BIOSCIENCE JOURNAL

A META-ANALYSIS OF PHYSICOCHEMICAL CHANGES IN THE RHIZOSPHERE AND BULK SOIL UNDER WOODLANDS

Ana Paula Hummes[1], Jaqueline Huzar Novakowiski[2], Ivan Ricardo Carvalho[3], Edson Campanhola Bortoluzzi[4]

[1] USDA-ARS, National Laboratory for Agriculture and the Environment, Ames, Iowa, United States.
[2] Agricultural Microbiology Laboratory, Universidade de Passo Fundo, Passo Fundo, Rio Grande do Sul, Brazil.
[3] Agroscience Department, Universidade Regional do Noroeste do Estado do Rio Grande do Sul, Ijuí, Rio Grande do Sul, Brazil.
[4] Land Use and Natural Resources Laboratory, Universidade de Passo Fundo, Passo Fundo, Rio Grande do Sul, Brazil.

Corresponding author:
Ivan Ricardo Carvalho
carvalho.irc@gmail.com

How to cite: HUMMES, A.P., et al. A meta-analysis of physicochemical changes in the rhizosphere and bulk soil under woodlands. *Bioscience Journal*. 2024, **40**, e40005. https://doi.org/10.14393/BJ-v40n0a2024-63637

Abstract

Monoculture for timber production has been replacing natural environments as the demand for renewable energy sources increases. The lack of nutrient compensation may increase the risk of soil depletion, thus changing soil properties. To summarize the impact of forestry activities in edaphic environments, we present a meta-analysis on the rhizosphere effects of coniferous and broadleaved trees established as monoculture and natural regeneration on soil physicochemical properties. Records of soil attributes published in peer-reviewed journals from eight countries were collected. Clay content changed only in monoculture sites, decreasing 55.51% in the rhizosphere, while silt and sand presented significant variations in both monoculture and naturally regenerated areas. Conifers affected the soil more than broadleaved trees, evidenced by higher pH reduction (-2.96% vs. -1.98%) and higher increase of Al^{3+} (197.43% vs. 50.68%), K^+ (80.40% vs. 69.90%), CEC (24.61% vs. 17.35%), and total organic carbon (82.21% vs. 69.89%). Also, the rhizosphere affected regeneration soils more than monoculture, indicated by higher Al^{3+} (50.68% vs. *ns*) and available P (32.31% vs. *ns*), K^+ (203.44% vs. *ns*), CEC (34.90% vs. 20.93), and total organic carbon (91.55% vs. 63.23%). These results indicate higher nutrient availability in naturally regenerated than monoculture sites, as higher species diversity and better plant litter quality are expected. This meta-analysis shows that coniferous and naturally regenerated trees had a higher influence on the rhizosphere and soil properties than broadleaved and monocultures. Management practices must be revisited to ensure the long-term sustainability of forestry activity, and studies in tropical zones must be intensified.

Keywords: Broadleaf. Coniferous. Monoculture. Regeneration. Rhizosphere.

1. Introduction

Sustainable forest policies require increased renewable energy production, implying more intensive land use worldwide (Lauri et al. 2014) and raising the risk of depleting the soil base cations that support forest growth (Akselsson et al. 2019; Rosenstock et al. 2019). Thus, the demand for planted forest expansion is evident, highlighting the need to assess the impacts on soil quality (Doran and Parkin 1994; Islam and Weil 2000; Usharani et al. 2019).

Soil characteristics may vary due to plant species, establishment forms, and management (Malysz and Overbeck 2018), even in species grown in equivalent locations and conditions (Wang et al. 2001). Temporal and spatial scales are relevant for soil processes, and studies on tree rhizospheres are promising to predict the long-term nutrient supply for sustainable forest growth, considering that forestry activity requires longer timescales. The number of studies on the rhizosphere's physical, chemical, and biological properties is appreciable. At the same time, these properties significantly differ from those of the surrounding bulk soil (Hinsinger 1998; Calvaruso et al. 2011; Collignon et al. 2011; Bortoluzzi et al. 2019; Hummes et al. 2019; Liu et al. 2019). Although the rhizosphere usually occupies between 1% and 5% of the soil, changes occur up to twice as fast as in the bulk portion (Kuzyakov and Blagodatskaya 2015).

Coniferous and broadleaved trees modify the soil differently, comparing mixed forests to monoculture stands, and these changes are evident in the rhizosphere compared to bulk soil (Calvaruso et al. 2011; Guan et al. 2016; Bu et al. 2020). Peng et al. (2020) found higher forest floor carbon stock in coniferous than in broadleaved forests, but Hou et al. (2020) verified a higher soil organic carbon rate in broadleaved than in coniferous trees. The nutrient availability in the rhizosphere and bulk soil of mixed coniferous (*Cunninghamia lanceolata*) and broadleaved (*Michelia macclurei* or *Schima superba*) species is higher than in pure coniferous trees (Bu et al. 2020). Malysz and Overbeck (2018) found differences in soil conditions caused by monocultures and regenerated tree patterns. However, a systematic review has never synthesized the potential of trees from the two high plant botanical groups and their establishment forms to influence physicochemical properties in the rhizosphere.

A meta-analysis is an efficient statistical approach for conducting systematic literature reviews. It combines results from two or more individual quantitative studies (Koutsos et al. 2019), estimates treatment effects more precisely, adjusting for experimental homogeneity (Lovatto et al. 2007), and provides objective, transparent, and replicable summaries of topics addressed in scientific research (Del Re 2015). General rhizosphere reviews have been recently published (Dotaniya and Meena 2014; Sokolova 2015; Dessaux et al. 2016; Broeckling et al. 2018), as well as systematic reviews considering carbon dynamics in forests (Hou et al. 2020; Peng et al. 2020). However, the literature lacks syntheses of individual studies across various conditions and sites statistically testing the rhizosphere effect from tree botanical groups and stand establishment forms on soil physicochemical properties.

This meta-analysis examined soil attributes under different tree botanical groups and establishment forms reported in published peer-reviewed studies over the last 20 years to address the rhizosphere effect of trees. Two research questions have guided the present study: (*i*) Do different botanical groups (coniferous and broadleaved trees) tend to influence the rhizosphere effect? (*ii*) Do rhizosphere effects change due to stand establishment forms (monoculture and regeneration sites)?

2. Material and Methods

Literature review

Published peer-reviewed journals were searched from July 11 to 12, 2020, in the *Web of Science Core Collection*. We considered soil attributes of the rhizosphere and bulk soil of trees grown in field conditions reported in studies published after 2000. The keywords were "rhizosphere AND bulk AND forest." The selection criteria were (*i*) rhizosphere *vs*. bulk soil, (*ii*) botanical group (coniferous and broadleaved), (*iii*) studies in field conditions, (*iv*) trees grown spontaneously from self-seedling (regeneration) or planted seedlings raised in forest nurseries (monoculture), (*v*) soils without chemical contamination and that did not receive chemical fertilizers, and (*vi*) observations that presented dispersion measures or, if absent, imputable to Furukawa et al. (2006).

Our search retrieved 240 publications, of which 90 were downloaded for detailed examination, and only 32 fulfilled all established criteria (Table 1). A total of 170 studies from eight countries were considered, including 66 on coniferous trees, 104 on broadleaved species, 95 on planted trees (monoculture), and 75 on naturally regenerated species (regeneration) (Table 2). We gathered sample size, mean, and standard deviation/standard error from ten soil attributes for the control (bulk soil) and the treatment (rhizosphere): (*i*) pH, (*ii*) available phosphorus (P_{av}), (*iii*) potassium (K^+), (*iv*) calcium (Ca^{2+}), (*v*) aluminum (Al^{3+}), (*vi*) total organic carbon (TOC), (*vii*) effective cation exchange capacity (*e*CEC), and particle-size distribution – (*viii*) sand, (*ix*) silt, and (*x*) clay. These data were extracted from tables or digitized from figures using Web Plot Digitizer software (Rohatgi 2019). When dispersion measures were not reported, as in Calvaruso et al. (2011) for pH and *e*CEC and Cloutier-Hurteau et al. (2010) for Al^{3+}, the standard deviation (SD) was imputed to Furukawa et al. (2006). If the dataset presented dispersion measures equal to zero, we changed them to 0.0001 to prevent statistical errors. The units were standardized before the statistical analysis. Furthermore, we considered two moderator variables: (*i*) botanical group – coniferous or broadleaved trees, and (*ii*) establishment form – monoculture or regeneration sites.

Table 1. Original publications used in the meta-analysis.

Reference	Journal	Number of studies
(Agnelli et al. 2016)	*Plant and Soil*. 2016, 400, 297–314	7
(Álvarez et al. 2010)	*Journal of Soils and Sediments*. 2010, 10, 1236–1245	1
(Álvarez et al. 2011)	*Journal of Soils and Sediments*. 2011, 11, 221–230	1
(Angst et al. 2016)	*Geoderma*. 2016, 264, 179–187	1
(Bu et al. 2020)	*Forests*. 2020, 11, 461-477	4
(Calvaruso et al. 2011)	*Plant and Soil*. 2011, 342, 469–480	9
(Chen 2003)	*Forest Ecology and Management*. 2003, 178, 301–310	1
(Chen et al. 2016)	*J. Plant Nutr. Soil Sci*. 2016, 179, 67–77	4
(Chen et al. 2018)	*Soil Biology and Biochemistry*. 2018, 126, 237–246	12
(Chiellini et al. 2019)	*Applied Soil Ecology*. 2019, 138, 69–79	8
(Cloutier-Hurteau et al. 2007)	*Environ. Sci. Technol*. 2007, 41, 8104–8110	6
(Cloutier-Hurteau et al. 2010)	*J. Environ. Monit*. 2010, 12, 1274–1286	2
(Collignon et al. 2012)	*Plant and Soil*. 2012, 357, 259–274	12
(Collignon et al. 2011)	*Plant and Soil.* 2011, 349, 355–366	24
(Courchesne et al. 2006)	*Environmental Toxicology and Chemistry*. 2006, 25, 635–642	9
(Dai et al. 2018)	*Canadian Journal of Forest Research.* 2018, 48, 1398–1405	3
(De Feudis et al. 2017)	*Geoderma.* 2017, 302, 6–13	2
(Fang et al. 2017)	*PLoS ONE.* 2017, 12, e0186905	4
(Guan et al. 2016)	*Journal of Tropical Forest Science*. 2016, 28, 159–166	3
(He et al. 2020)	*Geoderma*. 2020, 374, 114424	20
(Hu et al. 2019)	*Environ Monit Assess*. 2019, 191, 99-114	1
(Korchagin et al. 2019)	*Catena*. 2019, 175, 132–143	1
(Liu et al. 2018)	*Applied Soil Ecology*. 2018, 132, 91–98	2
(Liu et al. 2019)	*Plant and Soil*. 2019, 436, 365–380	2
(Phillips and Yanai 2004)	*Water, Air, & Soil Pollution*. 2004, 159, 339–356	2
(Séguin et al. 2004)	*Plant and Soil.* 2004, 260, 1–17	9
(Turpault et al. 2007)	*Geoderma*. 2007, 137, 490–496	6
(Wang et al. 2016)	*Journal of Soils and Sediments*. 2016, 16, 1858–1870	2
(Yin et al. 2014)	*Soil Biology & Biochemistry.* 2014, 78, 213-221	4
(Zhang et al. 2019)	*Journal of Soils and Sediments*. 2019, 19, 2913–2926	4
(Zhao et al. 2015)	*J Arid Land*. 2015, 7, 475–480	2
(Zheng et al. 2016)	*Biogeochemistry*. 2016, 131, 65–76	2

Statistical analysis

A random-effects model provided the effect size, the outcome measure for meta-analyses. This model assumes that sets of studies are not identical in their methods and characteristics, potentially introducing heterogeneity/variability among the actual effects. An option to model heterogeneity is considering it completely random (Viechtbauer 2010).

The effect size is a quantitative index that reflects the magnitude of association among variables of interest in each study (Konstantopoulos 2006). To estimate the rhizosphere effect on soil properties, the *metafor* package (Viechtbauer 2010) in R software (R Core Team 2019) calculated the effect size for each data point as the natural log of the response ratio (*ln RR*): $ln(R| \quad |R) = ln(X_t/X_c)$; where X_t is the rhizosphere mean (treatment), and X_c is the bulk soil mean (control). Log transformation balanced positive and negative effects and maintained symmetry in the analysis, especially when the data showed discrepancies. The variance (v) of RR associated with each effect size was calculated by the equation: v $\frac{SD_t^2}{n_t X_t^2} + \frac{SD_C^2}{n_C X_C^2}$; where SD_t and SD_c are the standard deviations for treatment and the control, respectively, and n_t and n_c are the sample sizes for treatment and the control, respectively. ln (RR) = 0 indicates no rhizosphere effect, ln (RR) > 0 represents a positive rhizosphere effect, and ln (RR) < 0 characterizes a negative rhizosphere effect.

The estimates for each soil attribute, represented by effect sizes, were transformed into percentages for better understanding. Negative rates indicated a numerical value decrease in soil attributes from the treatment compared to the control, whereas positive values indicated an increase. When a 95% confidence interval did not overlap with zero, a significant rhizosphere effect was considered.

A correlation analysis measured the correlation strength between the two crucial climatic factors that affect soil processes – mean annual precipitation (MAP) and mean annual temperature (MAT) - and pH, TOC, and *e*CEC in the rhizosphere and bulk soil. MAP was divided into three categories: low (<900 mm), moderate (900-1,500 mm), and high (> 1,500 mm). The same occurred for MAT: low (< 5°C), moderate (5-20°C), and high (>20°C). The three soil attributes were selected due to substantial records in the included manuscripts (116 for pH, 93 for TOC, and 41 for *e*CEC), relatively well distributed among the studies.

Table 2. The number of studies by country, botanical group, and establishment form.

Country		Number of studies			
		Botanical group		Establishment form	
		Coniferous	Broadleaved	Monoculture	Regeneration
Brazil	1	-	1	1	-
Canada	26	4	22	3	23
China/Tibet	66	35	31	32	34
France	51	27	24	48	3
Germany	1	-	1	1	-
Italy	17	-	17	10	7
Spain	2	-	2	-	2
USA	6	-	6	-	6
TOTAL	170	66	104	95	75

Heterogeneity and moderator variables

In an overall random effect size meta-analysis, the effect size means of all studies are estimated to verify potential homogeneity. Heterogeneity was quantified with I^2, an index that describes the percentage of total variability over studies and compares meta-analyses of various study types and sizes with different outcome data and effect measures (Higgins et al. 2003). Approximate 25, 50, and 75% values indicate low, moderate, and high heterogeneity, respectively (Higgins et al. 2003). Significant I^2 values required a sensitivity analysis.

The meta-analysis considered study-level variables, or moderators, promoting a mixed-effects model that may account for at least part of heterogeneity in the actual effects (Viechtbauer 2010). Moderator variables of interest were the tree botanical group (coniferous and broadleaved trees) and stand establishment forms (monoculture and natural regeneration sites). However, conclusions were drawn from the subgroups with only one study to prevent misleading statements.

Publication bias and sensitivity analysis

A potential publication bias was assessed statistically with the *funnel* function in the *metafor* package and graphically represented with funnel plots of effect sizes vs. their standard errors) to verify whether the literature review was subject to a publication bias, in which significant treatment differences are more likely to be published than non-significant ones. Without a publication bias, studies with high precision are assumed to be plotted near the average, and those with low precision to be spread evenly on both sides, creating a funnel-shaped distribution. Deviation from this shape may indicate a publication bias. The trim and fill analysis was also performed to estimate the number of potentially missing articles from the meta-analysis from suppressing the most extreme studies on one side of the funnel plot. This analysis demonstrates how the overall summary effect size would shift when removing an apparent bias.

Sensitivity was analyzed by assessing the variance and contribution of each study for the overall summary effect size. Studies with high variance and low contribution compared to others in the dataset were removed one at a time, and the meta-analysis was performed again. That shows the extent of changes in heterogeneity and summary effect size without the removed study.

All statistical analyses were conducted in R software (R Core Team 2019), and *SigmaPlot* Version 13.0 (Systat Software Inc., San Jose, CA) created the forest plots.

3. Results

pH and total organic carbon

The rhizosphere pH decreased by 1.98% relative to bulk soil (Figure 1a). The pH studies (n=116) presented high heterogeneity (I^2=99.93%; 95% CI: 99.91 to 99.96%; df=115; $p \leq 0.01$), which could not be explained by botanical group and establishment form moderators because I^2 remained higher than 97%. However, when comparing the rhizosphere with bulk pH within groups, the pH of conifers decreased more (2.96%) than broadleaved trees (1.98%), and the pH reduction in monoculture and regeneration rhizosphere was the same (1.98%). Considering the numerous records on this soil attribute, accounting for the overall effect size, each contribution is well distributed across the dataset.

Total organic carbon (TOC) was the second feature most recorded in our literature review (n=96). After examining the overall meta-analysis for sensitivity, studies by Dai et al. (2018) were removed from the TOC dataset due to their high variability and low contribution to the overall summary effect size (< 0.0005%). TOC significantly increased in the rhizosphere by an average of 75.07% (n=93) compared to bulk soil (Figure 1b). The contribution of each study to the overall effect size was not computed because of the uniform distribution across the dataset.

The botanical group effect analysis showed that TOC increased 82.21% in the coniferous rhizosphere compared to bulk soil, which is higher than in the broadleaved rhizosphere (69.89%) compared to the respective bulk soil. Furthermore, the rhizosphere effect on regeneration sites was higher (91.55%) than on monocultures (63.23%). Heterogeneity across studies was high and statistically significant for TOC (I^2=98.19%), and the moderator variables could not explain it because I^2 remained high, i.e., the risk ratio estimate across studies was inconsistent.

Publication bias occurred for pH and TOC (Supplemental Material, Figure 4a-b), and the trim and fill analysis did not suggest plotting extra studies to balance the meta-analysis.

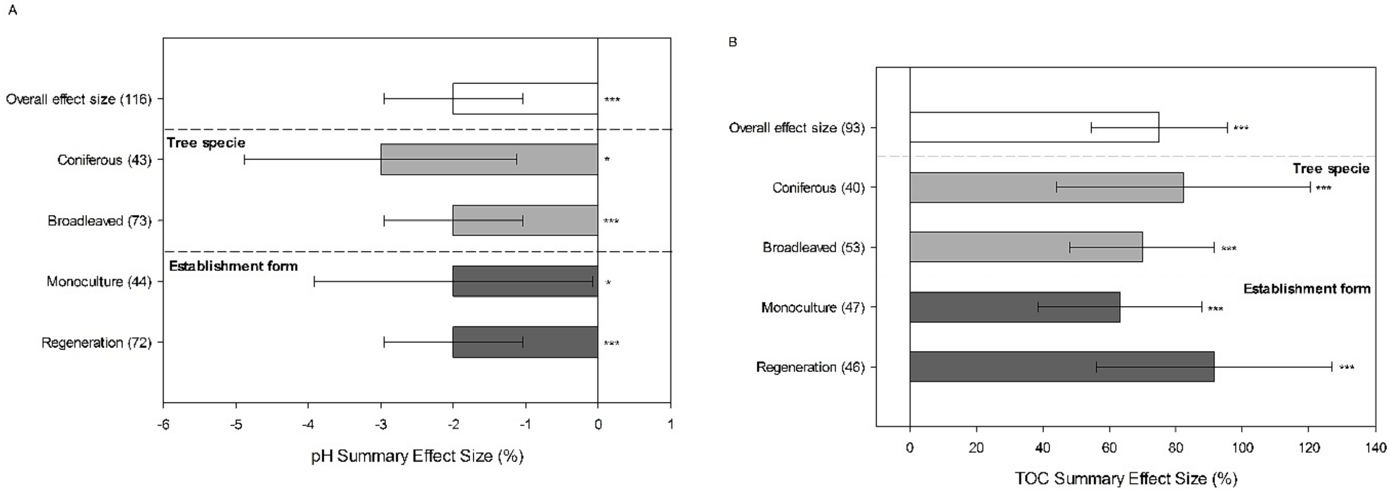

Figure 1. A - Rhizosphere summary effect size on pH and B - total organic carbon (TOC). Bars represent the response ratio (%) ± 95% confidence interval. The numbers in parentheses indicate the number of studies (*n*). Significance occurred at * $p\leq 0.1$; ** $p\leq 0.05$; *** $p\leq 0.01$; *ns:* not significant.

Particle size distribution and Al^{3+}

Sand and silt did not show a rhizosphere overall effect size, while clay was 55.51% lower in the rhizosphere than in bulk soil (Figure 2a). Clay decreased more in monocultures than in regeneration areas, and clay response to the botanical group could not be evaluated due to missing studies on coniferous trees.

The overall meta-analysis showed inconsistencies in risk ratio estimates among the studies for all particle sizes (I^2=*98*.95% for sand, 99.71% for silt, and 99.76% for clay). The establishment form moderator could not explain these high heterogeneities, whereas the I^2 index remained elevated (>98%) and highly significant ($p \leq 0.01$).

The contribution of studies to the summary effect size was assessed. Three out of 19 articles explained the 62.98% effect size for sand, and four of 19 studies accounted for 86.44% of the summary effect size on silt. However, four of 19 articles justified a 54.06% effect size for clay. The few studies explaining most of the effect size justify their high heterogeneity.

Twenty-two studies were considered for Al^{3+}, but the sensitivity analysis eliminated one (Álvarez et al. 2010). In the overall meta-analysis (*n*=21), Al^{3+} increased by 68.20% in the rhizosphere compared to bulk soil (Figure 2b), and Al^{3+} was 197.43% higher in the coniferous rhizosphere than in the coniferous bulk soil. As for broadleaved trees, Al^{3+} was 50.68% higher in the rhizosphere. Considering there were only two studies on monocultures, any conclusion about the effect of establishment forms could lead to error. The high heterogeneity of the overall meta-analysis (I^2=99.74%; 95% CI: 99.48 to 99.87%; *df*=20; $p \leq 0.01$) did not change when considering moderator variables. That means heterogeneity caused the most variability among studies, and moderators could not fully explain it. Five of 22 studies represented 86.30% of the overall summary effect size.

Particle size distribution (sand, silt, and clay) and Al^{3+} presented publication biases because the findings were not evenly distributed on both average sides, and many studies were plotted marginally or outside the funnel shape (Supplemental Material, Figure 5a-d). Regarding meta-analysis balance, the trim and fill method suggested that, for sand, three studies may be added to the left side of the average, adjusting I^2 to 99.03% and the effect size to -7.54% (Supplemental Material, Figure 5a), and five studies to the right side of the average for Al^{3+}, adjusting I^2 to 99.82% and the effect size to 98.40% (Supplemental Material, Figure 5d).

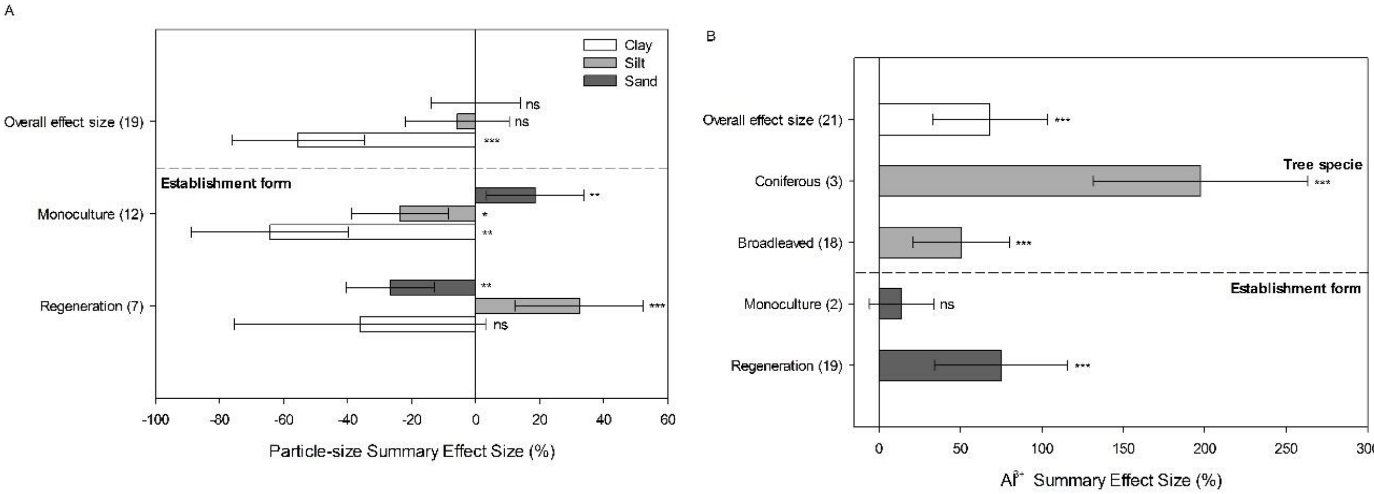

Figure 2. A - Rhizosphere summary effect size of particle size distribution and B - Al^{3+}. Bars represent the response ratio (%) ± 95% confidence interval. The numbers in parentheses indicate the number of studies (*n*). Significance occurred at * *p*≤ 0.1; ** *p*≤ 0.05; *** *p*≤ 0.01; *ns*: not significant.

Available P, K^+, Ca^{2+}, and effective CEC

The concentration of available phosphorus (P_{av}) was higher in the rhizosphere than in the bulk soil (18.53%, *n*=32) (Figure 3a). However, this rhizosphere effect was significant only for naturally regenerated stands, increasing by 32.31% compared to the bulk soil.

Potassium (K^+) showed a positive rhizosphere effect, with a 69.89% increase (*n*=18) relative to bulk soil (Figure 3b). The increase in the coniferous rhizosphere was higher (80.40%) than the broadleaved trees (69.90%), and the regeneration rhizosphere effect was even higher (203.44%) than monoculture (24.61%), even though the K^+ increase in the monoculture was insignificant.

Calcium (Ca^{2+}) in the rhizosphere did not differ from the bulk soil (Figure 3c). The large confidence interval (-30.23% to 29.69%) indicates high data dispersion, reducing estimate precision. The significant reduction (15.63%) was unreliable for monoculture because only one study recorded it.

Effective cation exchange capacity (*e*CEC) increased by 22.14% (*n*=41) in the rhizosphere compared to the bulk soil (Figure 3d). Coniferous trees had a higher *e*CEC (24.61%) than the respective broadleaved species (17.35%). Despite the few studies (*n*=4), the regeneration rhizosphere presented higher *e*CEC (34.99%) than monoculture (20.93%).

The overall meta-analysis showed high heterogeneity for these four attributes, as demonstrated by the high I^2 (93.54% for P_{av}, 98.92% for K^+, 99.55% for Ca^{2+}, and 85.65% for *e*CEC), suggesting inconsistency across studies. The attempt to explain part of heterogeneity through moderator variables was frustrated. However, the lower heterogeneity for P_{av} and K^+ in regeneration sites was because all or almost all studies were from the same publications and performed in equivalent conditions. Regarding *e*CEC, the heterogeneity of the regeneration subgroup decreased to zero, probably due to the small number of studies (*n*=4). The same occurred in the Ca^{2+} monoculture subgroup (*n*=1).

The publication bias analysis through funnel plot visual interpretation showed that P_{av}, K^+, and Ca^{2+} studies presented publication biases because they were not evenly distributed on both average sides, as more than 40% were plotted marginally or outside the funnel shape (Supplemental Material, Figure 6a-d). Therefore, the trim and fill method suggested adding five studies for Ca^{2+}, three for K^+, and 17 for *e*CEC. The Ca^{2+} studies were plotted on the right side of the average, and K^+ and *e*CEC on the left side. These additional studies adjusted I^2 and reduced the rhizosphere effect size: for Ca^{2+}, I^2=99.57% with a negative effect size of -22.79%; for K^+, I^2=98.86% with a positive effect size of 53.97%; and for *e*CEC, I^2=91.24% with a positive effect size of 9.63%.

The contribution of studies on P_{av} shows that five of 32 investigations represented over 50% of the overall effect size. Three of 18 studies on K^+ explain 77.02% of the overall effect size, four of 17 studies on Ca^{2+} explain 61.82%, and one of 41 studies on *e*CEC justify 76.92%.

Correlation analysis

pH was significantly correlated with MAP for the rhizosphere and bulk soil but not with MAT. However, TOC in the rhizosphere and bulk soil was significantly correlated with MAP and MAT, and *e*CEC did not significantly correlate with either MAP or MAT (Table 3).

Table 3. Pearson's correlation coefficients (*r*) between pH, total organic carbon (TOC), effective cation exchange capacity (*e*CEC), and the climatic factors of mean annual precipitation (MAP) and mean annual temperature (MAT).

			MAP	MAT	*n*
Total	pH	Rhizosphere	-0.47 **	0.02 ns	116
		Bulk soil	-0.36 **	0.02 ns	
	TOC	Rhizosphere	0.62 **	-0.51 **	93
		Bulk soil	0.36 **	-0.38 **	
	*e*CEC	Rhizosphere	-0.23 ns	-0.16 ns	41
		Bulk soil	-0.03 ns	-0.26 ns	

** Significant at $p \leq 0.05$; *ns*: not significant. *n*: the number of studies.

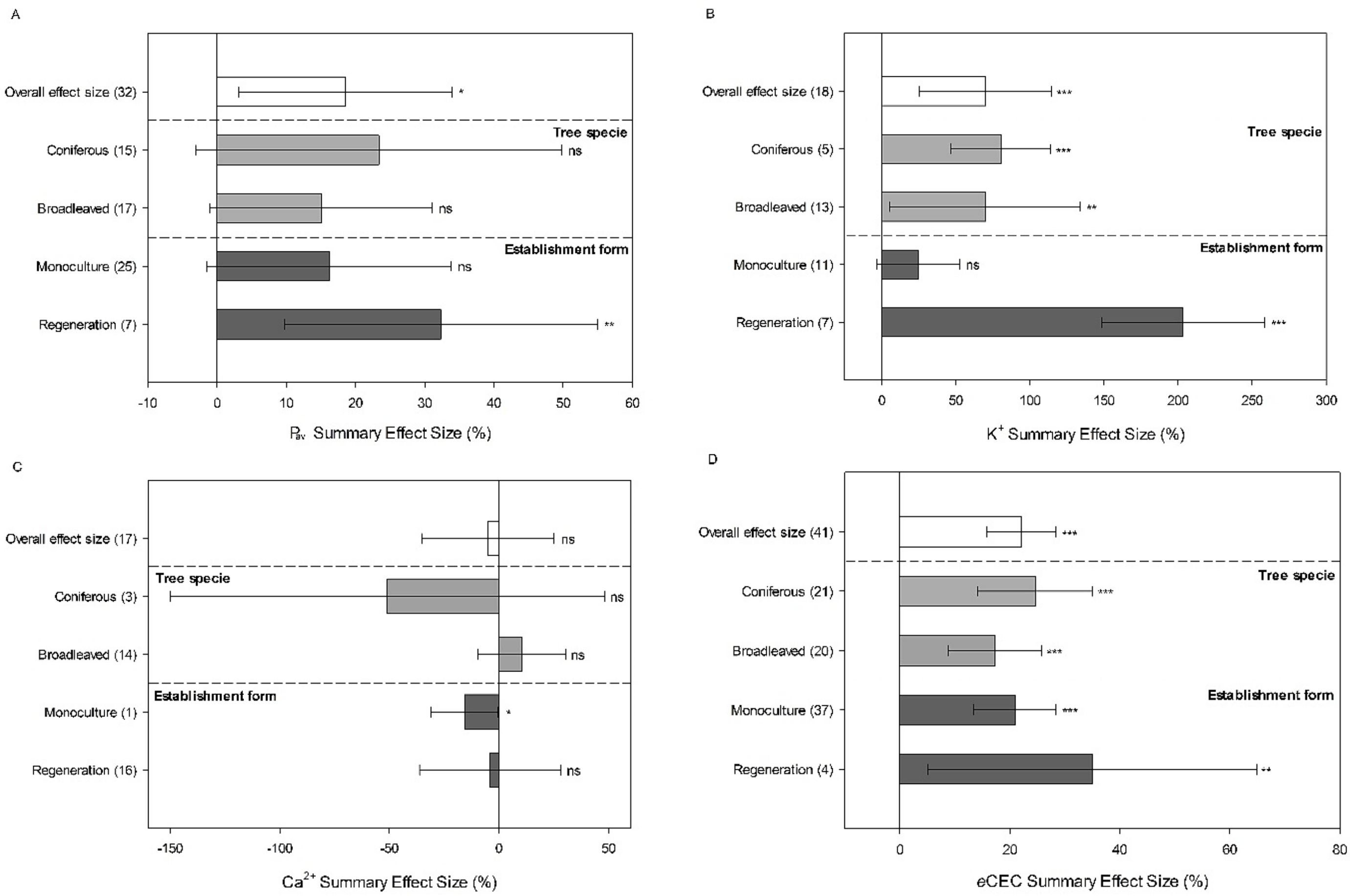

Figure 3. A - Rhizosphere summary effect size on available P (P_{av}), B - exchangeable K (K^+), C - exchangeable Ca^{2+}, and D - effective cation exchange capacity (*e*CEC). Bars represent the response ratio (%) ± 95% confidence interval. The numbers in parentheses indicate the number of studies (*n*). Significance occurred at * $p \leq 0.1$; ** $p \leq 0.05$; *** $p \leq 0.01$; *ns*: not significant.

4. Discussion

The rhizosphere effect of coniferous and broadleaved trees

Coniferous trees caused a higher rhizosphere effect than broadleaved ones. The rhizosphere changes the soil solution composition, and its impact depends on the specific functioning of different plant species, the related microbial community, and soil mineralogy (McGahan et al. 2014; Sokolova et al. 2019). Adjacent soils with the same land-use history under a uniform tree coverage may present diverse soil microbial communities, especially when comparing exotic species to native ones (Kourtev et al. 2002), but also when comparing the rhizosphere of coniferous to broadleaved trees (Sokolova et al. 2019). Regardless of the species, numerous studies have demonstrated that Ca, Mn, K, Fe, Mn, and Al saturations, proton activity, N, C, and BS are usually higher in the rhizosphere than in the bulk soil (Séguin et al. 2004; Turpault et al. 2005; Calvaruso et al. 2011; Collignon et al. 2012).

This meta-analysis showed that the pH of the coniferous rhizosphere decreased more (2.96%) than in the broadleaved rhizosphere (1.98%), and Al^{3+} increased more in coniferous (197.43%) than in the broadleaved (50.68%) rhizospheres. Therefore, the risk of Al toxicity is higher under coniferous than broadleaved species and agrees with the lower pH observed under conifers (Firn et al. 2007; Collignon et al. 2012). In acid soils, the rhizosphere plays an ecological role in Al detoxification by nutrient accumulation and Al complexation with organic compounds (Collignon et al. 2012). Sokolova et al. (2019) found similar changes in soil acidity due to forest species, reporting a lower pH in the rhizosphere and enclosing soil of the Norway spruce conifer (*Picea abies*) than in the Norway maple broadleaved tree (*Acer platanoides*). Also, the clay fraction showed smaller quantities of mica, kaolinite, and illite - more labile minerals associated with higher nutrient availability - under spruce than maple trees. These authors partially attributed the differences to the woody species and associated microbial community and partially to the clay fraction composition.

The higher H^+ activity in coniferous than broadleaved rhizospheres was followed by higher P_{av}, K^+, TOC, and *e*CEC. The increased proton activity (H^+) in the rhizosphere was most attributed to low-molecular-weight organic acids (LMWOAs) released by the microbiota, primarily ectomycorrhizal fungi (Sokolova 2011), as a plant nutrition mechanism through the balance charge (Wang et al. 2001; Churchman and Lowe 2012; Korchagin et al. 2019). Soil acidification affects base cation pools and implicates mineral weathering and forest sustainability (Rosenstock et al. 2019). For instance, the strategy of growing *Ericaceae* in very acid soil is to modify the rhizosphere pH from close to neutral to acid levels in the bulk soil, potentially related to the ability of Ca^{2+} accumulation in the root zone (Álvarez et al. 2011). pH reduction followed by an increase in soluble Al^{3+} and *e*CEC in the rhizosphere indicates the action of dissolution mechanisms (Wang et al. 2001). Also, the higher K^+ in the rhizosphere may be inferred to dissolution mechanisms followed by mineral transformation, with probable K^+ loss from illite interlayers, transforming it into vermiculite (Bortoluzzi et al. 2012).

These results indicate a higher impact on soil from coniferous than broadleaved trees, as mentioned in the literature (Firn et al. 2007; Collignon et al. 2012; Sokolova et al. 2019). However, considering the concentration of studies in temperate zones, the impact of botanical groups and tree species cannot be extrapolated to tropical and subtropical regions.

Changes in the rhizosphere due to establishment forms

The rhizosphere effect on naturally regenerated forest soils where trees grow spontaneously in a mixed-forest stand was higher than on monoculture sites. Despite the lack of pH differences, Al^{3+}, TOC, K^+, available P, and *e*CEC levels were higher in the rhizosphere of regeneration than in monoculture sites. These findings confirm the positive relationship between soil nutrient availability and species diversity. Considering that naturally regenerated woody environments favor the recolonization of species from the native flora, the diversity of organic materials promotes a similar nutrient availability to natural secondary forests and the maintenance of original edaphic conditions (Firn et al. 2007), with higher soil fertility (Malysz and Overbeck 2018). Also, replacing the monoculture with a mixed-specie forest promotes soil nutrient availability (Bu et al. 2020), and higher organic matter and K^+ contents were found in secondary forest soils than in artificial forests under the same geological conditions (Fan et al. 2019).

Organic mineral nutrient turnover is a relevant P source (Clevelário Junior 1996; Chen 2003) and K (Turpault et al. 2008) and the largest source of plant nutrients, especially in forests that have reached their climax (Uhlig and Von Blanckenburg 2019; Uhlig et al. 2020). However, the large nutrient inventory is geogenic, replenishing the reservoir through chemical weathering and sustaining forest ecosystem nutrition from centuries to millennia (Uhlig and Von Blanckenburg 2019; Dawson et al. 2020). The high biological activity in the rhizosphere increases nutrient recycling efficiency (Collignon et al. 2011), even though soil fertilization reduces microbial activity and nutrient availability due to fertilization (Phillips and Fahey 2008). For instance, P-deficient soils may enhance the phosphatase activity and organic acid production in the rhizosphere (Chen 2003; Fujii et al. 2012; Hofmann et al. 2016), and soil acidification dissolves apatite, the primary source of soil mineral P. Soil acidification may also transform micas and illite into chloritized structures and labile minerals (Sokolova 2011), releasing K from illite interlayers into the soil (Bortoluzzi et al. 2012).

The rhizosphere showed higher TOC than the bulk soil, and the significant correlation with MAP and MAT confirms the influence of climatic factors on soil carbon stocks. Warming and higher precipitation stimulate soil respiration and ecosystem photosynthesis. That increases aboveground biomass and productivity (Sullivan et al. 2008; Luo et al. 2009; Wu et al. 2011), with expressive responses in woody ecosystems (Rustad et al. 2001) as a consequence of higher microbial activity (Sardans et al. 2008), enhanced C inputs and net C uptake (Luo et al. 2009; Wu et al. 2011), and soil nutrient mineralization (Hartley et al. 1999). Precipitation is the only factor influencing soil pH, with a higher correlation between rhizosphere pH and MAP than the bulk soil. Effective CEC cannot be directly correlated to MAP and MAT because it depends on several cations related to different soil properties. Furthermore, ecosystems are less responsive to the interaction of warming and precipitation than expected from single-factor effects (Luo et al. 2008; Wu et al. 2011).

5. Conclusions

Timber production from coniferous and naturally regenerated tree stands affected soil properties more than broadleaved species and monocultures. This meta-analysis evidenced a higher rhizosphere effect on soil properties than the surrounding bulk soil. The coniferous rhizosphere effect was higher than broadleaved trees, and the same occurred for regeneration sites compared to monocultures. Soil fertility was higher in naturally regenerated mixed stands, favoring tree establishment and development and organic nutrient turnover. Knowledge of the rhizosphere effect on soil is crucial for better understanding forest system dynamics for biomass production, especially in a low-input perspective, as soil nutrients can be depleted and threaten soil sustainability. However, further research is required on the tropics (the new agricultural frontier) to assess the impact of botanical groups and tree species on soil quality worldwide, considering the concentration of previous studies in temperate zones. The reasons for choosing specific tree species and forest management practices must be revisited, and the replacement of monoculture with mixed species stands where naturally regenerated woody species are managed for timber production must be considered to meet the demand for renewable energy sources while protecting the environment.

Authors' Contributions: HUMMES, AP.: conception and design, acquisition of data, and analysis and interpretation of data; NOVAKOWISKI, JH.: conception and design, drafting the article, and critical review of important intellectual content; CARVALHO, IR.: critical review of important intellectual content; BORTOLUZZI, C.: critical review of important intellectual content. All authors have read and approved the final version of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Ethics Approval: Not applicable.

Acknowledgments: This study was supported by the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES) through the Prosuc/Capes fellowship to A.P. Hummes [grant number 88887.177571/2018-00]. We would like to thank the Brazilian Council for Scientific and Technological Development - CNPq for the fellowship granted to E.C. Bortoluzzi [Brasilia/Brazil: 304676/2019-5]. The authors would like to thank CNPq (National Council for Scientific and Technological Development - Brazil), CAPES (Brazilian Coordination for the Improvement of Higher Education Personnel), and FAPEGRS (Rio Grande do Sul Research Foundation).

References

AGNELLI, A., et al. Holm oak (Quercus ilex L.) rhizosphere affects limestone-derived soil under a multi-centennial forest. *Plant and Soil*. 2016, **400**, 297–314. https://doi.org/10.1007/s11104-015-2732-x

AKSELSSON, C., et al. Weathering rates in Swedish forest soils. *Biogeosciences*. 2019, **16**, 4429–4450. https://doi.org/10.5194/bg-16-4429-2019

ÁLVAREZ, E., et al. Aluminum speciation in the bulk and rhizospheric soil solution of the species colonizing an abandoned copper mine in Galicia (NW Spain). *Journal of Soils and Sediments*. 2011, **11**, 221–230. https://doi.org/10.1007/s11368-010-0295-2

ÁLVAREZ, E., et al. Aluminium geochemistry in the bulk and rhizospheric soil of the species colonising an abandoned copper mine in Galicia (NW Spain). *Journal of Soils and Sediments*. 2010. **10**, 1236–1245. https://doi.org/10.1007/s11368-010-0245-z

ANGST, G., et al. Spatial distribution and chemical composition of soil organic matter fractions in rhizosphere and non-rhizosphere soil under European beech (Fagus sylvatica L.). *Geoderma*. 2016, **264**, 179–187. https://doi.org/10.1016/j.geoderma.2015.10.016

BORTOLUZZI, E.C., et al. Accumulation and Precipitation of Cu and Zn in a Centenarian Vineyard. *Soil Science Society of America Journal*. 2019, ***83***, 492–502. https://doi.org/10.2136/sssaj2018.09.0328

BORTOLUZZI, E.C., et al. Mineralogical changes caused by grape production in a regosol from subtropical Brazilian climate. *Journal of Soils and Sediments*. 2012, **12**, 854–862. https://doi.org/10.1007/s11368-012-0509-x

BROECKLING, C.D., et al., 2019. Rhizosphere Ecology. In: B. Fath, ed. *Encyclopedia of Ecology*. United Kingdom: Oliver Walter, pp. 574–578. https://doi.org/10.1016/B978-0-12-409548-9.11132-7

BU, W.S., et al. Mixed broadleaved tree species increases soil phosphorus availability but decreases the coniferous tree nutrient concentration in subtropical China. *Forests*. 2020, **11**, 461–477. https://doi.org/10.3390/f11040461

CALVARUSO, C., N'DIRA, V. and TURPAULT, M.-P. Impact of common European tree species and Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco) on the physicochemical properties of the rhizosphere. *Plant and Soil*. 2011, **342**, 469–480. https://doi.org/10.1007/s11104-010-0710-x

CHEN, H. Phosphatase activity and P fractions in soils of an 18-year-old Chinese fir (Cunninghamia lanceolata) plantation. *Forest Ecology and Management*. 2003. **178**, 301–310. https://doi.org/10.1016/S0378-1127(02)00487-4

CHEN, L., ZHANG, C. and DUAN, W. Temporal variations in phosphorus fractions and phosphatase activities in rhizosphere and bulk soil during the development of Larix olgensis plantations. *Journal of Plant Nutrition and Soil Science*. 2016. **179** (1), 67–77. https://doi.org/10.1002/jpln.201500060

CHEN, X., et al. Greater variations of rhizosphere effects within mycorrhizal group than between mycorrhizal group in a temperate forest. *Soil Biology and Biochemistry*. 2018, **126**, 237–246. https://doi.org/10.1016/j.soilbio.2018.08.026

CHIELLINI, C., et al. Exploring the links between bacterial communities and magnetic susceptibility in bulk soil and rhizosphere of beech (Fagus sylvatica L.). *Applied Soil Ecology*. 2019, **138**, 69–79. https://doi.org/10.1016/j.apsoil.2019.02.008

CLOUTIER-HURTEAU, B., SAUVÉ, S. and COURCHESNE, F. Comparing WHAM 6 and MINEQL+ 4.5 for the Chemical Speciation of Cu 2+ in the Rhizosphere of Forest Soils. *Environmental Science and Technology*. 2007, **41**(23), 8104–8110. https://doi.org/10.1021/es0708464

CLOUTIER-HURTEAU, B., et al. The speciation of water-soluble Al and Zn in the rhizosphere of forest soils. *Journal of Environmental Monitoring*. 2010, **12**, 1274. https://doi.org/10.1039/c002497j

COLLIGNON, C., et al. Time change of aluminium toxicity in the acid bulk soil and the rhizosphere in Norway spruce (Picea abies (L.) Karst.) and beech (Fagus sylvatica L.) stands. *Plant and Soil*. 2012, **357**, 259–274. https://doi.org/10.1007/s11104-012-1154-2

COLLIGNON, C., CALVARUSO, C. and TURPAULT, M.-P. Temporal dynamics of exchangeable K, Ca and Mg in acidic bulk soil and rhizosphere under Norway spruce (Picea abies Karst.) and beech (Fagus sylvatica L.) stands. *Plant and Soil*. 2011, **349**, 355–366. https://doi.org/10.1007/s11104-011-0881-0

COURCHESNE, F., KRUYTS, N. and LEGRAND, P. Labile zinc concentration and free copper ion activity in the rhizosphere of forest soils. *Environmental Toxicology and Chemistry.* 2006. **25**(3), 635–642. https://doi.org/10.1897/04-593R.1

DAI, X., et al. C:N:P stoichiometry of rhizosphere soils differed significantly among overstory trees and understory shrubs in plantations in subtropical China. *Canadian Journal of Forest Research*. 2018, **48**, 1398–1405. https://doi.org/10.1139/cjfr-2018-0095

DAWSON, T.E., HAHM, W.J. and CRUTCHFIELD-PETERS, K. Digging deeper: what the critical zone perspective adds to the study of plant ecophysiology. *New Phytologist*. 2020, **226**(3), 666–671. https://doi.org/10.1111/nph.16410

DE FEUDIS, M., et al. Altitude affects the quality of the water-extractable organic matter (WEOM) from rhizosphere and bulk soil in European beech forests. *Geoderma*. 2017, **302**, 6–13. https://doi.org/10.1016/j.geoderma.2017.04.015

DEL RE, A.C. A Practical Tutorial on Conducting Meta-Analysis in R. *The Quantitative Methods for Psychology*. 2015, **11**, 37–50. https://doi.org/10.20982/tqmp.11.1.p037

DESSAUX, Y., GRANDCLÉMENT, C. and FAURE, D. Engineering the Rhizosphere. *Trends in Plant Science*. 2016, **21**, 266–278. https://doi.org/10.1016/j.tplants.2016.01.002

DORAN, J.W. and PARKIN, T.B., 1994. Defining and Assessing Soil Quality. In: *Defining Soil Quality for a Sustainable Environment*. Madison: SSSA Special Publication no. 35, pp. 1–21. https://doi.org/10.2136/sssaspecpub35.c1

DOTANIYA, M.L. and MEENA, V.D. Rhizosphere Effect on Nutrient Availability in Soil and Its Uptake by Plants: A Review. *Proceedings of the National. Academy of Sciences, India Section B: Biological Sciences*. 2014, **85**, 1–12. https://doi.org/10.1007/s40011-013-0297-0

FAN, Z., et al. Changes in plant rhizosphere microbial communities under different vegetation restoration patterns in karst and non-karst ecosystems. *Scientific Reports*. 2019, **9**, 8761–8773. https://doi.org/10.1038/s41598-019-44985-8

FANG, X.M., et al. Soil phosphorus functional fractions and tree tissue nutrient concentrations influenced by stand density in subtropical Chinese fir plantation forests. *PLoS One*. 2017, **12**, e0186905. https://doi.org/10.1371/journal.pone.0186905

FIRN, J., ERSKINE, P.D. and LAMB, D. Woody species diversity influences productivity and soil nutrient availability in tropical plantations. *Oecologia*. 2007, **154**, 521–533. https://doi.org/10.1007/s00442-007-0850-8

FUJII, K., AOKI, M. and KITAYAMA, K. Biodegradation of low molecular weight organic acids in rhizosphere soils from a tropical montane rain forest. *Soil Biology and Biochemistry*. 2012, **47**, 142–148. https://doi.org/10.1016/j.soilbio.2011.12.018

FURUKAWA, T.A., et al. Imputing missing standard deviations in meta-analyses can provide accurate results. *Journal of Clinical Epidemiology*. 2006, **59**, 7–10. https://doi.org/10.1016/j.jclinepi.2005.06.006

GUAN, X., WANG, S.L. and ZHANG, W.D. Availability of N and P in the rhizosphere of three subtropical species. *Journal of Tropical Forest Science*. 2016, **28**(2), 159–166.

HARTLEY, A.E., et al. Plant Performance and Soil Nitrogen Mineralization in Response to Simulated Climate Change in Subarctic Dwarf Shrub Heath. *Oikos*, 1999, **86**, 331. https://doi.org/10.2307/3546450

HE, Q., et al. Vegetation type rather than climate modulates the variation in soil enzyme activities and stoichiometry in subalpine forests in the eastern Tibetan Plateau. *Geoderma*. 2020, **374**, 114424. https://doi.org/10.1016/j.geoderma.2020.114424

HIGGINS, J.P.T., et al. Measuring inconsistency in meta-analyses. *British Medical Journal*. 2003, **327**, 557–560. https://doi.org/10.1136/bmj.327.7414.557

HINSINGER, P. How Do Plant Roots Acquire Mineral Nutrients? Chemical Processes Involved in the Rhizosphere. *Advances in Agronomy*. 1998, **64**, 225–265. https://doi.org/10.1016/S0065-2113(08)60506-4

HOFMANN, K., HEUCK, C. and SPOHN, M. Phosphorus resorption by young beech trees and soil phosphatase activity as dependent on phosphorus availability. *Oecologia*. 2016, **181**, 369–379. https://doi.org/10.1007/s00442-016-3581-x

HOU, G., et al. A meta-analysis of changes in soil organic carbon stocks after afforestation with deciduous broadleaved, sempervirent broadleaved, and conifer tree species. *Annals of Forest Science*. 2020, **77**, 92. https://doi.org/10.1007/s13595-020-00997-3

HU, X.F., et al. The effects of simulated acid rain on internal nutrient cycling and the ratios of Mg, Al, Ca, N, and P in tea plants of a subtropical plantation. *Environmental Monitoring Assessment*. 2019, **191**, 99. https://doi.org/10.1007/s10661-019-7248-z

HUMMES, A.P., et al. Transfer of copper and zinc from soil to grapevine-derived products in young and centenarian vineyards. *Water, Air & Soil Pollution*. 2019, **230**, 150. https://doi.org/10.1007/s11270-019-4198-6

ISLAM, K. and WEIL, R. Land use effects on soil quality in a tropical forest ecosystem of Bangladesh. *Agriculture, Ecosystems & Environment*. 2000, **79**, 9–16. https://doi.org/10.1016/S0167-8809(99)00145-0

KONSTANTOPOULOS, S., 2006. Fixed and Mixed Effects Models in Meta-Analysis. *IZA Discussion Papers Series* **2198**, 1–39. ISSN: 2365-9793.

KORCHAGIN, J., et al. Evidences of soil geochemistry and mineralogy changes caused by eucalyptus rhizosphere. *Catena*. 2019, **175**, 132–143. https://doi.org/10.1016/j.catena.2018.12.001

KOURTEV, P.S., EHRENFELD, J.G. and HAGGBLOM, M. Exotic plant species alter the microbial community structure and function in the soil. *Ecology*. 2002, **83**, 3152–3166. https://doi.org/10.2307/3071850

KOUTSOS, T.M., MENEXES, G.C. and DORDAS, C.A. An efficient framework for conducting systematic literature reviews in agricultural sciences. *Science of Total Environment*. 2019, **682**, 106–117. https://doi.org/10.1016/j.scitotenv.2019.04.354

KUZYAKOV, Y. and BLAGODATSKAYA, E. Microbial hotspots and hot moments in soil: Concept & review. *Soil Biology and Biochemistry*. 2015, **83**, 184–199. https://doi.org/10.1016/j.soilbio.2015.01.025

LAURI, P., et al. Woody biomass energy potential in 2050. *Energy Policy*. 2014, **66**, 19–31. https://doi.org/10.1016/j.enpol.2013.11.033

LIU, J., et al. Characteristics of bulk and rhizosphere soil microbial community in an ancient Platycladus orientalis forest. *Applied Soil Ecology*. 2018, **132**, 91–98. https://doi.org/10.1016/j.apsoil.2018.08.014

LIU, R., et al. Differential magnitude of rhizosphere effects on soil aggregation at three stages of subtropical secondary forest successions. *Plant and Soil*. 2019, **436**, 365–380. https://doi.org/10.1007/s11104-019-03935-z

LOVATTO, P.A., et al. Meta-análise em pesquisas científicas: enfoque em metodologias. *Revista Brasileira de Zootecnia*. 2007, **36**, 285–294. https://doi.org/10.1590/S1516-35982007001000026

LUO, Y., et al. Modeled interactive effects of precipitation, temperature, and [CO2] on ecosystem carbon and water dynamics in different climatic zones. *Global Change Biology*. 2008, **14**, 1986–1999. https://doi.org/10.1111/j.1365-2486.2008.01629.x

LUO, Y., et al. Terrestrial carbon-cycle feedback to climate warming: experimental evidence on plant regulation and impacts of biofuel feedstock harvest. *GCB Bioenergy*. 2009, **1**(1), 62–74. https://doi.org/10.1111/j.1757-1707.2008.01005.x

MALYSZ, M. and OVERBECK, G.E. Distinct tree regeneration patterns in Araucaria forest and old monoculture tree plantations. *Brazilian Journal of Botany*. 2018, **41**, 621–629. https://doi.org/10.1007/s40415-018-0475-7

MCGAHAN, D.G., SOUTHARD, R.J. and ZASOSKI, R.J. Rhizosphere effects on soil solution composition and mineral stability. *Geoderma*. 2014, **226–227**, 340–347. https://doi.org/10.1016/j.geoderma.2014.03.011

PENG, Y., et al. Tree species effects on topsoil carbon stock and concentration are mediated by tree species type, mycorrhizal association, and N-fixing ability at the global scale. Forest Ecology and Management. 2020, **478**, 118510. https://doi.org/10.1016/j.foreco.2020.118510

PHILLIPS, R.P. and FAHEY, T.J. The influence of soil fertility on rhizosphere effects in northern hardwood forest soils. *Soil Science Society of America Journal*. 2008, **72**, 453–461. https://doi.org/10.2136/sssaj2006.0389

PHILLIPS, R.P. and YANAI, R.D. The effects of $AlCl_3$ additions on rhizosphere soil and fine root chemistry of sugar maple (Acer saccharum). *Water, Air, & Soil Pollution*. 2004, **159**, 339–356. https://doi.org/10.1023/B:WATE.0000049187.35869.7d

R CORE TEAM. *R: A language and environment for statistical computing. R Foundation for Statistical Computing*. Vienna, Austria, 2019. https://www.R-project.org

ROHATGI, A. *WebPlotDigitizer: Web based tool to extract data from plots images and maps. Version 4.2.* 2019. https://automeris.io/WebPlotDigitizer

ROSENSTOCK, N.P., et al. Base cations in the soil bank: non-exchangeable pools may sustain centuries of net loss to forestry and leaching. *Soil*. 2019, **5**(2), 351–366. https://doi.org/10.5194/soil-5-351-2019

RUSTAD, L., et al. A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. *Oecologia*. 2001, **126**, 543–562. https://doi.org/10.1007/s004420000544

SARDANS, J., et al. Warming and drought alter C and N concentration, allocation and accumulation in a Mediterranean shrubland. *Global Change Biology*. 2008, **14**, 2304–2316. https://doi.org/10.1111/j.1365-2486.2008.01656.x

SÉGUIN, V., GAGNON, C. and COURCHESNE, F. Changes in water extractable metals, pH and organic carbon concentrations at the soil-root interface of forested soils. *Plant and Soil*. 2004, **260**, 1–17. https://doi.org/10.1023/B:PLSO.0000030170.49493.5f

SOKOLOVA, T.A. Specificity of soil properties in the rhizosphere: analysis of literature data. *Eurasian Soil Science*. 2015, **48**, 968–980. https://doi.org/10.1134/S1064229315050099

SOKOLOVA, T.A. The role of soil biota in the weathering of minerals: A review of literature. *Eurasian Soil Science.* 2011, **44**, 56–72. https://doi.org/10.1134/S1064229311010121

SOKOLOVA, T.A., et al. Acid–Base Characteristics and Clay Mineralogy in the Rhizospheres of Norway Maple and Common Spruce and in the Bulk Mass of Podzolic Soil. *Eurasian Soil Science*. 2019, **52**, 707–717. https://doi.org/10.1134/S1064229319060115

SULLIVAN, P.F., et al. Temperature and Microtopography Interact to Control Carbon Cycling in a High Arctic Fen. *Ecosystems.* 2008, **11**, 61–76. https://doi.org/10.1007/s10021-007-9107-y

TURPAULT, M.-P., GOBRAN, G.R. and BONNAUD, P. Temporal variations of rhizosphere and bulk soil chemistry in a Douglas fir stand. *Geoderma*. 2007, **137**, 490–496. https://doi.org/10.1016/j.geoderma.2006.10.005

TURPAULT, M.-P., RIGHI, D. and UTÉRANO, C. Clay minerals: Precise markers of the spatial and temporal variability of the biogeochemical soil environment. *Geoderma.* 2008, **147**, 108–115. https://doi.org/10.1016/j.geoderma.2008.07.012

TURPAULT, M.-P., et al. Influence of mature Douglas fir roots on the solid soil phase of the rhizosphere and its solution chemistry. *Plant and Soil*. 2005, **275**, 327–336. https://doi.org/10.1007/s11104-005-2584-x

UHLIG, D., AMELUNG, W. and BLANCKENBURG, F. Mineral Nutrients Sourced in Deep Regolith Sustain Long-Term Nutrition of Mountainous Temperate Forest Ecosystems. *Global Biogeochemical Cycles*. 2020, **34**, 1–21. https://doi.org/10.1029/2019GB006513

UHLIG, D. and VON BLANCKENBURG, F. How Slow Rock Weathering Balances Nutrient Loss During Fast Forest Floor Turnover in Montane, Temperate Forest Ecosystems. *Frontiers in Earth Science*. 2019, **7**:159. https://doi.org/10.3389/feart.2019.00159

USHARANI, K., ROOPASHREE, K. and NAIK, D. Role of soil physical, chemical and biological properties for soil health improvement and sustainable agriculture. *Journal of Pharmacognosy Phytochemistry*. 2019, **8**(5), 1256-1267.

VIECHTBAUER, W. Conducting meta-analyses in R with the metafor. *Journal of Statistical Software*. 2010, **36**(3), 1–48. https://doi.org/10.18637/jss.v036.i03

WANG, Y., et al. Environmental behaviors of phenolic acids dominated their rhizodeposition in boreal poplar plantation forest soils. *Journal of Soils and Sediments*. 2016, **16**, 1858–1870. https://doi.org/10.1007/s11368-016-1375-8

WANG, Z., GÖTTLEIN, A. and BARTONEK, G. Effects of growing roots of Norway spruce (Picea abies [L.] Karst.) and European beech (Fagus sylvatica L.) on rhizosphere soil solution chemistry. *Journal of Plant Nutrition & Soil Science*. 2001, **164**, 35–41. https://doi.org/10.1002/1522-2624(200102)164:1<35::AID-JPLN35>3.0.CO;2-M

WU, Z., et al. Responses of terrestrial ecosystems to temperature and precipitation change: A meta-analysis of experimental manipulation. *Global Change Biology*. 2011, **17**, 927–942. https://doi.org/10.1111/j.1365-2486.2010.02302.x

YIN, H., WHEELER, E. and PHILLIPS, R.P. Root-induced changes in nutrient cycling in forests depend on exudation rates. *Soil Biology and Biochemistry*. 2014, **78**, 213–221. https://doi.org/10.1016/j.soilbio.2014.07.022

ZHANG, W., et al. Phyllostachys edulis (moso bamboo) rhizosphere increasing soil microbial activity rather than biomass. *Journal of Soils and Sediments*. 2019, **19**, 2913–2926. https://doi.org/10.1007/s11368-019-02334-2

ZHAO, Q., et al. Rhizosphere organic phosphorus fractions of Simon poplar and Mongolian pine plantations in a semiarid sandy land of northeastern China. *Journal of Arid Land*. 2015, **7**, 475–480. https://doi.org/10.1007/s40333-015-0082-4

ZHENG, M., et al. Effects of phosphorus addition with and without nitrogen addition on biological nitrogen fixation in tropical legume and non-legume tree plantations. *Biogeochemistry*. 2016, **131**, 65–76. https://doi.org/10.1007/s10533-016-0265-x

Received: 19 October 2021 | **Accepted:** 17 January 2024 | **Published:** 15 March 2024