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A Meta-Analysis to Evaluate the Reliability of Depth-to-Water Maps in Predicting Areas Particularly Sensitive to Machinery-Induced Soil Disturbance

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Abstract

The careful planning of the extraction routes is one of the most important best management practices to limit soil disturbance related to ground-based forest operations. Over the recent years, this task has been commonly addressed in the framework of boreal forestry, by developing soil trafficability maps based on the depth-to-water (DTW) topographic index. The basic concept of trafficability maps developed with the DTW index is that soils at low DTW index, namely ≤1, could be more prone to soil compaction and rutting as they tend to have higher moisture content. However, previous studies that tried to assess the reliability of these maps reported contrasting results. Therefore, the present meta-analysis was developed to evaluate if soils at low DTW index (≤1) are actually more sensitive to soil compaction and rutting than soils at higher DTW index (>1). A database was created containing all the studies that assessed soil compaction and rutting in soils at low DTW index (experimental treatment) and high DTW index (control treatment), and a multivariate meta-analysis was used to check the presence of statistically significant effect size. Then the influence on the effect size of variables like soil texture, number of machine passage and weight of the machine, was checked by applying sub-group meta-analysis and meta-regression. Finally, a sensitivity analysis was performed by removing possible outliers from the database and repeating the analyses. No statistical differences were found in soil compaction and rutting severity in areas at low DTW index in comparison to the control areas (DTW index >1). The results showed that soil texture, number of machine passage and weight of the machine did not have a significant influence on the effect size. The sensitivity analysis developed after removing outliers from the database fully confirmed the obtained results. Thus our meta-analysis showed that the DTW index in its current form is not a fully reliable predictor of soil areas that could be particularly sensitive to machinery-induced disturbance. It is therefore recommended to use the DTW index to create trafficability maps, always taking into account that the results of the algorithms should be validated in the field before starting harvesting operations.

Keywords: soil trafficability maps, soil compaction, rutting, GIS, soil moisture

1. Introduction

The sustainability of forest operations has always been one of the most important topics of research in the forest engineering sector (Borz et al. 2023, Marchi et al. 2018, Proto et al. 2017, Bumber et al. 2023). Wood is indeed a fundamental resource for multiple purposes (Çiçekler et al. 2023, Łukawski et al. 2023, Pędzik et al. 2022), but forest operations to retrieve wooden products from the forest stands can be potentially harmful to the environment (Brennensthul et al. 2023). Disturbances can indeed occur at the soil, regeneration, residual stand, and biodiversity level (Latterini et al. 2023b, Picchio et al. 2020, Vancura et al. 2022). Soil compaction and displacement, for instance in the form of rutting, are among the most common and detrimental consequences of ground-based forest operations (Nazari et al. 2023, Piskunov

2023, Ring et al. 2021). The modification in soil physical properties after machine passage is just the first result of ground-based forest operations, considering that after compaction and/or rutting a series of disturbances can occur at various levels, for instance erosion (Jalali et al. 2022, Jourgholami et al. 2019), decreased water quality (Ring et al. 2023), soil organic carbon depletion (Mayer et al. 2020), litter decomposition rates modification (Latterini et al. 2023a), decreased plant nutrient uptake capacity (Latterini et al. 2024) and change of biodiversity of edaphic communities (Kudrin et al. 2023).

Taking all this into account, researchers in the topic have tried to develop several strategies to prevent or mitigate the negative consequences of ground-based forest operations on the soil (Ilintsev et al. 2021, Labelle et al. 2022), or even to restore the soil after the disturbance (Jourgholami et al. 2018). The proper planning of the extraction routes is considered one of the most powerful tools to avoid excessive damage to the soil after forest operations (Marčeta et al. 2020, Talbot and Astrup 2021). Modern technologies, including GIS (Geographic Information Systems) and GNSS (Global Navigation Satellite System), can be particularly helpful in planning an optimal extraction route network (Görgens et al. 2020, Keefe et al. 2022, Petković and Potočnik 2018). In recent years, mostly in countries such as Sweden, Canada, Finland and Norway, the GIS-planning of the extraction routes is more and more based on the development of soil trafficability maps (Hoffmann et al. 2022). These maps identify zones of the cutting block, prior to the harvesting operations, which could be highly sensitive to soil disturbance, thus indicating to the operators the zones that they should avoid while driving the machines.

Among the various possibilities for developing trafficability maps (Salmivaara et al. 2021), particular attention has been given to the Depth-to-Water (DTW) index. The DTW concept was created, refined, and tested in Canada, specifically at the University of New Brunswick (Faculty of Forestry and Environmental Management), by Fan-Rui Meng, Jae Ogilvie and Paul Arp (Murphy et al. 2011, 2008, 2007). The DTW index can be defined as the anticipated vertical distance between any given grid cell of a Digital Terrain Model (DTM) to the flow lines derived by a DTM-based flow accumulation (Hoffmann et al. 2022). The main advantages of the DTW index are essentially two, i.e. having as single input a DTM at a resolution of 1–2 m (Mohtashami et al. 2022), and the capacity of modelling different soil moisture conditions, by changing the Flow Initiation Area (FIA). Indeed, the accumulated flow value for each grid cell is calculated based on the area and convergent from the neighbouring cells. Based on a specified threshold, the collected area size is then used to start a flow line. Low values of FIA, for instance 0.25 ha or 0.50 ha, are used to represent very wet soil conditions, as the network of flow lines grows. Contrarily, higher FIA of 16 ha can be used to represent very dry soil conditions or high soil bearing capacity conditions (Jones and Arp 2019). The DTW concept applied to the development of soil trafficability maps consists of considering as potentially sensitive to soil disturbance all those areas with DTW index ≤1, while areas at DTW index >1 can be considered as more resistant to ground-based forest operations (Schönauer et al. 2022, 2021b). On the one hand, the relationship between high soil moisture and low DTW index has been demonstrated in several studies (Ågren et al. 2021, 2015, 2014), but on the other hand the results of the studies that tried to evaluate if the areas at low DTW index are actually more sensitive to soil compaction and rutting are more heterogeneous (Mohtashami et al. 2017, Schönauer et al. 2021a).

Therefore this meta-analytic review of the literature was developed, with the goal of testing the hypothesis that soil trafficability maps based on the DTW index can predict soils that are more prone to soil compaction and rutting. Meta-analysis is a statistical technique that can be applied to develop quantitative literature reviews, by summarising the results of the various studies dealing with the same topic in a numerical way (Ghorbani et al. 2023, Latterini et al. 2023c, Meaza et al. 2022). The fundamental advantage of utilising meta-analyses is that they statistically examine the findings from various research studies with comparable experimental designs to draw general conclusions that would not have been obvious from a single trial (Lajeunesse 2011). Additionally, meta-analysis offers the chance to acquire a quantitative and impartial assessment for subjects where the literature reports significant variability and a lack of a discernible trend. As a result, this technique proves to be ideally suited for researching if the compaction and rutting levels in the soil at low DTW index are actually higher than those on soils at DTW index>1.

The meta-analytic approach was further applied to test if the soil type, number of machine passages and weight of the machine used for forest operations could be influential parameters in defining the effectiveness of DTW maps in the prediction of soil sensitive areas.

2. Materials and Methods

2.1 Systematic Literature Review and Database Creation

A thorough search of the literature references listed in the Google Scholar, Scopus, and Web of Science databases was carried out in the first half of October 2023. Literature search was performed by using the Boolean operators AND or OR in combination with the following keywords: depth-to water; DTW; trafficability map; rutting; soil compaction; forwarder; forwarding; skidder; skidding; logging (Fig. 1).

The snowball method was also employed, which involves looking up extra suitable references in a list of recent papers in order to gather more literature sources. The snowball method was performed starting from the reference list of the papers published in 2023 and 2022. In this manner, two other papers were discovered. At this stage, 73 papers could be eligible for inclusion in the database. First, the duplicate studies were removed, and then papers whose titles and abstracts did not relate to the subject were omitted. A total of 31 papers were obtained. Finally, the remaining papers were examined and the following inclusion criteria were applied:

- ⇒ the paper must provide a quantitative measurement of soil compaction (bulk density, penetration resistance or shear resistance) or rutting depth in skid trails or strip roads established in areas at DTW index ≤1
- ⇒ the paper must have a control treatment, consisting of areas at DTW index >1 in which the quantitative measurement of soil compaction and rutting was carried out as well.

In this way five papers were identified, which generated 18 comparisons treatment vs control, suitable for our meta-analysis (Ågren et al. 2015, Campbell et al. 2013, Jones and Arp 2019, Latterini et al. 2022, Schönauer et al. 2021a). Two papers were from Canada, one from Sweden, one from Italy and one from Germany.

The above five papers were analysed to obtain values of soil compaction and rutting depth in the experimental treatment (DTW index≤1) and control treatment (DTW index>1). In particular, the following values were extracted: average, standard deviation, and sample numerosity for both the experimental treatment and the control one. For data which were not directly available in numerical form in tables or main text, the software WebplotDigitizer was used to extract data from graphs. In all the studies a dispersion measure, mostly the standard deviation, was reported, therefore no imputation was needed.

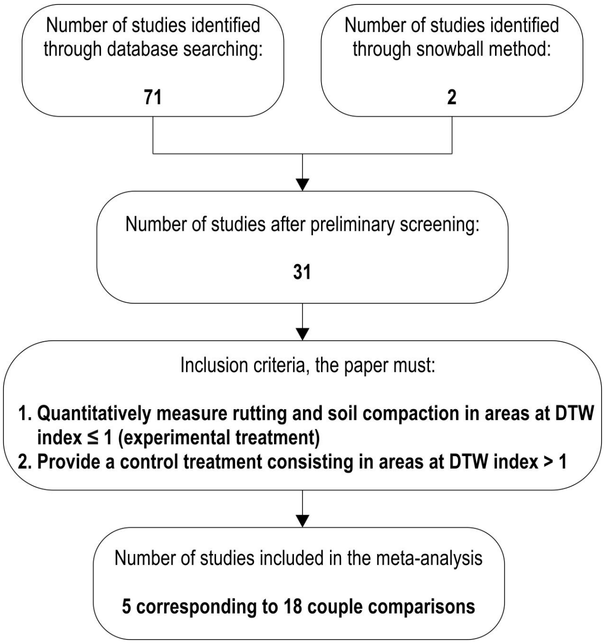

Fig. 1 Meta-analysis chart for this review

Data regarding the following variables were also retrieved from the papers: soil texture in the investigated cutting block, number of machine passages experienced by the analysed skid trail/strip road, weight of the machine that established the skid trail/strip road. The effect of these variables was tested by subgroup meta-analysis and meta-regression, in the framework of meta-analysis named moderators on the effect size variation (Table 1).

2.2 Implementation of Meta-Analysis

The natural log of the response ratio was selected among the possible effect size estimators (McGaw and Glass 1980). The response ratio is the ratio between the value in the experimental treatment (DTW≤1) and the value in the control treatment (DTW>1), and it is calculated according to Eq. 1 (Hedges et al. 1999):

$$lnRR = \ln(Xt/Xc) \qquad (1)$$

Where:

RR	is the response ratio of a given comparison
Xt and Xc	denote the average values of the variables in the experimental and control treatments,¸respectively.

We chose to account for within-study dependence using random effects in mixed-effects, encompassing the spatio-temporal autocorrelation and comparable

Table 1 Moderators used in sub-group meta-analysis and meta-regression

Moderator	Type	Average ± Standard deviation, range (only for continuous moderator)	Notes
Soil texture	Categorical	–	–
Parameter	Categorical	–	Soil compaction (bulk density, penetration resistance, shear resistance) or rutting depth
Number of machine passages	Continuous	13 ± 9, 5 – 30	–
Machine weight, Mg	Continuous	10.5 ± 7.3, 0.5 – 19.8	–

methodological approaches (Cheung 2014), as the majority of the studies in our database contributed with more than one comparison (Cheung 2019). Therefore, to take into account the issue of data nested structure, the study ID was used as a random effect in the models. The metafor::rma.mv() function was used to create multivariate mixed-effects meta-analytical linear models (Viechtbauer 2010). Using Akaike's information criterion (AIC), the fitness of the models was evaluated and the ones with the lowest AIC were chosen. Funnel plots were used to visualise the link between the effect size and standard error and evaluated potential publication bias, the variability of the data, as well as possible outliers in the effect size distribution. To display the model results, orchard plots were used for categorical moderators and bubble plots for continuous moderators, both included in the orchard package (Nakagawa et al. 2021).

The analyses were also repeated using a subset of the original data to guarantee the reliability of our findings. Possible outliers individuated by the funnel plot were excluded from the database. It is important to highlight that we decided to apply the subset analysis for checking the robustness of our results because it was not possible to apply the typical »leave-one out« approach for sensitivity analysis. This approach is indeed not applicable to a complex database characterised by multilevel heterogeneity structures, such as this one.

QE, QM, and I^2 were presented as three heterogeneity metrics for reporting results. The metafor::rma.mv() function (Viechtbauer 2010) explicitly tests the QM, i.e. the heterogeneity explained by moderators, while QE is a test statistic for residuals heterogeneity (Viechtbauer 2007). In a dataset, I^2 offers details on the heterogeneity between research (Higgins and Thompson 2002). The total I^2 for between-clusters and within-clusters heterogeneity was calculated. The software R 4.3.1 (R Development Core Team 2023) was used for all the statistical analyses.

3. Results

3.1 DTW Reliability According to Meta-Analysis

Multivariate meta-analysis carried out without considering any moderator revealed no statistically significant difference between the values of soil disturbance measured in an area at low and high DTW index. The average effect size was 0.2054, with 95% confidence intervals (CIs) of –0.0288 and 0.4396. Obtained values for Q (102.26) and I^2 (91.66%) statistics revealed very high heterogeneity among the various effect sizes deriving from the different studies, as highlighted by the large dimension of the prediciton intervals (Fig. 2). AIC of the model was 55.5023, thus lower than AIC_0 of 56.3594.

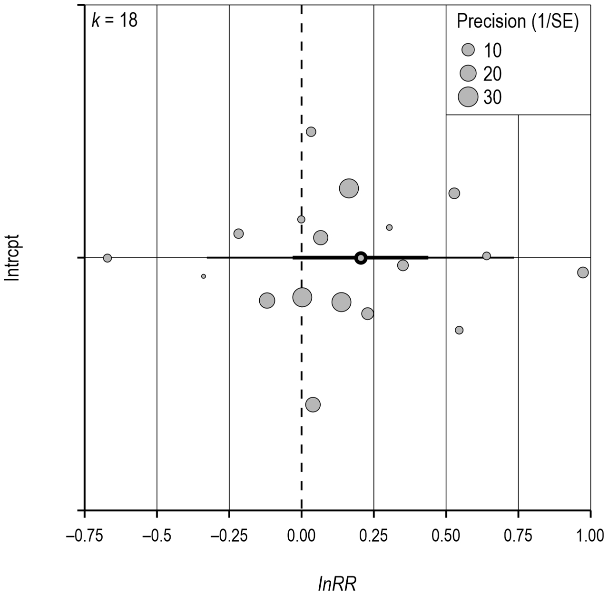

Fig. 2 Orchard plot of *lnRR* of studies assessing effects of DTW index (bubbles), with effect sizes (black dots), 95% confidence intervals (thick lines) and prediction intervals according to the heterogeneity (thin lines) estimated using multivariate meta-analysis. *k* denotes the number of effect sizes per estimate

The multivariate meta-analysis revealed no effect for any of the investigated moderators. The model results for the moderator soil texture revealed positive average effect size for sandy (0.3742) and clayey (0.3919) soils, however large confidence intervals and even larger prediction intervals revealed high heterogeneity and lack of any statistically significant effect of the moderator. The confidence intervals did not overlap with the 0 line only for sandy soil, thus proving a significant difference between disturbance in soil at low DTW and in soil at DTW>1. However, the prediction intervals still predict that it is possible to have a negative effect size. The average effect size for silty soil was even negative (–0.0309) but also in this case there was no statistical significance. QE was 84.05, QM was 5.06 resulting in an overall large I^2 of 84.56% (Fig. 3A). Model AIC was 54.9870 vs an AIC_0 of 58.9870.

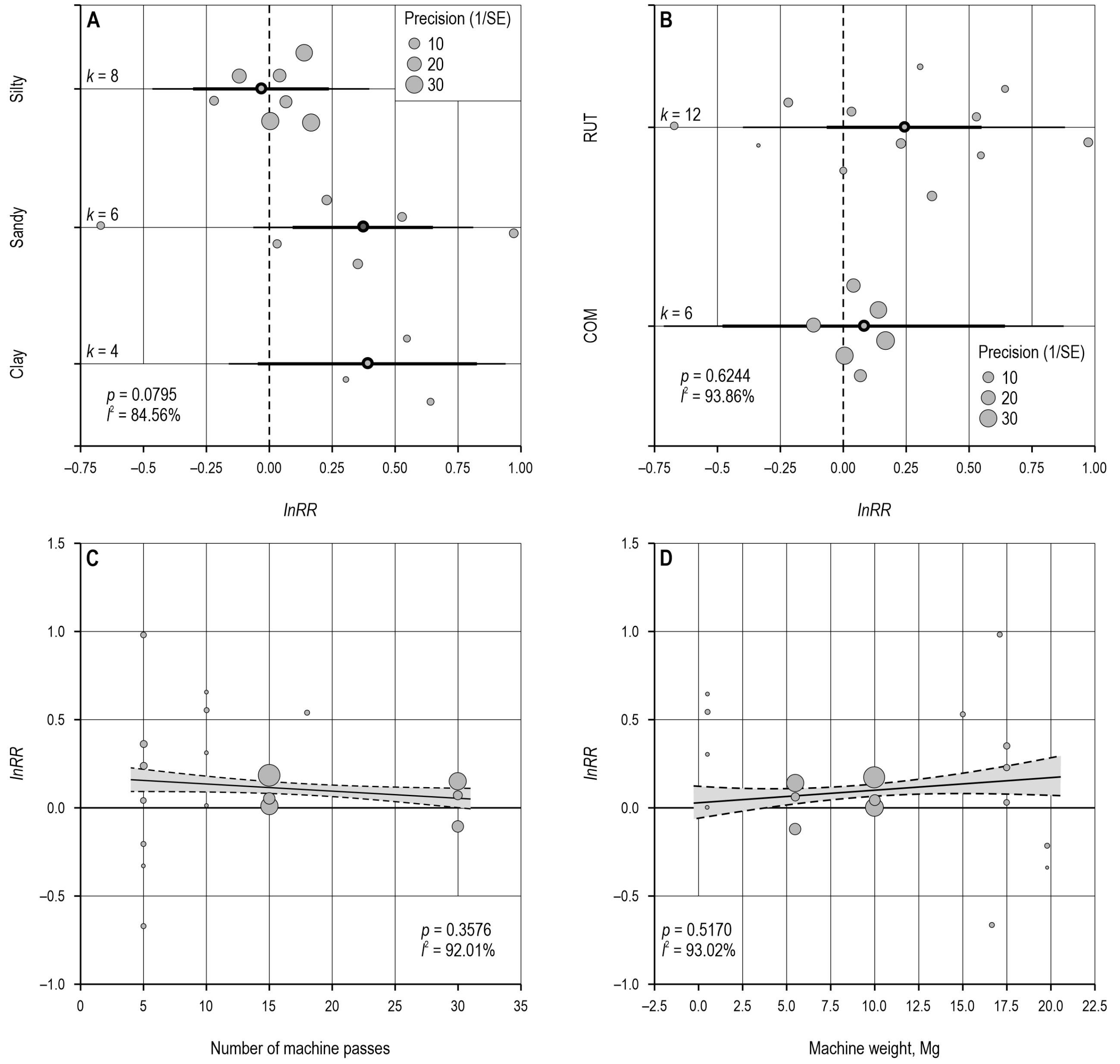

Fig. 3 Orchard plots of *lnRR* of studies assessing effects of DTW index and soil type – (A) as well as DTW index and investigated parameter (COM – compaction and RUT – rutting) – (B), with effect sizes (black dots), 95% confidence intervals (thick lines) and prediction intervals according to heterogeneity (thin lines) estimated using multivariate meta-analysis. *k* denotes the number of effect sizes per estimate. Bubble plots of *lnRR* of studies assessing effects of DTW index and number of machine passages – (C) as well as DTW index and machine weight – (D)

The kind of investigated parameter (compaction vs rutting) did not reveal a significant influence on the effect size. The average effect size was 0.0832 for soil compaction and 0.2433 for rutting depth, but with confidence intervals and prediction intervals overlapping with the 0 line. QE was 92.16, QM was 0.2397 resulting in an overall large I^2 of 93.86% (Fig. 3B). Model AIC was 56.3941 in comparison to an AIC_0 of 58.3941.

The analysis concerning the effects of the number of machine passages revealed no effect of the moderator. Large heterogeneity also characterised this analysis, with QE of 98.74, QM of 0.8465 and overall I^2 of 92.01% (Fig. 3C). Model AIC was 63.5059 in comparison to an AIC_0 of 91.5059. The same applies to the weight of the machine which established the various skid trails/strip roads in the investigated trials. No trend of effect size variation with increasing or decreasing machine weight could be detected. QE resulted equal to 100.01, QM was 0.4198 resulting in an overall I_2 equal to 93.02% (Fig. 4D). Model AIC was 58.3150 in comparison to an AIC_0 of 60.3150.

3.2 Funnel Plot Analysis and Detection of Possible Outliers

Funnel plot analysis revealed a very high heterogeneity in the effect size, with studies at lower standard error and higher standard error, which are located practically at the same distance from the expected effect size. Funnel plot analysis was helpful to individuate two possible outliers (dots located outside the funnel shape), both originating from the study by Ågren et al. (2015). In particular one positive and one negative outlier were individuated (Fig. 4).

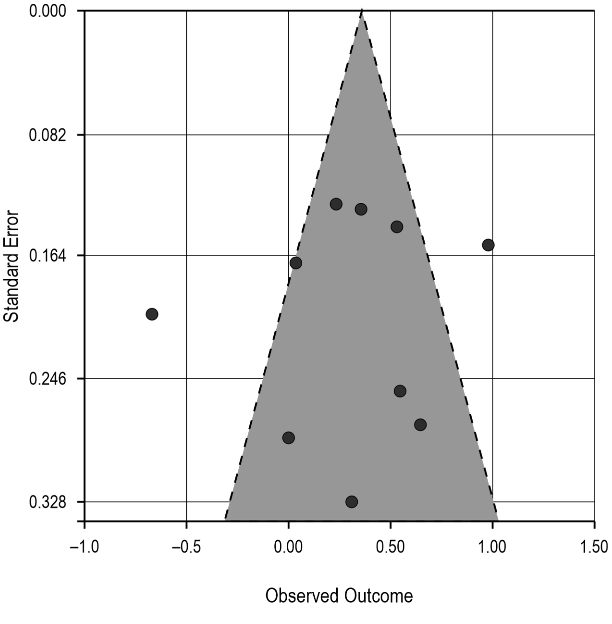

Fig. 4 Funnel plots showing the relationship between effect size (*x*-axis) and standard error of the studies (*y*-axis). Studies falling outside the shape of the funnel can be considered theoretical outliers

3.3 Sensitivity Analysis

Repeating the analysis with the subset excluding the two theoretical outliers did not affect the obtained results. The model without considering the moderators showed no significant effect of the DTW index on soil disturbance, and heterogeneity remained at a very similar level at 92.26% (Fig. 5).

The same results were obtained concerning the sensitivity analysis carried out with the models considering the effect of the various moderators. Significant effect of the DTW index was not confirmed for the reduced subset, and the levels of overall heterogeneity also remained very high after the removal of possible outliers (Fig. 6).

4. Discussion

The results suggest that the research hypothesis stating that machinery-induced soil disturbance is stronger in areas at DTW index≤1 cannot be accepted. Although the average effect sizes were generally positive, thus highlighting an average higher soil disturbance

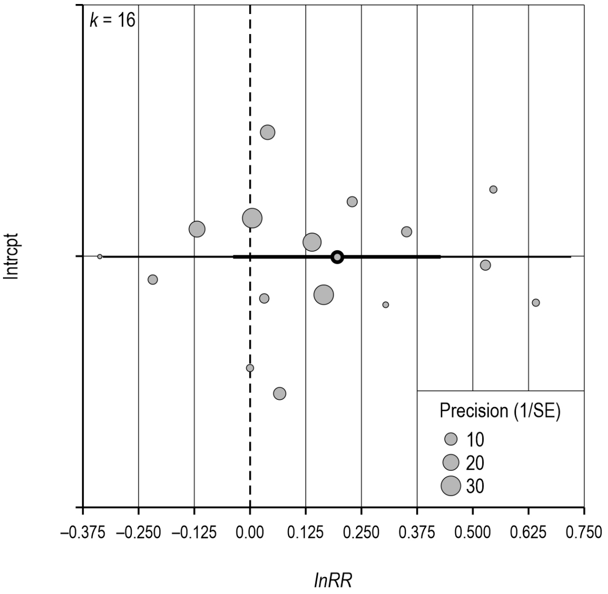

Fig. 5 Orchard plot of *lnRR* of studies assessing effects of DTW index (bubbles) calculated with the dataset obtained after removing two theoretical outliers, with effect sizes (black dots), 95% confidence intervals (thick lines) and prediction intervals according to heterogeneity (thin lines) estimated using multivariate meta-analysis. *k* denotes the number of effect sizes per estimate

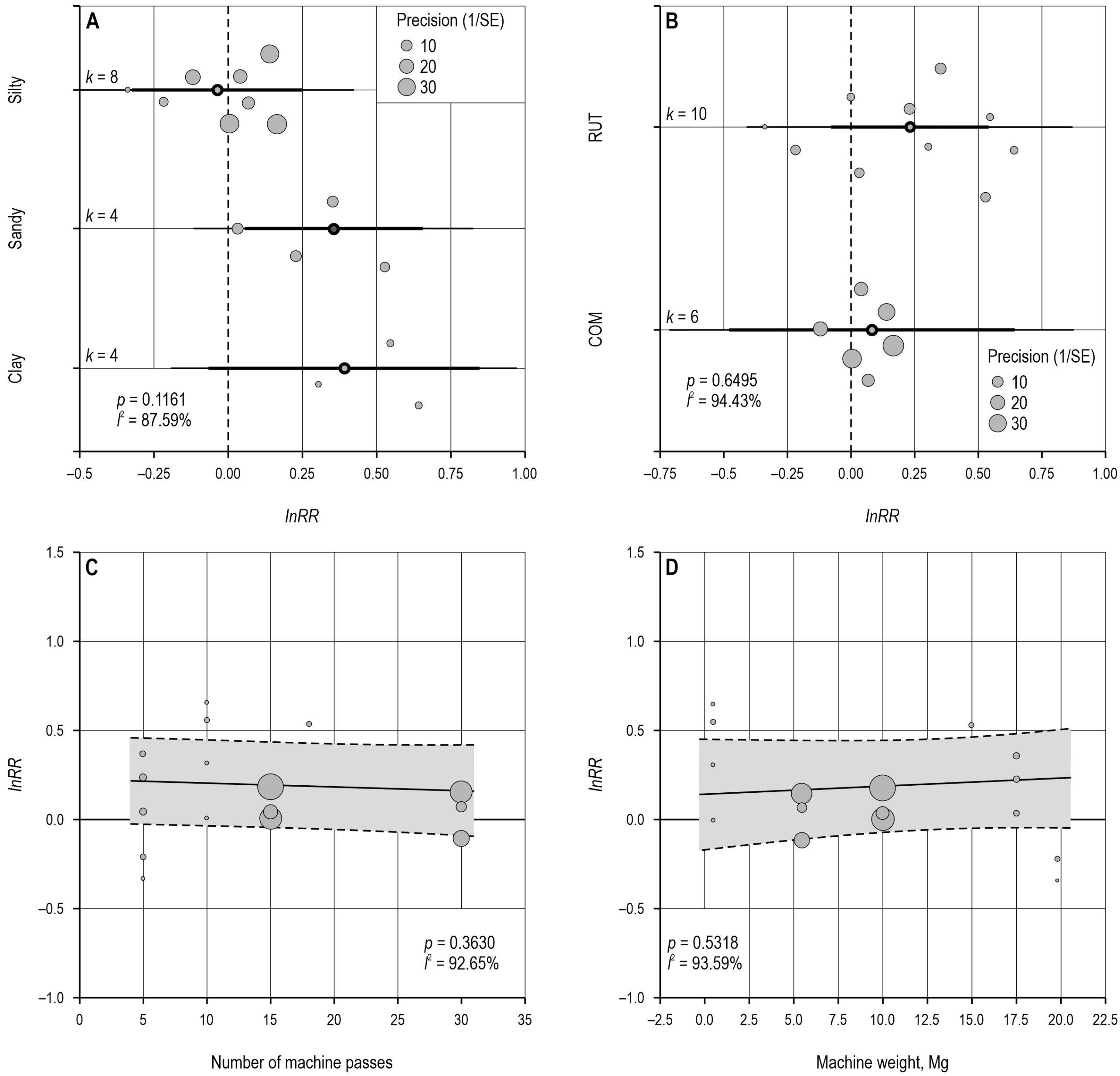

Fig. 6 Results of sensitivity analysis for the models considering various moderators. Orchard plots of *lnRR* of studies assessing effects of DTW index and soil type – (A), as well as DTW index and investigated parameter (COM – compaction and RUT – rutting) – (B), with effect sizes (black dots), 95% confidence intervals (thick lines) and prediction intervals according to heterogeneity (thin lines) estimated using multivariate meta-analysis. *k* denotes the number of effect sizes per estimate. Bubble plots of *lnRR* of studies assessing effects of DTW index and number of machine passages – (C), as well as DTW index and machine weight – (D)

in areas at DTW≤1, practically none of the investigated cases of difference between soil disturbances at low DTW index and high DTW index were statistically significant (Fig. 2).

The same applies to the more complex models (Fig. 3), including moderators influence, considering that the multivariate sub-group analyses and meta-regressions did not reveal any influence on the effect size of parameters such as soil texture, number of passages on the skid trail/strip road and weight of the machinery establishing the skid trail/strip road. Moreover, the effects of DTW index on compaction and rutting did not differ between each other.

By analysing the influence on the effect size of the continuous moderators (number of machine passages and weight of the machine), no trend was established, as shown by the very high p values, but also explicitly shown by the almost null slope of the regression lines and the related distribution of the effect sizes (bubbles in Fig. 3C and 3D). It is worth highlighting that this does not mean that the two moderators do not influence the level of soil compaction or rutting, an aspect which is well known from the literature (Naghdi et al. 2016, Nazari et al. 2021), but that the effect size calculated comparing disturbance in areas at low and high DTW did not change in relation to the number of passages and the weight of the machine. Analysing instead the orchard plots for categorical moderators (Fig. 3A and 3B), it is evident that generally the effect sizes are positive, suggesting that in several cases soil disturbance in areas at DTW index≤1 was actually higher than in areas at higher DTW index. However, there is a very high heterogeneity with the presence of negative effect sizes or effect sizes which are very close to the 0 line (no effect). This suggests that there are different situations in which the DTW index was not a reliable predictor of particularly sensitive soil areas. Merging the results of all the various trials, which is exactly the goal and strength of the meta-analytic approach, generates high heterogeneity with large confidence intervals and even larger prediction intervals, demonstrating that the development of trafficability maps based on the DTW index can lead to some failures.

It is obvious that more studies in the topic are needed. The main limitation of the present meta-analysis is the small dimension of the database, as a consequence of the few studies conducted to quantitatively evaluate the effects of the DTW index on soil disturbance. Having such a limited database could indeed exacerbate the influence of some »negative« trials on the overall effect size by increasing the heterogeneity. However, it is worth highlighting that a strong sensitivity analysis was carried out to check the influence of possible outliers on the final results, and no variation of the model results was detected when applying the subset developed excluding the possible outliers (Fig. 5 and 6). Thus, it can be stated that our findings are reliable and represent the current state of the art of the topic in a clear and quantitative way. Moreover, in the forestry sector, it is not uncommon to have meta-analyses based on a database of similar dimensions (Janiszewska-Latterini and Pizzi 2023, Koricheva and Gurevitch 2014).

It should be pointed out that the output of this review does not imply abandoning the approach of developing trafficability maps based on the DTW index, but that improvement and understanding is needed in this approach and its reliability. It is fundamental to highlight that large-scale trials based on qualitative evaluations confirmed the realibility of DTW maps in predicting severe rutting, but it should also be observed that in these studies there was a considerable amount of variability related to different site conditions (Heppelmann et al. 2022, Mohtashami et al. 2017). In our opinion, the selection of the appropriate flow initiation area threshold is one of the most important aspects to be further investigated. Indeed, if on the one hand the possibility of setting different FIA levels is extremely helpful in modelling different soil moisture scenarios, a wrong selection of the FIA can jeopardise the reliability of the trafficability map in output. In our opinion, the relationship FIA – DTW index should be studied mostly in environments different from the boreal context, where the research on DTW applicability is still at the very beginning. Furthermore, it is important to note that soil disturbance related to ground-based forest operations is much more than the mere compaction and rutting, as it creates several other negative impacts on the forest ecosystem. Modern studies highlighted that the DTW index can also be used to predict zones characterised by higher biodiversity levels (Bartels et al. 2019, Echiverri and Macdonald 2019, Mykrä et al. 2023). Therefore, avoiding these areas while driving the forest machines can be even more important than just avoiding the zones theoretically more sensitive to compaction and rutting.

From the operational point of view, it is recommended to use the DTW maps and to always check them on the field to evaluate their effectiveness. Fortunately, this is the approach of expert forest practitioners who have been using the DTW maps for different years in the context of boreal forestry.

5. Conclusion

To test the hypothesis that soils in areas at DTW index ≤1 are particularly sensitive to soil disturbance, a multivariate meta-analytic synthesis of the studies, conducted to quantitatively assess the reliability of the DTW maps, was developed. Multivariate sub-group analysis and meta-regression were then applied to test the influence on the effect size (disturbance in soil at DTW≤1 – treatment vs disturbance in soil at DTW>1 – control) of soil texture, number of machine passages, and machine weight. No statistically significant difference was detected in any of the performed analyses between the experimental treatment and the control. Furthermore, none of the investigated moderators revealed a significant influence on the effect size, thus leading to the rejection of the research hypothesis. In our opinion, further research efforts are needed to improve the reliability of the trafficability maps based on the DTW index. Therefore, scientific research in the topic should put more effort in increasing the knowledge of the complex relationship between soil texture, soil moisture, machine traffic level, and extraction technique to improve the overall accuracy of the trafficability maps. The application of the DTW index is further recommended for the development of trafficability maps, but always keeping in mind that the output of the algorithms should be verified on the field before starting the harvesting operations.

Acknowledgments

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