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A Meta-analysis of Soil Susceptibility to Machinery-Induced Compaction in Forest Ecosystems Across Global Climatic Zones

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Abstract

Purpose of Review Predicting, preventing, and minimizing machinery-induced soil compaction are of paramount importance in forest ecosystems. Understanding the soil's susceptibility to compaction is crucial in achieving these goals. This meta-analysis assessed the relevance of climatic and soil conditions for the susceptibility of forest soils to wood-harvesting-associated compaction across global climatic zones. We utilized soil bulk density change data (effect sizes; compacted versus uncompacted) from 81 forest sites worldwide, and mapped global patterns of the susceptibility of forest soils to compaction using climate and soil data.

Recent Findings Wood-harvesting operations by harvester-forwarder technologies disturb the soil less as compared to skidders and cable yarders. It has been shown that a high number of vehicle passages (> 20 times) lead to maximum soil damage, although this contradicts the general belief that major soil disturbance occurs within the first few vehicle passages. Despite these important findings, a global compilation of local information on forest soil compaction induced by mechanized wood harvesting is currently lacking. A map that illustrates the global pattern of soil susceptibility to compaction is also required to identify particularly susceptible forest regions.

Summary Forest soils in tropical and temperate zones were most susceptible to compaction (48% and 30% bulk density increase, respectively), while forest soils in arid and cold zones were less susceptible (15% and 18% bulk density increase, respectively). Soils in tropical and temperate forests receive high annual precipitation amounts, are characterized by high soil organic carbon content and low bulk density, and are often wet, resulting in high susceptibility to compaction. Since tropical and temperate forests are biodiversity hotspots, forest managers and policymakers should pay particular attention to mechanized wood-harvesting operations in these zones, as the recovery of compacted forest soils requires decades.

Keywords Bioeconomy · Climate · Forest soils · Logging · Soil compaction · Wood harvesting

Introduction

Forests make up around 30% of the terrestrial area of the Earth. Forest ecosystems are essential for the survival of many organisms and supply numerous important ecosystem services such as food, timber, flood prevention, water and nutrient cycling, and climate regulation [1, 2]. However, human demand for forest products is growing, which can impair the delivery of some of these ecosystem services and cause environmental and societal problems [3, 4].

Timber and wood are the most desired forest products that are exploited for industrial and economic purposes. Quick and efficient forest management and wood harvesting, on a large scale, require the use of forestry vehicles such as skidders and forwarders. Wood-harvesting-associated

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vehicle traffic affects 10–70% of the harvested area, showing its enormous risk to damage the forest soil and ecosystem [5, 6]. The efficiency and capacity of wood-harvesting equipment have grown in recent years due to an increase in power and performance, but the machinery's increasing weights (up to 45 Mg) have elevated the risk of soil compaction [7–9]. Soil compaction occurs when mechanical stresses from machinery exceed soil strength and result in soil structural degradation, which is one of the most striking unintended consequences of mechanized wood harvesting [10]. Soil compaction leads to the creation of ruts and to mixing of upper soil layers, both having negative effects on soil physical, chemical, and biological functions, consequently disharmonizing the forest ecosystem [10–13]. Such machinery-induced disturbances to soil and forest health can persist for decades [14]. Thus, alleviating the impact of soil compaction induced by mechanized wood harvesting is necessary for sustainable forest management [15••].

Soil compaction is an increase in soil bulk density [16, 17]. Soils with low bulk densities are more susceptible to compaction [18]. Forest soils have low bulk density due to high organic matter contents, particularly in upper soil layers [19]. An increase in soil bulk density by wood-harvesting vehicles has remarkable negative consequences for the soil and forest ecosystem functioning. For instance, machinery-induced increases in bulk density and associated decreases in soil total porosity can lead to dramatic reductions in gas and water transport in forest soils [5, 6, 20–22]. Such impairments of gas and water exchange between atmosphere and soil can restrict the availability of oxygen and water to tree roots and soil micro-organisms, damaging forest productivity and the delivery of ecosystem services [12, 23, 24]. Decreased soil porosity due to wood harvesting can reduce soil hydraulic conductivity and water infiltration and enhance the risk of surface runoff and erosion [25–28].

In a recent meta-analysis with 67 published articles, the influence of mechanized wood harvesting on soil microbial biomass carbon, bulk density, total porosity, and saturated hydraulic conductivity affected by such factors as soil texture and depth, vehicle weight, vehicle passage number, and the time since the compaction event was evaluated [29•]. Fine-textured (clayey) forest soils were more susceptible to compaction than coarse-textured (sandy) soils, mainly because of their higher water-holding capacity that decreases frictional forces between soil particles [10, 29, 30]. Forest upper soil layers were more susceptible to compaction, due to considerable amounts of organic matter, lower bulk density, and higher mechanical stresses from vehicles than deeper soil layers [19, 29]. Furthermore, the stresses propagate vertically and decrease with soil depth. Hence, upper layers susceptibility to compaction for forest soils is a suitable indicator for the potential of forest soil compaction. Despite these important findings that assist forest managers and policymakers in reducing the detrimental impacts of soil compaction, a global compilation of local information on forest soil compaction induced by mechanized wood harvesting is currently lacking. There is a knowledge gap of how climate affects the susceptibility of soils to compaction across global forest zones through altering the initial soil conditions. More importantly, we require a global map that illustrates the susceptibility of forest soils to compaction.

Here, using an updated article set of [29•] and new climatic and soil data, we provide a global picture of soil susceptibility to compaction in forest ecosystems across climatic zones and highlight the controlling climatic and soil factors. The meta-analysis aimed (i) to investigate the influence of climatic and soil conditions on the susceptibility of soils to wood-harvesting-associated compaction, and (ii) to identify global patterns of compaction susceptibility and the most susceptible regions in forest ecosystems worldwide. A map that shows the global pattern of soil susceptibility to compaction can help to find particularly susceptible forest regions.

Methods

Publication Search and Selection Criteria

Peer-reviewed studies published between 1983 and 2022 were identified through the online search engines Web of Science and Google Scholar. Keywords used for the search were composite terms: "forest," "soil," "compaction," "harvest," "logging," "skid trail," and "bulk density." Three major criteria were considered to select the studies: (1) Compaction was imposed on soils using wood-harvesting vehicles (i.e., we did not consider animal logging and cable yarders) in forest ecosystems (i.e., we did not consider laboratory studies); (2) Bulk density was reported in uncompacted (control) and compacted (treatment) forest soils; (3) Bulk density was measured in the upper mineral soil layers (< 30 cm depth). Certain studies provided measurements of bulk density for both the soil unaffected by vehicle passage in the harvested area and the soil in a nearby unharvested stand. In such instances, we regarded the soil unaffected by vehicle passage in the harvested area as the uncompacted control.

Data Collection

We reviewed more than 500 articles and detected that only 70 of them met the three selection criteria [5, 12, 21, 24, 26, 30–94]. In total, 162 bulk density observations of 81 forest sites (Fig. 1), related to both uncompacted and compacted treatments ($81 \times 2 = 162$), were extracted from the

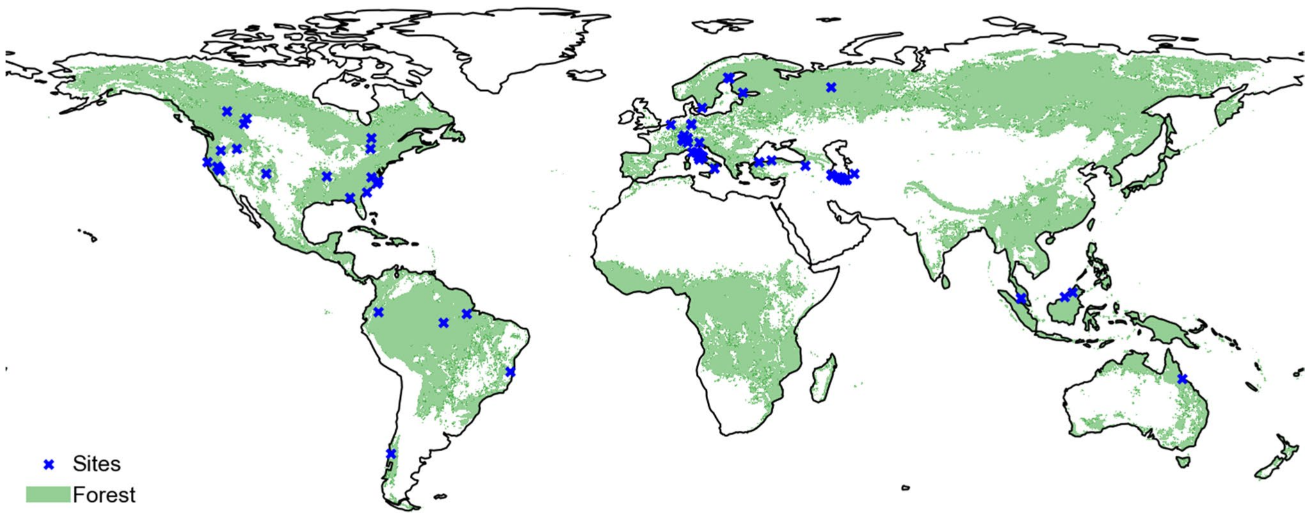

Fig. 1 Global forest coverage. Sampling sites are indicated by blue crosses. Note that not all forest areas are shown at the current resolution

articles to calculate the effect size (*k*; BD increase in compacted versus uncompacted soils) for groups of climatic and soil conditions. We only considered one data pair per site to avoid repeated measurements and the dependence of the effect sizes. When a study presented multiple data pairs with the same control, involving different soil depths, vehicle types, or slopes, we selected only one depth, one vehicle type, and one slope for the analysis. In such cases, we selected the uppermost measured depth representing the upper mineral soil layers (< 30 cm depth), chose the vehicle similar to the ones from most of the studies (e.g., forwarder), and selected the lowest slope. Note that a few of the selected studies investigated more than one forest site, resulting in the total number of 81 forest sites. Data presented in graphs were digitized using WebPlotDigitizer 4.4 (https://automeris.io/WebPlotDigitizer). The data on climatic zone and annual precipitation amount were recorded wherever available. Also, soil organic carbon content, volumetric water content, and initial (i.e., before vehicle traffic) bulk density data were collected wherever available.

The grouping of the climatic and soil conditions was performed according to the corresponding data of the 70 selected articles. Climatic zones were classified as tropical, arid, temperate, and cold according to the updated Köppen-Geiger climate classification system [95]. Annual precipitation amounts were grouped as low (< 500 mm), moderate (500–1500 mm), and high (> 1500 mm). Soil organic carbon contents were grouped as low (< 1%), moderate (1–5%), and high (> 5%). Soil volumetric water contents were categorized as low (< 20%), moderate (20–30%), and high (> 30%). Soil bulk densities before compaction were classified as low (< 1.0 g cm^{-3}), moderate (1.0–1.3 g cm^{-3}), and high (> 1.3 g cm^{-3}).

Statistical Analyses

A random-effects model was used in this meta-analysis, assuming that the observed treatment effect could vary across the studies due to different treatments as well as sampling variability. This meta-analysis is concerned with the magnitude of change (the effect size) of bulk density and the significance of this change in response to a treatment. The natural logarithm of the response ratio (RR) was used to calculate the effect size of bulk density due to wood-harvesting-associated soil compaction [96]:

$$\ln(\mathrm{RR}) = \ln\left(\frac{\mathrm{BD_C}}{\mathrm{BD_U}}\right)$$

where $\mathrm{BD_U}$ and $\mathrm{BD_C}$ are the means of bulk density in the uncompacted and compacted soils, respectively. The RR can be converted to a percentage change by back-transformation as $(e^{\ln(\mathrm{RR})} - 1) \times 100$ [97]. For the effect size, lower and upper limits of the confidence intervals (CIs) were estimated using bias-corrected bootstrapping with 5000 iterations [2, 98]. The statistical significance of the effect size was tested using the 95% CIs. If the 95% CIs did not overlap the zero line, the effect size was considered statistically significant at $\alpha = 0.05$. The group means were considered significantly different from each other if their 95% CIs did not overlap.

Meta-regression analyses were implemented to identify overall effects and effect sizes of the climatic and soil moderators (at $\alpha = 0.05$). Linear mixed effects model was applied to detect relations between bulk density change and climatic and soil conditions, using study area as a random effect to account for spatial variability (at $\alpha = 0.05$). The presence of publication bias was assessed by Spearman's rank correlation test (at $\alpha = 0.05$) and Kendall's Tau rank correlation test (at $\alpha = 0.05$) correlating the replicate number of each study and the effect size [2, 99]. No publication bias was diagnosed across the studies based on Spearman's rank (p-value = 0.273, $r = -0.123$, $n = 81$) and Kendall's Tau rank correlation test (p-value = 0.258, $r = -0.089$, $n = 81$). The lack of publication bias means that the studies published both significant and non-significant results. IBM SPSS Statistics for Windows, version 28 (IBM Corp., Armonk, NY, USA) was used to perform all analyses and to generate bias-corrected CIs for the effect sizes of the forest plots.

Spatial Mapping of Forest Soil Compaction Potential

A Gaussian process regression model was used to map the spatial distribution of forest area that is susceptible to compaction based on expected changes in bulk density after traffic. Where available, local information from the 81 sample locations (Fig. 1) was used, and the missing observation values were imputed from global raster data. Additionally, covariates were added based on the latitude and longitude pairs. The covariates included environmental variables: mean annual precipitation [100], climatic water content [101, 102]; elevation, mean annual temperature and radiation [103], bulk density, soil organic carbon content, cation exchange capacity, and soil pH [104]; and net primary productivity [105]. Also, we included clay content and the dominant clay minerals kaolinite and smectite [106] due to their importance for soil hydro-mechanical properties [107]. We also used soil depth as a covariate to model forest soil compaction risk at the specific soil depth of 15 cm. All covariate layers were at 0.1° resolution for model fitting and spatial prediction. The model was trained on all data points using scikit-learn 1.2.1 [108]. We used an inhomogeneous quadratic kernel to specify the covariance. The model simultaneously estimates the mean and standard deviation of the target variable (bulk density change after traffic). To mask forest area, we used the Copernicus Global Land Service land cover of 2019 [109].

Results

Impact of Climatic Conditions on the Susceptibility of Forest Soils to Compaction

Wood-harvesting operations significantly compacted forest soils across climatic zones (Fig. 2). Forest soils in tropical and temperate zones were more susceptible to compaction (48% and 30% increase in bulk density, respectively) compared with forest soils in arid and cold zones (15% and 18% increase in bulk density, respectively) (Fig. 2). Annual precipitation had a significant effect on the susceptibility of forest soils to compaction (overall effect size = 28%; Fig. 3a). Climatic zones with high (> 1500 mm) and moderate (500–1500 mm) annual precipitation amounts had the most susceptible soil conditions to compaction (36% and 26% increase in bulk density, respectively), whereas soils of climatic zones with low (< 500 mm) annual precipitation amounts were less susceptible (11% increase in bulk density) (Fig. 2).

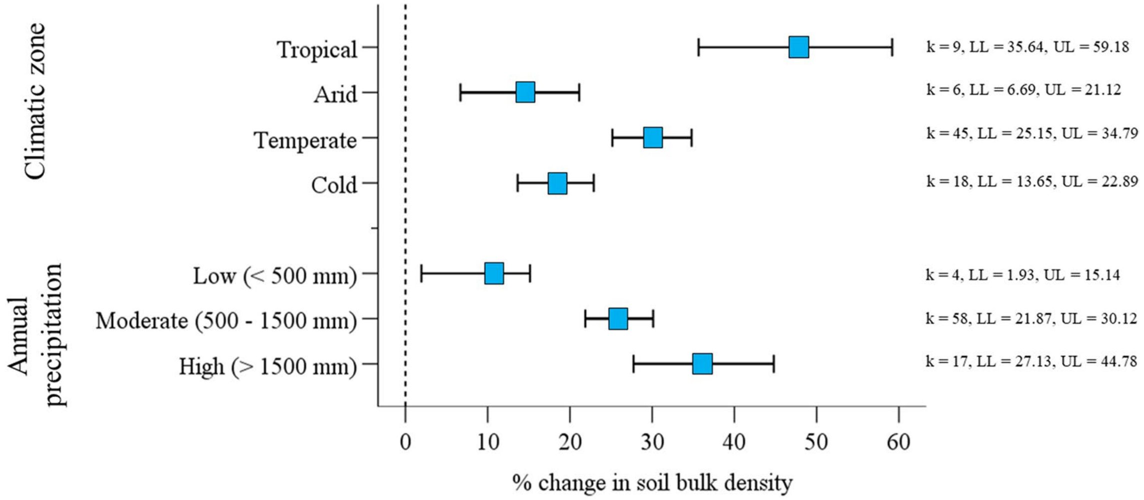

Fig. 2 Changes of soil bulk density (compaction) due to wood-harvesting operations by heavy machinery in forests, affected by climatic zone and annual precipitation amount. Results are presented as mean effect sizes ± 95% confidence intervals. Groups with confidence intervals not overlapping the dashed reference line indicate a statistically significant change in soil bulk density due to compaction at $\alpha = 0.05$. Groups with confidence intervals overlapping each other are not significantly different at $\alpha = 0.05$. k, number of effect sizes or forest sites; LL, lower limit confidence interval; UL, upper limit confidence interval

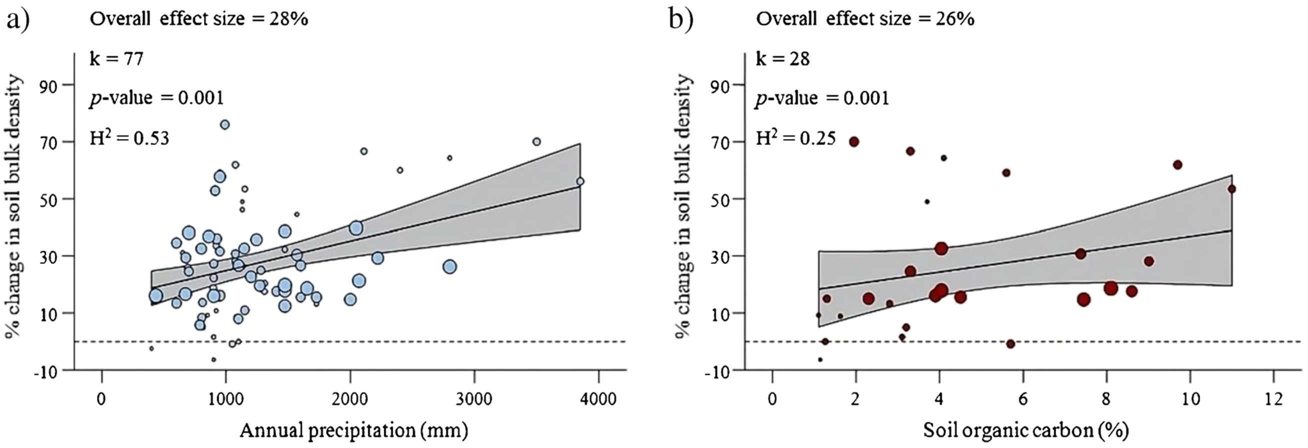

Fig. 3 Meta-regression bubble plots of changes of soil bulk density (compaction) due to wood-harvesting operations by heavy machinery in forests, affected by annual precipitation amount (**a**) and soil organic carbon (**b**). The bubble size represents the weight of each study, which is inversely proportional to the variance of the estimated treatment effect. Bubbles overlapping with the dashed zero line demonstrate non-significant effects. A p-value smaller than 0.05 indicates an overall significant effect. Grey areas around the meta-regression prediction line are 95% confidence intervals. $H^2 = 1$ indicates perfect homogeneity. k, number of effect sizes or forest sites. Among the various studies analyzed, graphic (**a**) shows an average low heterogeneity, while graphic (**b**) shows an average high heterogeneity

Impact of Soil Conditions on the Susceptibility of Forest Soils to Compaction

Soil organic carbon significantly affected the susceptibility of forest soils to compaction (overall effect size = 26%; Fig. 3b). Wood-harvesting operations increased the bulk density of soils with high (> 5%) and moderate (1–5%) organic carbon contents by 30% and 21%, whereas soils with low (< 1%) organic carbon contents were not significantly affected (Fig. 4). Soil water content significantly impacted on the susceptibility of forest soils compaction (overall effect size = 35%; Fig. 5a). Increases in the bulk density of soils with high (> 30%), moderate (20–30%), and low (< 20%) water contents were 44%, 39%, and 17%, respectively (Fig. 4). Soil initial bulk density also had a significant influence on the susceptibility of soils to compaction (Fig. 5b). Soils with low (< 1 g cm^{-3}) initial bulk density (i.e., before vehicle traffic) were most susceptible to compaction (32%

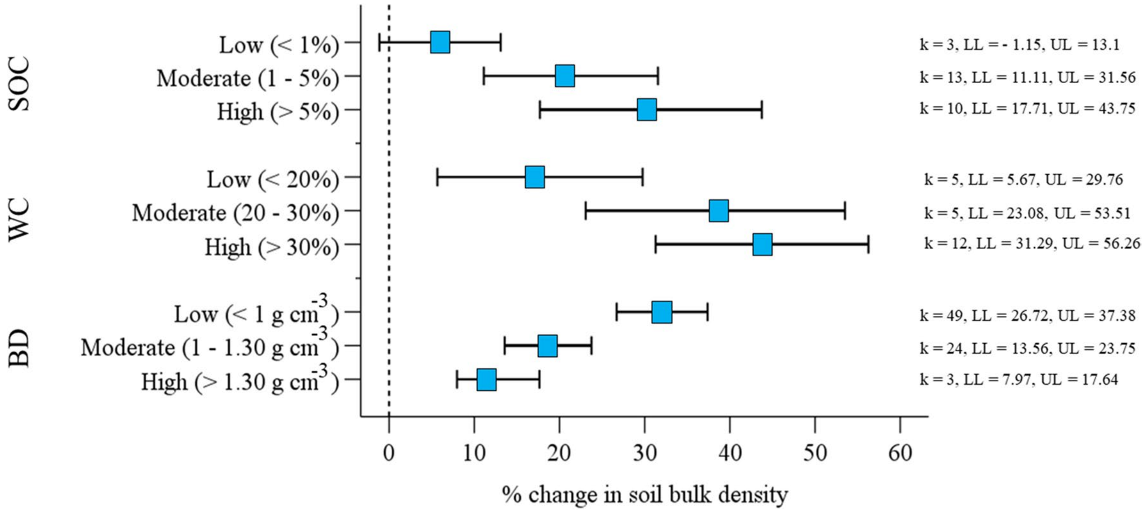

Fig. 4 Changes of soil bulk density (compaction) due to wood-harvesting operations by heavy machinery in forests, affected by soil organic carbon (SOC), volumetric water content (WC), and initial (i.e., before vehicle traffic) bulk density (BD). Results are presented as mean effect sizes ± 95% confidence intervals. Groups with confidence intervals not overlapping the dashed reference line indicate a statistically significant change in soil bulk density due to compaction at $\alpha = 0.05$. Groups with confidence intervals overlapping each other are not significantly different at $\alpha = 0.05$. k, number of effect sizes or forest sites; LL, lower limit confidence interval; UL, upper limit confidence interval

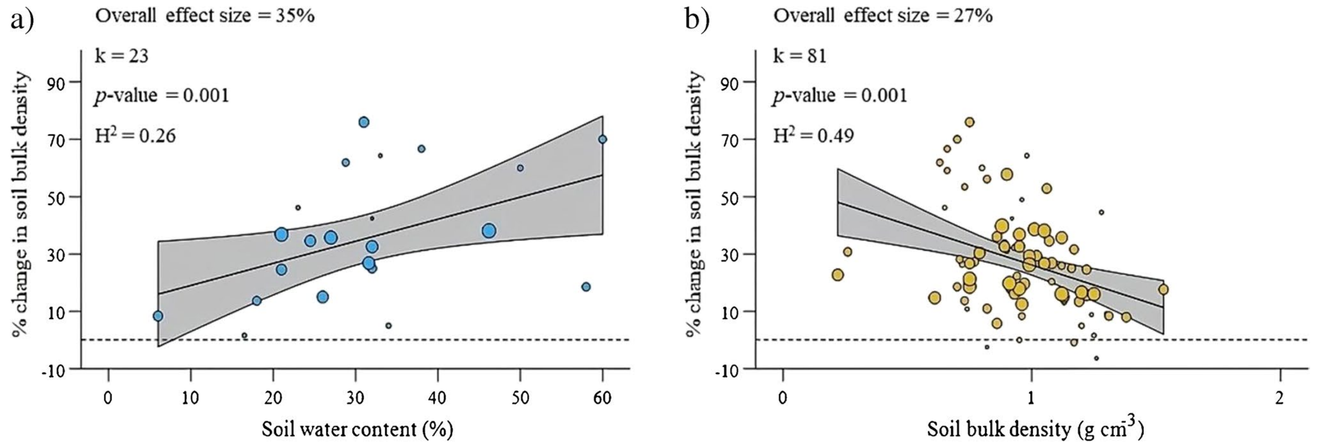

Fig. 5 Meta-regression bubble plots of changes of soil bulk density (compaction) due to wood-harvesting operations by heavy machinery in forests, affected by soil volumetric water content (**a**) and soil initial (i.e., before vehicle traffic) bulk density (**b**). The bubble size represents the weight of each study, which is inversely proportional to the variance of the estimated treatment effect. Bubbles overlapping with the dashed zero line demonstrate non-significant effects. A *p*-value smaller than 0.05 indicates an overall significant effect. Grey areas around the meta-regression prediction line are 95% confidence intervals. H^2 = 1 indicates perfect homogeneity. k: number of effect sizes or forest sites. Among the various studies analyzed, graphic (**a**) shows an average high heterogeneity, while graphic (**b**) shows an average low heterogeneity

increase in bulk density), while soils with high (> 1.3 g cm^{-3}) and moderate (1–1.3 g cm^{-3}) initial bulk density were less susceptible (11% and 19% increase in bulk density, respectively) (Fig. 4).

Relation Between Climatic and Soil Conditions

There was a significant positive linear relation between soil organic carbon content and annual precipitation amount (Fig. 6a) and a significant negative linear relation between initial bulk density (i.e., before vehicle traffic) and soil organic carbon content (Fig. 6b). Soil water content had a significant positive linear relation with soil organic carbon content and annual precipitation (Fig. 7a, b).

Global Pattern of Forest Soil Susceptibility to Compaction

The predicted mean of the bulk density changes after wood-harvesting operations by heavy machinery is high in tropical regions of Africa, India, South America, and Southeast Asia (Fig. 8a). The estimates have high uncertainty in northern

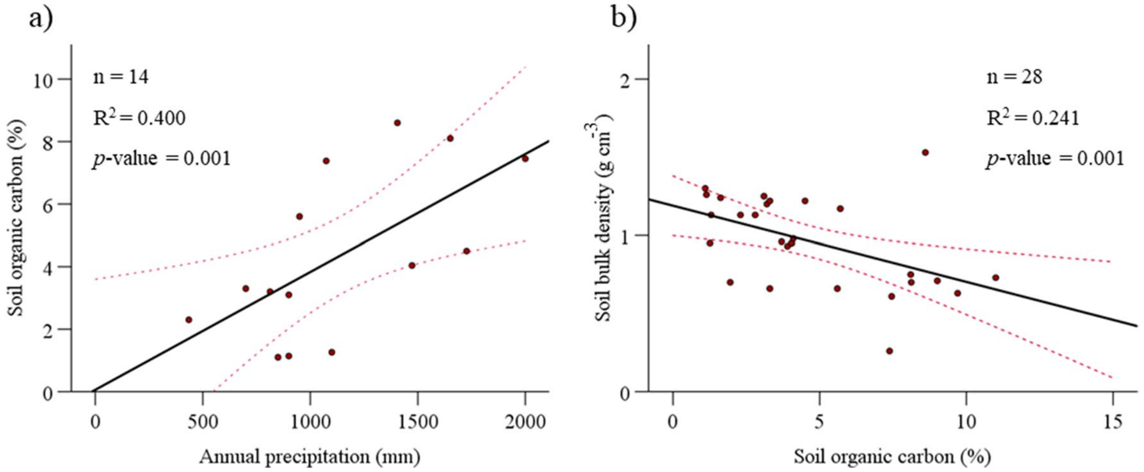

Fig. 6 Linear relation between soil organic carbon content and annual precipitation amount (**a**) and between initial (i.e., before vehicle traffic) soil bulk density and soil organic carbon content (**b**), tested by linear mixed effects model using study area as a random effect (at α = 0.05). *p*-values smaller than 0.05 indicate a significant relation. Red dashed lines show 95% confidence intervals. R^2, coefficient of determination; n, number of data points

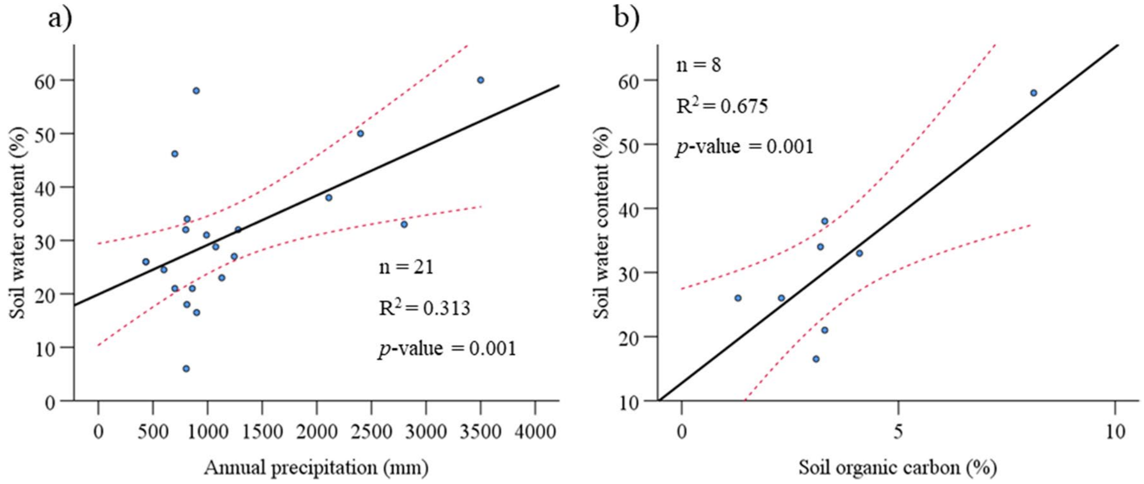

Fig. 7 Linear relation between soil volumetric water content and annual precipitation amount (**a**) and between soil volumetric water content and soil organic carbon content (**b**), tested by linear mixed effects model using study area as a random effect (at $\alpha = 0.05$). *p*-values smaller than 0.05 indicate a significant relation. Red dashed lines show 95% confidence intervals. R^2, coefficient of determination; n, number of data points

latitudes, the Andes, and Indonesia (Fig. 8b). Globally, most tropical forests soils are susceptible to compaction while a broader response distribution is observed for cold and temperate forests (Fig. 8c). The multivariate Gaussian process regression model was in good agreement with observations resulting in R^2 values of 0.69 and root mean squared error of 10% (Fig. 8d).

Discussion

There are several interconnected mechanisms through which climate affects soil conditions and the soil susceptibility to external disturbances. Here, the focus is on discussing the alteration of soil organic carbon and water contents by climate, and how this may influence the soil susceptibility to wood-harvesting-associated compaction.

Our analyses reveal that climatic zones with high annual precipitation amounts (i.e., tropical and temperate) have higher soil organic carbon input compared to climatic zones with low annual precipitation amounts (e.g., arid and cold). This is likely because of a greater net primary biomass production, higher plant inputs to soils, more dissolved organic matter input from aboveground, and enhanced mineral-associated organic matter formation [110–113]. Moreover, soils of high-precipitation climatic zones are more likely to be saturated for a relatively long time which creates anoxic conditions and restricts soil organic matter mineralization, leading to net soil organic carbon accumulation particularly in colder regions [114]. In the investigated forest sites of this meta-analysis, soil organic carbon content linearly increased with increasing annual precipitation amount (Fig. 6a). Higher soil organic carbon content was associated with lower bulk density (Fig. 6b) through enhanced aggregation and lower soil particle density resulting in a more porous soil structure which makes the soil more susceptible to compaction (Fig. 3b and Fig. 4b). The present meta-analysis suggests that high soil organic carbon content is an important factor for the high susceptibility of forest soils to compaction in high-precipitation tropical and temperate zones. Thus, forest managers should carefully assess the impact of heavy machinery for wood harvesting on soils with high organic matter content.

Higher annual precipitation amounts and high soil organic carbon contents lead to high soil water contents (Fig. 7a, b) in forests of tropical and temperate zones, and our analyses show that forest soils with high water contents were more susceptible to compaction (Fig. 4 and Fig. 5a). At higher water contents, soil cohesion is reduced, which decreases soil strength and increases soil susceptibility to compaction [29, 30]. Thus, wetter soils of tropical and temperate forests are more susceptible to compaction than the soils of arid and cold forests. Our findings highlight the importance of cautiously selecting the best time windows for mechanized wood-harvesting operations based on low soil water content and high bearing capacity to resist mechanical stresses from forestry vehicles.

In the light of a changing climate towards warmer and wetter winter and spring with higher precipitation in Northern, Eastern, and Central Europe, Northern America, and China [115, 116], the time windows with dry and frozen soil to prevent soil compaction are expected to become fewer and shorter. This may have drastic consequences for the forest management in the near future because the logging periods

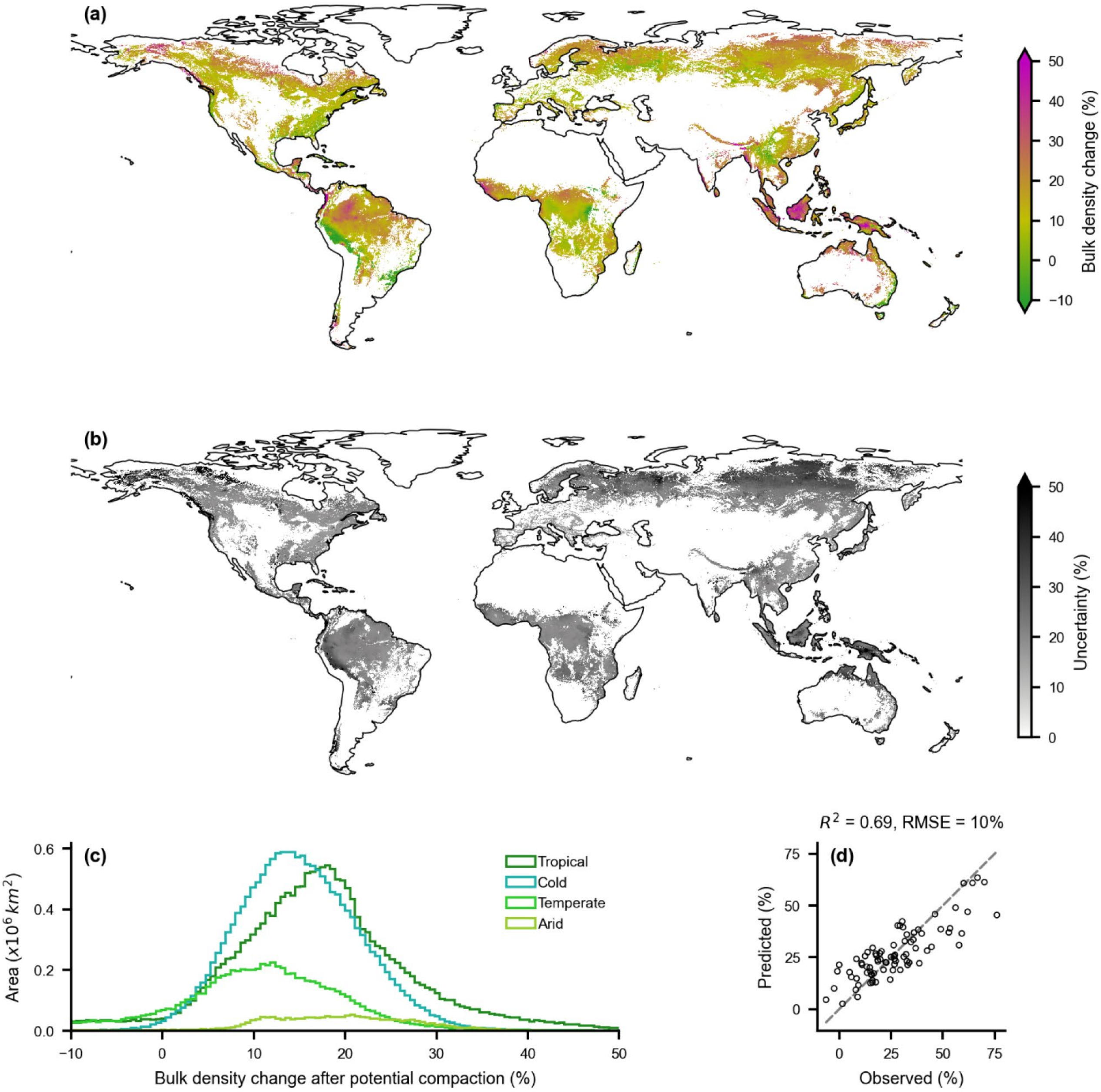

Fig. 8 Modelled soil compaction at 15 cm depth due to traffic by forestry vehicles. **a** Global map of forest soil bulk density change. **b** Uncertainty (standard deviation) of the estimates. **c** Affected area for each climate type. **d** Performance of the Gaussian process regression model

of least susceptibility (dry soil) could become periods of highest susceptibility (wet soil). A temporal shift from spring and winter logging to performing logging operations during summer and autumn, when soils are generally drier and less susceptible to compaction, will have to be balanced by heavier loads. However, the timing requires careful planning as the water content of timber is higher in summer, amounting to heavier loads and undesirable properties of the wood.

The modelled bulk density changes fitted well with the observed changes (Fig. 8d), indicating the efficiency of the Gaussian process regression model in producing global spatial maps. The model provides a conservative estimate of potential bulk density change after compaction. We recommend the use of the non-parametric model to map soil compaction susceptibility and the estimated uncertainty also for agricultural and grassland ecosystems in future studies. The model results show that tropical forests are particularly susceptible to compaction (Fig. 8a), in line with the results of the present meta-analysis (Fig. 2). This is partly because of high annual precipitation amounts, high soil organic carbon contents, and low initial bulk density of soils in these zones, which fits well with the existing global maps of precipitation, soil organic carbon, and soil bulk density. In particular, clay soils are most susceptible to compaction [10, 29] and soil clay content and clay mineral type [107] could also influence the global soil susceptibility pattern. The overlap of high precipitation amounts and high soil clay contents in tropical and temperate forests can lead to very high soil water contents and unfavorable hydro-mechanical soil properties that exacerbate the soil compaction problem in forests of these climate zones.

Tropical and temperate forests are hotspots of soil faunal and plant diversity [117]. Our study shows that the soils of these ecosystems have enhanced levels of susceptibility to compaction. We urgently recommend that mechanized wood-harvesting operations are performed with maximum care to minimize soil compaction and its long-lasting impairment of soil functions. While this recommendation applies to all forests, we find a particular need to protect the sensitive ecosystems of tropical and temperate forests that are highly susceptible to compaction.

Conclusions

In this meta-analysis, we investigated how climatic conditions and soil properties affect the forest soil susceptibility to wood-harvesting-associated compaction across global forest ecosystems. Wood-harvesting operations resulted in significant soil compaction in all climatic zones. Tropical and temperate forests were most susceptible to compaction, due to their high soil organic carbon contents, low bulk densities, and high soil water contents at the time of vehicle traffic, which are related to considerable amounts of annual precipitation in these zones. Mechanized wood-harvesting operations should be avoided during wet soil conditions and only be done during periods when soils are dry enough, so that mechanical stresses from forestry vehicles do not exceed soil bearing capacity. Overall, our results emphasize the key role of climate in shaping soil conditions and controlling susceptibility to compaction. Forest managers and policymakers should pay special attention to the timing of mechanized wood-harvesting operations in cold regions that may undergo changes in seasonal patterns, and to conserving the soils of tropical and temperate forests that are hotspots of biodiversity.

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Compliance with Ethical Standards

Conflict of Interest Meisam Nazari, Emmanuel Arthur, Mathieu Lamandé, Thomas Keller, Nataliya Bilyera, and Samuel Bickel declare that they have no conflict of interest.

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

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- • Of importance
- •• Of major importance

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15.•• Picchio R, Mederski PS, Tavankar F. How and how much, do harvesting activities affect forest soil, regeneration and stands? Curr For Rep. 2020;6:115–28. **The article comprehensively investigated how and how much mechanized wood-harvesting operations affect forest ecosystem functions (e.g., soil functions), and the contribution of good practices to the mitigation of the negative environmental impacts of mechanized harvesting operations. One of the key conclusions of this study was that forest operations by harvester-forwarder technologies damaged the soil on a smaller scale than forest operations by skidders and cable yarders. Moreover, the lack of post-harvesting control on soil disturbance and its recovery was highlighted.**

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