increase in soil bulk density was found to be the most important moderator, mostly for belowground growth. A threshold of 30% increase in soil bulk density resulted in statistically significant decreased belowground growth of seedlings. Results for aboveground growth are still statistically significant but to a lesser extent, considering the high variability in the database	Soil bulk density increase should be always reported in every future study of the topic. From the operational point of view, the application of best management practices to decrease soil compaction are recommended also to limit the disturbance to natural regeneration

Labelle et al. 2022, Ring et al. 2021). To conclude, a summary of the research hypotheses, main findings, and future research suggestions is reported in Table 5.

It should be highlighted that our meta-analysis is based on studies from only four countries (Canada, Iran, New Zealand and the USA). Therefore further research in the topic is recommended mostly in other forestry contexts, by testing the effects of forest operations on seedling growth in the presence of different soils, vegetation and operational frameworks.

5. Conclusions

The results confirmed our hypothesis that the impact of ground-based forest operations is stronger on broadleaf species and natural regeneration. However, this mostly applied to belowground growth, which was generally more affected by forest operations than aboveground biomass and lenght. A recovery was observed with increasing time after harvesting, but it is a complex process that seems to take some time to start. About 10–20 years seem to be needed to recover the seedling features. We showed that machine mass and the number of machine passes are not directly correlated with a stronger impact, thus suggesting that more complex interactions among the machine, the way in which forest operations are carried out, and the soil features are the actual drivers of disturbance. Finally, we observed a strong effect of soil compaction, with an increase in soil bulk density in the trail, which resulted to be the main driver of disturbance to seedling growth, mostly dealing with belowground features. Therefore, soil compaction was found to be the factor that could mostly hamper forest regeneration development in the skid trails. Therefore, the implementation of all those best management practices to reduce machinery-induced soil compaction should be also applied to decrease the negative effects of ground-based forest operations on seedling development. For instance the application of logging mats on the soil prior to the machine passage to prevent soil compaction; defining a permanent skid trail network designed to decrease the surface affected by the machine passage and also the damages to the residual stand; or using bogie-tracks or semi-tracks to decrease the pressure of the machine on the ground.

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Appendix A

Supplementary files are available at https://zenodo.org/records/13888993

6. References

Ala-Ilomäki, J., Lindeman, H., Mola-Yudego, B., Prinz, R., Väätäinen, K., Talbot, B., Routa, J., 2021: The effect of bogie track and forwarder design on rut formation in a peatland. Int. J. of Forest Eng. 32(1): 12–19. https://doi.org/10.1080/14942119.2021.1935167

Ares, A., Terry, T.A., Miller, R.E., Anderson, H.W., Flaming, B.L., 2005: Ground-Based Forest Harvesting Effects on Soil Physical Properties and Douglas-Fir Growth. Soil Sci. Soc. Am. J. 69(6): 1822–1832. https://doi.org/10.2136/sssaj2004.0331

Asbeck, T., Großmann, J., Paillet, Y., Winiger, N., Bauhus, J., 2021a: The Use of Tree-Related Microhabitats as Forest Biodiversity Indicators and to Guide Integrated Forest Management. Curr. For. Rep. 7(1): 59–68. https://doi.org/10.1007/s40725-020-00132-5

Asbeck, T., Sabatini, F., Augustynczik, A.L.D., Basile, M., Helbach, J., Jonker, M., Knuff, A., Bauhus, J., 2021b: Biodiversity response to forest management intensity, carbon stocks and net primary production in temperate montane forests. Sci. Rep. 11(1): 1625. https://doi.org/10.1038/s41598-020-80499-4

Borz, S.A., Marcu, M.V., Cataldo, M.F., 2021: Evaluation of an HSM 208F 14tone HVT-R2 forwarder prototype under conditions of steep-terrain low-access forests. Croat. J. For. Eng. 42(2): 185–200. https://doi.org/10.5552/crojfe.2021.775

Borz, S.A., Crăciun, B.C., Marcu, M.V., Iordache, E., Proto, A.R., 2023: Could timber winching operations be cleaner? An evaluation of two options in terms of residual stand damage, soil disturbance and operational efficiency. Eur. J. For. Res. 142(3): 475–491. https://doi.org/10.1007/s10342-023-01536-1

Brais, S., 2001: Persistence of Soil Compaction and Effects on Seedling Growth in Northwestern Quebec. Soil Sci. Soc. Am. J. 65(4): 1263–1271. https://doi.org/10.2136/sssaj2001.6541263x

Brander, L.M., Tankha, S., Sovann, C., Sanadiradze, G., Zazanashvili, N., Kharazishvili, D., Memiadze, N., Osepashvili, I., Beruchashvili, G., Arobelidze, N., 2018: Mapping the economic value of landslide regulation by forests. Ecosyst. Serv. 32: 101–109. https://doi.org/10.1016/j.ecoser.2018.06.003

Bürgi, M., Schuler, A., 2003: Driving forces of forest management – an analysis of regeneration practices in the forests of the Swiss Central Plateau during the 19th and 20th century. For. Ecol. Manage. 176(1–3): 173–183. https://doi.org/10.1016/S0378-1127(02)00270-0

Cataldo, M.F., Proto, A.R., Macrì, G., Zimbalatti, G., 2020: Evaluation of different wood harvesting systems in typical Mediterranean small-scale forests: A Southern Italian case study. Ann. Silvic. Research 45(1): 1–11. https://doi.org/10.12899/asr-1883

Cheung, M.W.L., 2019: A Guide to Conducting a Meta-Analysis with Non-Independent Effect Sizes. Neuropsychol. Rev. 29(4): 387–396. https://doi.org/10.1007/s11065-019-09415-6

Çiçekler, M., Tutus, A., Üzüm, V., 2023: The Use of Eucalyptus Grandis Bark and Root as Raw Material in Pulp and Paper Production. Drewno 66(211): 00002. https://doi.org/10.12841/wood.1644-3985.425.02

DeArmond, D., Ferraz, J.B.S., Higuchi, N., 2021: Natural recovery of skid trails: a review. Can. J. For. Res. 51(7): 948–961. https://doi.org/10.1139/cjfr-2020-0419

European Commission, 2021: EU Soil Strategy for 2030 Reaping the benefits of healthy soils for people, food, nature and climate. Available online at chrome–extension: https://efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=https%3A%2F%2Feur-lex.europa.eu%2Flegal-content%2FEN%2FTXT%2FP

European Commission, 2020: EU Biodiversity Strategy for 2030. Bringing nature back into our lives. Brussels, 20.5.2020.

European Union, 2021: New European Forest Strategy for 2030. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0572. (Accessed on 15th August)

Evans, P.D., Matsunaga, H., Preston, A.F., Kewish, C.M., 2022: Wood Protection for Carbon Sequestration – a Review of Existing Approaches and Future Directions. Curr. For. Rep. 8(5): 181–198. https://doi.org/10.1007/s40725-022-00166-x

Forkuo, G.O., Borz, S.A., 2023: Accuracy and inter-cloud precision of low-cost mobile LiDAR technology in estimating soil disturbance in forest operations. Front. For. Glob. Change. 6: 1224575. https://doi.org/10.3389/ffgc.2023.1224575

Filothei, M., Petros, G., 2023: Effect of land preparation methods on restoration success of degraded oak forest ecosystems. Dendrobiology 89: 56–64. https://doi.org/10.12657/denbio.089.006

Fjeld, D., Østby-Berntsen, Ø., 2020: The effects of an auxiliary axle on forwarder rut development – a Norwegian field study. Int. J. For. Eng. 31(3): 192–196. https://doi.org/10.1080/14942119.2020.1765645

Froehlich, H.A., 1976: The Effect of Soil Compaction by Logging on Forest Productivity, Bureau of Land Management Final Report.

Gelin, O., Björheden, R., 2020: Concept evaluations of three novel forwarders for gentler forest operations. J. Terramechanics 90: 49–57. https://doi.org/10.1016/j.jterra.2020.04.002

Hedges, L.V., 1981: Distribution Theory for Glass's Estimator of Effect size and Related Estimators. J. Educ. Stat. 6(2): 107–128. https://doi.org/10.3102/10769986006002107

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999: The meta-analysis of response ratios in experimental ecology. Ecology 80(4): 1150–1156. https://doi.org/10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2

Hedges, L.V, Olkin, I., 2014: Statistical methods for meta-analysis. J. Educ. Stat. 20(1)

Higgins, J.P.T., Green, S., 2008: Cochrane handbook for systematic reviews of interventions. Wiley online libarary, editors Higgins J.P.T. and Green, S., 1–649 p. https://doi.org/10.1002/9780470712184

Higgins, J.P.T., Thompson, S.G., 2002: Quantifying heterogeneity in a meta-analysis. Stat. Med. 21(11): 1539–1558. https://doi.org/10.1002/sim.1186

Hoeben, A.D., Stern, T., Lloret, F., 2023: A Review of Potential Innovation Pathways to Enhance Resilience in Wood-Based Value Chains. Curr. For. Rep. 9(5): 301–318. https://doi.org/10.1007/s40725-023-00191-4

Hoffmann, S., Schönauer, M., Heppelmann, J., Asikainen, A., Cacot, E., Eberhard, B., Hasenauer, H., Ivanovs, J., Jaeger, D., Lazdins, A., Mohtashami, S., Moskalik, T., Nordfjell, T., Stereńczak, K., Talbot, B., Uusitalo, J., Vuillermoz, M., Astrup, R., 2022: Trafficability Prediction Using Depth-to-Water Maps: the Status of Application in Northern and Central European Forestry. Curr. For. Rep. 8(1): 55–71. https://doi.org/10.1007/s40725-021-00153-8

Holub, S.M., Terry, T.A., Harrington, C.A., Harrison, R.B., Meade, R., 2013: Tree growth ten years after residual biomass removal, soil compaction, tillage, and competing vegetation control in a highly-productive Douglas-fir plantation. For. Ecol. Manage. 305: 60–66. https://doi.org/10.1016/j.foreco.2013.05.031

Houšková, K., Sendecký, M., Martiník, A., 2023: The effect of prolonged stratification and shading on the emergence of *Pseudotsuga menziesii* (Mirb.) Franco seedlings. Dendrobiology 89: 82–91. https://doi.org/10.12657/denbio.089.009

Jamshidi, R., Jaeger, D., Dragovich, D., 2018: Establishment of pioneer seedling species on compacted skid tracks in a temperate Hyrcanian forest, northern Iran. Environ Earth Sci. 77(3): 1–13. https://doi.org/10.1007/s12665-018-7233-9

Janiszewska-Latterini, D., Pizzi, A., 2023: Application of Liquefied Wood Products for Particleboard Manufacturing: a Meta-analysis Review. Curr. For. Rep. 9: 291–300. https://doi.org/10.1007/s40725-023-00192-3

Jourgholami, M., Fathi, K., Labelle, E.R., 2020: Effects of litter and straw mulch amendments on compacted soil properties and Caucasian alder (*Alnus subcordata*) growth. New For. 51(4): 349–365. https://doi.org/10.1007/s11056-019-09738-5

Konstantopoulos, S., 2011: Fixed effects and variance components estimation in three-level meta-analysis. Res. Synth. Methods 2(1): 61–76. https://doi.org/10.1002/jrsm.35

Koricheva, J., Gurevitch, J., 2014: Uses and misuses of meta-analysis in plant ecology. J. Ecol. 102(4): 828–844. https://doi.org/10.1111/1365-2745.12224

Kranabetter, J.M., Dube, S., Lilles, E.B., 2017: An investigation into the contrasting growth response of lodgepole pine and white spruce to harvest-related soil disturbance. Can. J. For. Res. 47(3): 340–348. https://doi.org/10.1139/cjfr-2016-0386

Kranabetter, J.M., Sanborn, P., Chapman, B.K., Dube, S., 2006: The Contrasting Response to Soil Disturbance between Lodgepole Pine and Hybrid White Spruce in Subboreal Forests. Soil Sci. Soc. Am. J. 70(5): 1591–1599. https://doi.org/10.2136/sssaj2006.0081

Labelle, E.R., Hansson, L., Högbom, L., Jourgholami, M., Laschi, A., 2022: Strategies to Mitigate the Effects of Soil Physical Disturbances Caused by Forest Machinery: a Comprehensive Review. Curr. For. Rep. 8(11): 20–37. https://doi.org/10.1007/s40725-021-00155-6

Lajeunesse, M.J., 2011: On the meta-analysis of response ratios for studies with correlated and multi-group designs. Ecology 92(11): 2049–2055. https://doi.org/10.1890/11-0423.1

Langmaier, M., Lapin, K., 2020: A Systematic Review of the Impact of Invasive Alien Plants on Forest Regeneration in European Temperate Forests. Front. Plant Sci. 11: 524969. https://doi.org/10.3389/fpls.2020.524969

Latterini, F., Dyderski, M.K., Horodecki, P., Picchio, R., Venanzi, R., Lapin, K., Jagodziński, A.M., 2023: The Effects of Forest Operations and Silvicultural Treatments on Litter Decomposition Rate: a Meta–analysis. Curr. For. Rep. 9(4): 276–290. https://doi.org/10.1007/s40725-023-00190-5

Latterini, F., Dyderski, M.K., Horodecki, P., Rawlik, M., Stefanoni, W., Högbom, L., Venanzi, R., Picchio, R., Jagodziński, A.M., 2024a: A Meta–analysis of the effects of ground–based extraction technologies on fine roots in forest soils. Land Degrad. Dev. 35(1): 9–21. https://doi.org/10.1002/ldr.4902

Latterini, F., Mederski, P.S., Jaeger, D., Venanzi, R., Tavankar, F., Picchio, R., 2023b: The Influence of Various Silvicultural Treatments and Forest Operations on Tree Species Biodiversity. Curr. For. Rep. 9(2): 59–71. https://doi.org/https://doi.org/10.1007/s40725-023-00179-0

Latterini, F., Spinelli, R., Venanzi, R., Picchio, R., 2024b: Acorn Review: Focus on ground–based extraction systems: Is skidding really more impactful than forwarding? For. Ecol. Manage. 551: 121514. https://doi.org/10.1016/j.foreco.2023.121514

Latterini, F., Venanzi, R., Papa, I., Đuka, A., Picchio, R., 2024c: A Meta-Analysis to Evaluate the Reliability of Depth–to–Water Maps in Predicting Areas Particularly Sensitive to Machinery–Induced Soil Disturbance. Croat. J. For. Eng. 45(2): 433–444. https://doi.org/10.5552/crojfe.2024.2559

Latterini, F., Venanzi, R., Picchio, R., Jagodziński, A.M., 2023c: Short-term physicochemical and biological impacts on soil after forest logging in Mediterranean broadleaf forests: 15 years of field studies summarized by a data synthesis under the meta-analytic framework. Forestry 96(4) 547–560. https://doi.org/10.1093/forestry/cpac060

Łukawski, D., Hochmańska-Kaniewska, P., Janiszewska-Latterini, D., Lekawa-Raus, A., 2023: Functional materials based on wood, carbon nanotubes, and graphene: manufacturing, applications, and green perspectives. Wood. Sci. Technol. 57(5): 989–1037. https://doi.org/10.1007/s00226-023-01484-4

Lyczak, S.J., Kabrick, J.M., Knapp, B.O., 2021: Long-term effects of organic matter removal, compaction, and vegetation control on tree survival and growth in coarse-textured, low-productivity soils. For. Ecol. Manage. 496: 119428. https://doi.org/10.1016/j.foreco.2021.119428

Magagnotti, N., Spinelli, R., Güldner, O., Erler, J., 2012: Site impact after motor-manual and mechanised thinning in Mediterranean pine plantations. Biosyst. Eng. 113(2): 140–147. https://doi.org/10.1016/j.biosystemseng.2012.07.001

Mariotti, B., Hoshika, Y., Cambi, M., Marra, E., Feng, Z., Paoletti, E., Marchi, E., 2020: Vehicle-induced compaction of forest soil affects plant morphological and physiological attributes: A meta–analysis. For. Ecol. Manage. 462: 118004. https://doi.org/10.1016/j.foreco.2020.118004

Marra, E., Laschi, A., Fabiano, F., Foderi, C., Neri, F., Mastrolonardo, G., Nordfjell, T., Marchi, E., 2022: Impacts of wood extraction on soil: assessing rutting and soil compaction caused by skidding and forwarding by means of traditional and innovative methods. Eur. J. For. Res. 141: 71–86. https://doi.org/10.1007/s10342-021-01420-w

Mayer, M., Prescott, C.E., Abaker, W.E.A., Augusto, L., Cécillon, L., Ferreira, G.W.D., James, J., Jandl, R., Katzensteiner, K., Laclau, J.P., Laganière, J., Nouvellon, Y., Paré, D., Stanturf, J.A., Vanguelova, E.I., Vesterdal, L., 2020: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. For. Ecol. Manage. 466: 118127. https://doi.org/10.1016/j.foreco.2020.118127

Mederski, P.S., Borz, S.A., Đuka, A., Lazdiņš, A., 2021: Challenges in forestry and forest engineering – Case studies from four countries in East Europe. Croat. J. of For. Eng. 42(1): 117–134. https://doi.org/10.5552/crojfe.2021.838

Miura, S., Amacher, M., Hofer, T., San-Miguel-Ayanz, J., Ernawati, Thackway, R., 2015: Protective functions and ecosystem services of global forests in the past quarter-century. For. Ecol. Manage. 352: 35–46. https://doi.org/10.1016/j.foreco.2015.03.039

Naghdi, R., Solgi, A., Labelle, E.R., Zenner, E.K., 2016: Influence of ground-based skidding on physical and chemical properties of forest soils and their effects on maple seedling growth. Eur. J. For. Res. 135: 949–962. https://doi.org/10.1007/s10342-016-0986-3

Naghdi, R., Tavankar, F., Solgi, A., Nikooy, M., Marchi, E., Picchio, R., 2023: Effects on soil physicochemical properties and seedling growth in mixed high forests caused by cable skidder traffic. IForest 16(2): 127–135. https://doi.org/10.3832/ifor4103-016

Nakagawa, S., Lagisz, M., O'Dea, R.E., Rutkowska, J., Yang, Y., Noble, D.W.A., Senior, A.M., 2021: The orchard plot: Cultivating a forest plot for use in ecology, evolution, and beyond. Res. Synth. Methods 12(1): 4–12. https://doi.org/10.1002/jrsm.1424

Nazari, M., Arthur, E., Lamandé, M., Keller, T., Bilyera, N., Bickel, S., 2023: A Meta-analysis of Soil Susceptibility to Machinery-Induced Compaction in Forest Ecosystems Across Global Climatic Zones. Curr. For. Rep. 9(5): 370–381. https://doi.org/10.1007/s40725-023-00197-y

Nazari, M., Eteghadipour, M., Zarebanadkouki, M., Ghorbani, M., Dippold, M.A., Bilyera, N., Zamanian, K., 2021: Impacts of Logging-Associated Compaction on Forest Soils: A Meta-Analysis. Front. For. Glob. Change. 4: 780074. https://doi.org/10.3389/ffgc.2021.780074

Neaves, C.M., Aust, W.M., Bolding, M.C., Barrett, S.M., Trettin, C.C., Vance, E., 2017: Loblolly pine (*Pinus taeda* L.) productivity 23 years after wet site harvesting and site preparation in the lower Atlantic coastal plain. For. Ecol. Manage. 401: 207–214. https://doi.org/10.1016/j.foreco.2017.07.007

Norris, C.E., Hogg, K.E., Maynard, D.G., Curran, M.P., 2014: Stumping trials in british columbia – organic matter removal and compaction effects on tree growth from seedlings to midrotation stands. Can. J. For. Res. 44(11): 1402–1418. https://doi.org/10.1139/cjfr-2014-0168

Picchio, R., Tavankar, F., Nikooy, M., Pignatti, G., Venanzi, R., Lo Monaco, A., 2019: Morphology, Growth and Architecture Response of Beech (*Fagus orientalis* Lipsky) and Maple Tree (*Acer velutinum* Boiss.) Seedlings to Soil Compaction Stress Caused by Mechanized Logging Operations. Forests 10(9): 771. https://doi.org/10.3390/f10090771

Picchio, R., Tavankar, F., Venanzi, R., Lo Monaco, A., Nikooy, M., 2018: Study of forest road effect on tree community and stand structure in three italian and Iranian temperate forests. Croat. J. For. Eng. 39(1): 57–70.

R Development Core Team, 2023: R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing, Vienna Austria. Available online: http://www.r-project.org/ (accessed on 6th October 2023).

Ring, E., Andersson, M., Hansson, L., Jansson, G., Högbom, L., 2021: Logging mats and logging residue as ground protection during forwarder traffic along till hillslopes. Croat. J. For. Eng. 42(3) 445–462. https://doi.org/10.5552/crojfe.2021.875

Rosnow, R.L., Rosenthal, R., 1996: Computing contrasts, effect sizes, and counternulls on other people's published data: General procedures for research consumers. Psychol. Methods 1(4): 331–340. https://doi.org/10.1037/1082-989X.1.4.331

Simcock, R.C., Parfitt, R.L., Skinner, M.F., Dando, J., Graham, J.D., 2006: The effects of soil compaction and fertilizer application on the establishment and growth of *Pinus radiata*. Can. J. For. Res. 36(5): 1077–1086. https://doi.org/10.1139/X06-009

Solgi, A., Naghdi, R., Marchi, E., Laschi, A., Keivan Behjou, F., Hemmati, V., Masumian, A., 2019a: Impact Assessment of Skidding Extraction: Effects on Physical and Chemical Properties of Forest Soils and on Maple Seedling Growing along the Skid Trail. Forests 10(2): 134. https://doi.org/10.3390/f10020134

Solgi, A., Naghdi, R., Zenner, E.K., Tsioras, P.A., Hemmati, V., 2019b: Effects of Ground-Based Skidding on Soil Physical Properties in Skid Trail Switchbacks. Croat. J. For. Eng. 40(2): 341–350. https://doi.org/10.5552/crojfe.2019.535

Spinelli, R., Magagnotti, N., Visser, R., O'Neal, B., 2021: A survey of the skidder fleet of Central, Eastern and Southern Europe. Eur. J. For. Res. 140: 901–911. https://doi.org/10.1007/s10342-021-01374-z

Starke, M., Derron, C., Heubaum, F., Ziesak, M., 2020: Rut Depth Evaluation of a Triple-Bogie System for Forwarders–Field Trials with TLS Data Support. Sustainability 12(16): 6412. https://doi.org/10.3390/su12166412

Stekhoven, D.J., Bühlmann, P., 2012: MissForest—non-parametric missing value imputation for mixed-type data. Bioinformatics 28(1): 112–118. https://doi.org/10.1093/bioinformatics/btr597

Tan, X., Chang, S.X., Kabzems, R., 2015: Soil compaction and forest floor removal reduced microbial biomass and enzyme activities in a boreal aspen forest soil. Biol. Fertil. Soils 51: 523. https://doi.org/10.1007/s00374-015-1014-3

Tavankar, F., Picchio, R., Nikooy, M., Jourgholami, M., Naghdi, R., Latterini, F., Venanzi, R., 2021: Soil Natural Recovery Process and *Fagus orientalis* Lipsky Seedling Growth after Timber Extraction by Wheeled Skidder. Land 10(2): 113. https://doi.org/10.3390/land10020113

Treasure, T., Watmough, S.A., Eimers, M.C., Murray, H., 2019: Impact of selection harvesting on the foliar chemistry of sugar maple seedlings established on base-poor soils in central Ontario, Canada. For. Ecol. Manage. 435: 1–7. https://doi.org/10.1016/j.foreco.2018.12.033

Triviño, M., Morán-Ordoñez, A., Eyvindson, K., Blattert, C., Burgas, D., Repo, A., Pohjanmies, T., Brotons, L., Snäll, T., Mönkkönen, M., 2023: Future supply of boreal forest ecosystem services is driven by management rather than by climate change. Glob. Chang. Biol. 29(6): 1484–1500. https://doi.org/10.1111/gcb.16566

Viechtbauer, W., 2010: Conducting Meta–Analyses in R with the metafor Package. J. Stat. Softw. 36(3): 1–48. https://doi.org/10.18637/jss.v036.i03

Viechtbauer, W., 2007: Accounting for Heterogeneity via Random-Effects Models and Moderator Analyses in Meta-Analysis. Z. fur Psychol. / J. Psychol. 215(2): 104–121. https://doi.org/10.1027/0044-3409.215.2.104

Youngberg, C.T., 1959: The Influence of Soil Conditions, Following Tractor Logging, on the Growth of Planted Douglas–Fir Seedlings. Soil Sci. Soc. Am. J. 23(1): 76–78. https://doi.org/10.2136/sssaj1959.03615995002300010028x

Zhang, B., Lan, K., Harris, T.B., Ashton, M.S., Yao, Y., 2023: Climate-smart forestry through innovative wood products and commercial afforestation and reforestation on marginal land. P. Natl. Acad. Sci. USA 120(23): e2221840120. https://doi.org/10.1073/pnas.2221840120

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