forests

Article

Variation in Hydraulic Properties of Forest Soils in Temperate Climate Zones

Victoria Virano-Riquelme [1,*], Karl-Heinz Feger [1] and Stefan Julich [1,2]

[1] Institute of Soil Science and Site Ecology, Faculty of Environmental Sciences, Technische Universität Dresden, 01737 Tharandt, Germany
[2] Faculty of Landscape Management and Nature Conservation, Eberswalde University for Sustainable Development, 16225 Eberswalde, Germany
* Correspondence: victoria.virano@tu-dresden.de

Abstract: The structure of forests in temperate climates has been changing to ensure the resilience of trees. This change affects the local water balance. Knowledge of soil hydraulic properties (SHP) is essential to assess the water cycle in ecosystems. There is little knowledge about the impact of tree species on SHP and the water balance. Based on a compilation of 539 related studies we aimed at identifying the effects of tree species and age on SHP in temperate climates. However, most studies concentrated on soil biogeochemical properties, whereas only 256 studies focused on SHP. The literature presents no standard methods for assessing SHP and there is no knowledge of their variations in forests. We present a systematic overview of the current state of knowledge on variations in SHP based on forest type in temperate climates. We identify the gaps and weaknesses in the literature and the difficulties of evaluating the reviewed studies. More studies following standardised methodologies are needed to create a robust database for each forest type and soil texture. It would improve the assessment of the forest water balance through calibrated plot/site-scale process models. Such a database does not yet exist, but it would greatly improve the management and development of future forest ecosystems.

Keywords: soil hydraulic properties; saturated hydraulic conductivity; bulk density; temperate forests

Citation: Virano-Riquelme, V.; Feger, K.-H.; Julich, S. Variation in Hydraulic Properties of Forest Soils in Temperate Climate Zones. *Forests* **2022**, *13*, 1850. https://doi.org/10.3390/f13111850

Received: 1 September 2022
Accepted: 29 October 2022
Published: 4 November 2022

1. Introduction

In recent decades, forest ecosystems have shown a decline in productivity, exhibiting tree species with negative physiological processes undergoing high and abrupt mortality [1]. According to Allen et al. [2], the increasing tree death rate is caused by climate change with concomitant drought and heat as the main factors compromising the prosperity of the forests. The severity of droughts and the high stress in temperate forest ecosystems create conditions favouring pests and pathogens [3], creating an environment of high risk, especially in areas with low water availability [4].

In addition, future scenarios foresee increasing drought frequency, intensity, and duration as well as additional impacts such as wildfires and severe storms, leading to elevated tree mortality rates [1,2,4]. Long-term droughts, coupled with rapid tree decline, represent considerable challenges to the management and policy-making communities. In response to changing conditions, forests of the temperate zone are transforming, being managed to withstand these adverse constraints.

In the past, monocultures of needle-leaved trees (i.e., of Norway spruce—*Picea abies*) were widely used in Central Europe as a promising economic resource. However, in the context of climate change, spruce monocultural stands have weakened and are rapidly dying out. Therefore, current forest management considers the use of native broad-leaved tree species as mitigation to endure drought stress and preserve the vitality of trees. As reported by Pretzsch et al. [5], the process of transformation and adaptation from non-natural and widespread coniferous monocultures towards mixed forests including deciduous tree species will be of great ecological interest considering different rates and species.

This strategy plays a key role in overcoming the current climatic conditions and in the development of future forest ecosystems. The introduction of broad-leaved and hardwood species in needle-leaved stands should be performed carefully as it changes several soil properties (i.e., humus, litter deposition), likely affecting the soil hydraulic properties [6–8]. Therefore, the assessment of possible consequences on the water balance is essential for efficient forest productivity [9].

The evaluation of the water balance of forest stands in terms of different species can be achieved by using calibrated plot/site-scale process models such as LWF-Brook90 [10,11], which depend on soil hydraulic properties (SHP). SHP are essential to assess the water cycle in ecosystems. The evaluation of these parameters allows the description of several hydrological processes within the soil profile, such as water infiltration, surface runoff and water storage, the availability of water for root uptake, percolation, and the generation of surface runoff as a function of the soil management practices [12,13]. Furthermore, the soil hydraulic conductivity is particularly relevant since it allows the estimation of water movement towards the root zone and the recharge of underground aquifers, as well as the transport of minerals and nutrients into the deeper layers of the soil profile [14,15].

Some studies compare SHP between forested and non-forested sites, but only a few focus on the different management practices within forest ecosystems. In contrast to other land uses, studies reveal that forest soils usually show higher hydraulic conductivity [14,16,17], improved water retention [17], decreased runoff and increased soil moisture [17,18], with often lower density [19]. Moreover, the infiltration capacity and soil water retention in forested soils control the formation of surface runoff acting as a natural flood regulator [16,20,21]. However, most studies addressing the variation in soil properties as a result of forest management focus on aboveground characteristics including biomass [22–24], vegetation traits [25–27], and soil biochemical properties [28–32].

Articles assessing SHP in temperate forests are extremely scarce and present a great variety in findings. Differing values for soil bulk density, hydraulic conductivity, and the accumulation of soil organic carbon in relation to forest type and tree age have been observed [8,14,21,33–35]. In addition, the relief of the sites has a noticeable implication for the assessment of the SHP. On steep slopes, needle-leaved forests have revealed enhanced hydraulic conductivity in contrast to smoother surfaces [36]. However, under similar conditions, broad-leaved forests create conditions less prone to surface runoff generation compared to needle-leaved forests [34]. SHP may vary according to a vast combination of soil texture, tree species, root distribution, and the inherent complexity of the interacting site conditions, likely affecting the water dynamics in a catchment [6,16,33,37,38].

The objective of this study is to review the available literature on information for the SHP of forested sites in temperate zones. Our aim is to evaluate and assess the impact of tree species and age on soil hydraulic properties based on the reported values. We expect to find differences in SHP in terms of broad-leaved and needle-leaved tree species as reported by Archer et al. [14], Julich et al. [16], and Wahren et al. [17]. We hypothesize that in needle-leaved stands (at least for comparable soil geological settings), the overall hydraulic conductivity is lower, together with higher bulk density, compared to broad-leaved stands.

2. Materials and Methods

2.1. Nature and Classification of the Studies

For the review, a systematic search was conducted based on the PRISMA Statement [39]. The academic databases Scopus and Web of Science were used to search for information, with the last search performed on 24 March 2022. This review targeted peer-reviewed publications in English until the year 2021. Publications in other languages were excluded as a thorough analysis requires an adequate understanding of the study site descriptions.

Figure 1 shows the search steps we followed to create our database. Firstly, we performed a broad search ("Search 1", Figure 1), considering the terms "soil hydraulic properties" and "forests", obtaining a total of 462 articles. The results were classified according to "temperate forests" and "tropical forests (+others)", with the latter group presenting the highest number of studies regarding soil properties. In this step the articles that were not related to the study of soil properties (i.e., soil fauna, soil fungi, root development), that were not specifically carried out in forested areas, that did not specify the type of climate, or articles where it was not clear, were excluded. Then, the focus of our study was specifically directed to temperate forests as our first research revealed that the studies conducted on these forests were deficient.

After the first literature review, we carried out a complementary search using the same academic databases to aim for studies addressing SHP in temperate forests, including the words "hydraulic conductivity", "water retention", and "water content" to make certain of covering relevant soil hydraulic properties ("Search 2", Figure 1). For each of the beforementioned words, different combinations of keywords such as "temperate forest", "temperate climate", "coniferous", "deciduous", "stand", "species", "mixed forest(s)", and "forest conversion" were used.

Although we collected a total of 539 articles up to 2021, several of these studies referred to the term "soil properties" in a general context. Therefore, 267 studies were discarded before the assessment as they focused specifically on soil biogeochemical properties, traits, and root water uptake, rather than on soil hydraulic properties. Moreover, some of those studies were discarded since they concerned other land uses. After neglecting the studies that were not within the scope of this review, the compilation consisted of 272 studies. Since our analysis aimed at soil hydraulic properties obtained between 0 and 30 cm depth, 16 additional studies not reporting depth of measurement or performed at greater depths were excluded from the database. In addition, studies that used units deviating from the standard were discarded to avoid confusion and misinterpretation over converted values. Once all these steps were completed, the final database was subdivided into those articles containing studies related to soil bulk density, hydraulic conductivity, and soil water content.

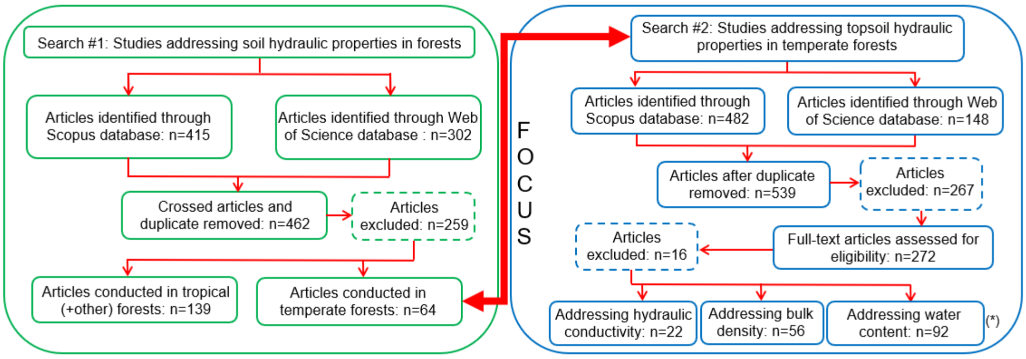

Figure 1. The flowchart on the left displays the steps performed in a first broad search, which shows the current state of the literature in relation to the variation in soil hydraulic properties in different climatic zones. The flow chart on the right illustrates the steps followed to filter the studies related to soil hydraulic properties in temperate forests (the focus) and how the final database

based on current literature was compiled. The number of papers found (n) and the studies that were discarded at each step along the literature review are included. (*) Some articles are repeated between the subdivisions.

To assess the effect of the different forest ecosystems on the soil properties, we defined a classification for this study according to needle-leaved, broad-leaved, and mixed forests. Within each forest group, we attempted to classify the studies in terms of site parameters such as soil texture, organic matter concentration, tree age, and tree mixing rate (in the case of mixed forests). Still, due to the limited information, we were able to classify the articles only in terms of soil texture and tree age. The classification of soil texture was performed based on fine for clay-dominated soils, medium for mostly loamy soils, and coarse for mostly sandy soils. Given the range in ages of the trees in the reviewed studies, and for the purpose of our study, we decided to group the values collected according to the following criteria: young forest for trees < 50 years old, mature stand for those containing trees of 50–100 years old, and old forest for trees older than 100 years.

When evaluating the articles that assess soil water content, we observed that most of the studies were concerned with variations in water content over a given period of time. Such results are of interest for assessing temporal fluctuations in soil moisture content; however, they are relative to seasonal and climatic factors. Therefore, we focused on measurements of water holding capacity, as this property is relevant to assess the effect of forest type. From the 92 articles collected that addressed water content, only 15 could be used for our research.

In the case of saturated hydraulic conductivity, 3 out of 22 articles performed their measurements under laboratory conditions, which were excluded since such measurements likely neglect the site characteristics. Regarding the experiments performed in the field, one article did not specify the measurement device, whereas 10 studies used permeameters and nine used infiltrometers. Although both methods work under different techniques, we considered all the 20 articles in our analysis. From these studies, we compiled a total of 145 values for analysis. Regarding soil bulk density, from a total of 56 studies, we collected 145 values to be further assessed.

2.2. Statistical Analysis

As most of the results came from diverse studies and were performed under specific conditions, the collected data could not be assumed to be uniformly distributed. Even when some of the reviewed papers presented comparable site parameters, they frequently differed in other aspects, such as measurement approaches, devices, and sampling designs. Therefore, the Kruskal–Wallis test was used to assess whether the data presented significant differences between the forest types under the assumption that all data points were obtained independently under the same experimental conditions.

3. Results

The compilation of studies was screened for values of SHP in terms of water holding capacity, saturated hydraulic conductivity, and soil porosity. However, the available information on the aforementioned parameters was limited. Thus, it was not possible to add most of these hydraulic parameters to the analysis. Only for soil hydraulic conductivity could sufficient information be extracted for further assessment. Since soil bulk density was present in almost all the reviewed articles, it was included in the analysis, as it provides relevant information regarding soil structure.

In order to appropriately compare each soil hydraulic property in terms of comparable site parameters, we classified the data according to forest type (i.e., tree species and age of the trees) and the soil texture where the parameters were measured. We found that not all the collected articles reported these relevant parameters, hence several studies were unsuitable for further analysis. As a result, we created two datasets containing all values found in the pool of collected articles. Database A contains all results obtained for a soil depth of 0–30 cm (independent of the site description) and database B contains the filtered information of database A, comprising only those articles reporting forest type and soil texture. Furthermore, all values were converted to the same units for further comparison.

Table 1 presents the number of studies included in databases A and B, the latter containing the results that are suitable to assess the collected bulk density and hydraulic conductivity values. To visualize the information, the distribution was performed by forest type, and each field was additionally sorted by soil texture and tree age. It can be seen that most studies comprised information regarding bulk density and fewer studies measured hydraulic conductivity. It is also evident that the majority of the studies were conducted in needle-leaved and broad-leaved forests.

Table 1. Classification of values found in the reviewed literature filtered by forest type as main field and further divisions by soil texture and tree age, which were defined by this study. The left side of the table (a) corresponds to the hydraulic conductivity (K) and right side (b) refers to the soil bulk density (BD). All values are measurements between 0 and 30 cm soil depth.

Needle-Leaved Forest									
(a) K	**Young**	**Mature**	**Old**	**Total**	**(b) BD**	**Young**	**Mature**	**Old**	**Total**
Coarse	10	1	0	11	Coarse	4	11	2	17
Medium	0	1	0	1	Medium	2	1	2	5
Fine	0	0	0	0	Fine	0	0	0	0
Total	10	2	0	12	Total	6	12	4	22
Broad-Leaved Forest									
Coarse	0	6	9	15	Coarse	2	12	2	16
Medium	1	4	0	5	Medium	3	1	12	16
Fine	0	0	0	0	Fine	11	0	0	11
Total	1	10	9	20	Total	16	13	14	43
Mixed Forest									
Coarse	0	12	2	14	Coarse	0	14	0	14
Medium	0	0	0	0	Medium	0	0	0	0
Fine	0	0	0	0	Fine	0	0	0	0
Total	0	12	2	14	Total	0	14	0	14

3.1. Soil Water Retention

Table 2 summarises the information regarding soil water retention characteristics found in the screened articles. From 15 studies a total of 30 values were found, yet not all studies referred to the same measurements of soil water holding capacity, resulting in limited information for the individual soil water types. Field capacity (FC) ranged from 0.12 $m^3 m^{-3}$ for sandy soils up to 0.44 $m^3 m^{-3}$ for silty clay soils. Regarding plant available water (PAW), only a little amount of information was available with values ranging from 0.02 to 0.33 $m^3 m^{-3}$. For water content at the permanent wilting point (PWP), values between 0.05 and 0.20 $m^3 m^{-3}$ were reported.

Table 2. Detailed information on soil water holding capacity from the reviewed literature. In the division Forest Type, the abbreviations Nee, Broa, and Mix stand for needle-leaved, broad-leaved, and mixed forest type, respectively.

Author References	FC [1]	PAW [2]	PWP [3]	Forest Type	Soil Texture Class	Tree Age
	(m^3 m^{-3})					
Bittner et al. [40]	-	-	0.06	Broa	Silty clay	Old
	-	-	0.06	Broa	Silty clay	Old
	-	-	0.09	Broa	Silty clay	Old
Grant et al. [41]	0.28	0.09	-	Broa	Silty	Mature
Metzger et al. [42]	0.44	-	-	Broa	Fine textured	-
	0.42	-	-	Broa	Fine textured	-
Baldocchi et al. [43]	0.16	-	-	Nee	Sandy	Old
Archer et al. [14]	-	0.290	-	Nee	Sandy	Young
	-	0.240	-	Nee	Sandy	Mature
	-	0.220	-	Nee	Sandy	Old
	-	0.180	-	Nee	Sandy	Old
Dusek and Vogel [44]	-	-	0.20	Nee	Sandy	-
	-	-	0.20	Nee	Sandy	-
Tor-Ngern et al. [9]	0.15	-	-	Nee	Sandy	Young
	0.15	-	0.05	Nee	Sandy	Mature
Almahayni and Houska [45]	0.12	0.02	-	Nee	Sandy	-
Duarte et al. [46]	0.30	-	0.14	Nee	-	Old
Kirchen et al. [47]	0.40	-	0.18	Broa	Fine textured	Young
	0.40	-	0.28	Broa	Fine textured	Young
	0.31	-	0.15	Broa	Fine textured	Young
	0.34	-	0.17	Broa	Fine textured	Young
Leuschner [48]	-	0.32	0.13	Broa	Sandy	-
	-	0.14	0.13	Nee	-	Young
Curiel Yuste et al. [49]	0.12	-	-	Mix	Sandy	-
Julich et al. [16]	0.43	0.29	0.14	Broa	Silty	Young
	0.40	0.29	0.11	Broa	Silty	Old
	0.40	0.30	0.10	Nee	Silty	Mature
Wahren et al. [17]	-	0.22	-	Mix	Sandy loam	Mature
Schwärzel et al. [50]	-	0.27	-	Broa	Silty	Mature
	-	0.33	-	Nee	Silty	Old

[1] Soil water at field capacity. [2] Soil plant available water. [3] Soil water at permanent wilting point.

3.2. Soil Bulk Density

Figure 2 compares the values for soil bulk density of the topsoil by using dataset A, which contains all values found in the literature screening, and dataset B containing those that were filtered regarding the available information on tree age and soil texture. Dataset A comprised a total of 163 bulk density values, whereas dataset B was reduced to 79, excluding about 52% of the information. For dataset A, the highest and lowest means were observed in the broad-leaved and needle-leaved forests, respectively, whereas dataset B showed comparable mean values between forest types (Figure 2).

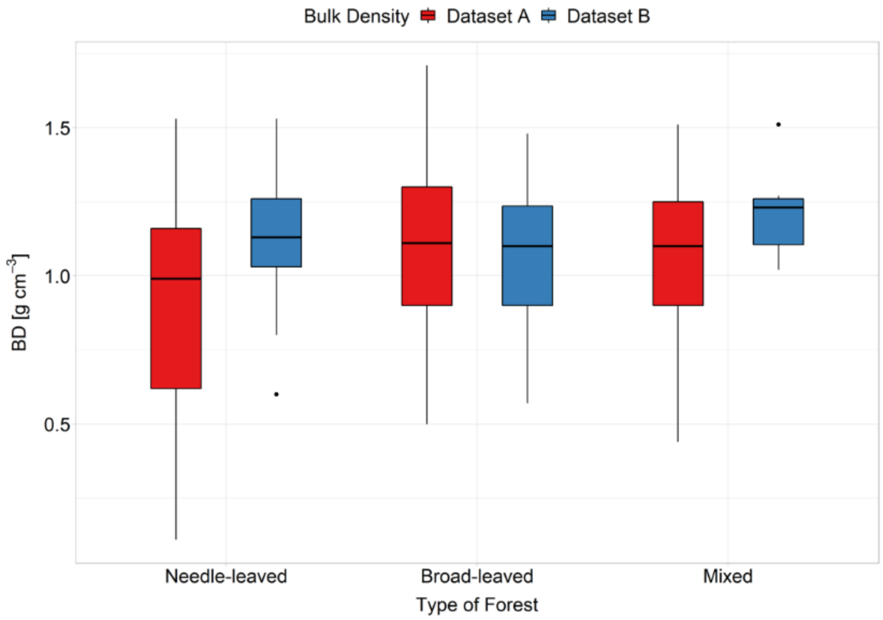

Figure 2. Descriptive statistics of top mineral soil bulk density by forest type considering the two data sets: dataset A containing all values found and dataset B filtered values based on available information on tree age and the soil particle size. All values refer to the topsoil (0–30 cm depth). Black dots represent the outliers.

Table 3 shows the number of studies and descriptive statistics of bulk density for datasets A and B. The *p*-values suggest that in dataset A there is an effect of forest type on the soil bulk density (*p*-values < 0.05); however, the *p*-values in dataset B show no effect of forest type on this soil property. The comparison with mixed forest is not adequate in both cases since the number of studies on this forest type is not sufficient in contrast to the others (Table 3).

Table 3. Summary of statistics for soil bulk density and saturated hydraulic conductivity sorted according to forest type. Dataset A contains all results found in the screened articles; dataset B considers only those values reported with additional information on soil particle size and tree age. All values refer to the topsoil (0–30 cm depth). G Mean refers to the geometric mean. (*) indicates the group of forest with significantly different BD values.

	Bulk Density (g cm⁻³)					
	Forest Type	***n***	**Mean**	**Min**	**Max**	***p*-Value**
A	Needle-leaved	45	0.89	0.11	1.53	0.0098 (*)
	Broad-leaved	83	1.09	0.50	1.71	0.2396
	Mixed	17	1.02	0.44	1.51	0.4682
B	Needle-leaved	19	1.12	0.60	1.53	0.5807
	Broad-leaved	40	1.10	0.57	1.48	0.3541
	Mixed	11	1.20	1.02	1.51	0.1241
	Hydraulic Conductivity (cm d⁻¹)					
	Forest Type	***n***	**G. Mean**	**Min**	**Max**	***p*-Value**
A	Needle-leaved	20	132	6	1200	0.9806
	Broad-leaved	23	160	12	1400	0.4261
	Mixed	16	224	27	1201	0.3460
B	Needle-leaved	12	116	17	538	0.9379
	Broad-leaved	20	127	12	1096	0.1498
	Mixed	14	239	27	1201	0.1415

Figure 3 and Table 4 provide the descriptive statistics of dataset B regarding the bulk density of the topsoil. Most of the reviewed studies with information regarding tree age were conducted on broad-leaved forests, whereas for mixed forests only a few studies were carried out. Values for bulk density do not follow any trend (in terms of forest type or tree age) and reveal that mature and young stands are the dominant stages in the reviewed studies.

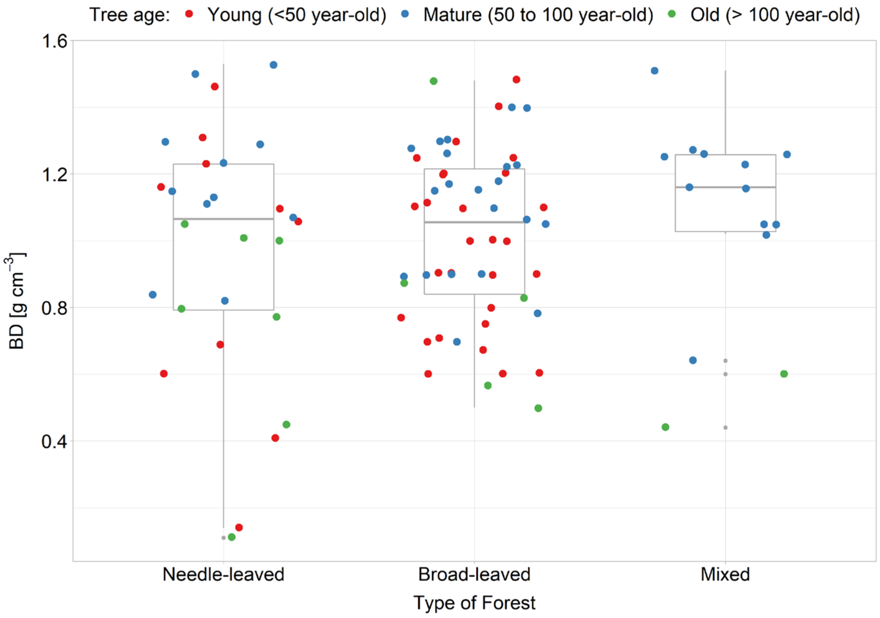

Figure 3. Descriptive statistics of the top mineral soil bulk density in relation to the tree age and forest type for dataset B. Scattered points represent the individual values classified by the different forest stages. Values correspond to the 0–30 cm soil depth. Grey points indicate the outliers.

Table 4. Summary of reported values on topsoil bulk density and hydraulic conductivity for the different forest types, data are subdivided based on the information on tree age: young (Y) less than 50 years, mature (M) 50 to 100 years, and old (O) more than 100 years.

Bulk Density (g cm^{-3})	Needle-Leaved			Broad-Leaved			Mixed		
Tree age	Y	M	O	Y	M	O	Y	M	O
mean values	0.92	1.18	0.74	0.98	1.11	0.85	-	1.16	0.52
n	10	11	7	28	21	5	-	12	2
max	1.46	1.53	1.05	1.48	1.40	1.48	-	1.51	0.60
min	0.14	0.82	0.11	0.60	0.70	0.50	-	0.64	0.44
Hydraulic Conductivity (cm d^{-1})	**Needle-Leaved**			**Broad-Leaved**			**Mixed**		
Tree age	Y	M	O	Y	M	O	Y	M	O
mean values	140	409	306	692	171	233	-	483	352
n	13	2	2	2	9	10	-	12	2
max	538	468	538	1096	312	751	-	1201	418
min	6	349	75	288	35	12	-	27	286

The topsoil bulk density for needle-leaved and broad-leaved forests presented the highest values in the mature stage; however, comparison with mixed forests was not possible since values for the young stage were not found. Most values for the old stages under needle-leaved and broad-leaved forests were lower in contrast to the other stages.

Figure 4 and Table 5 describe the reported values for bulk density in relation to soil texture and forest type. Most of the screened studies with information on soil texture were conducted in broad-leaved forests, whereas only a few were conducted in mixed stands. The distribution of values reveals no apparent relationship between bulk density and soil texture for the different forest types. Figure 4 also shows that very few reported values correspond to the Oh-horizon in contrast to those measured in the first 30 cm of soil.

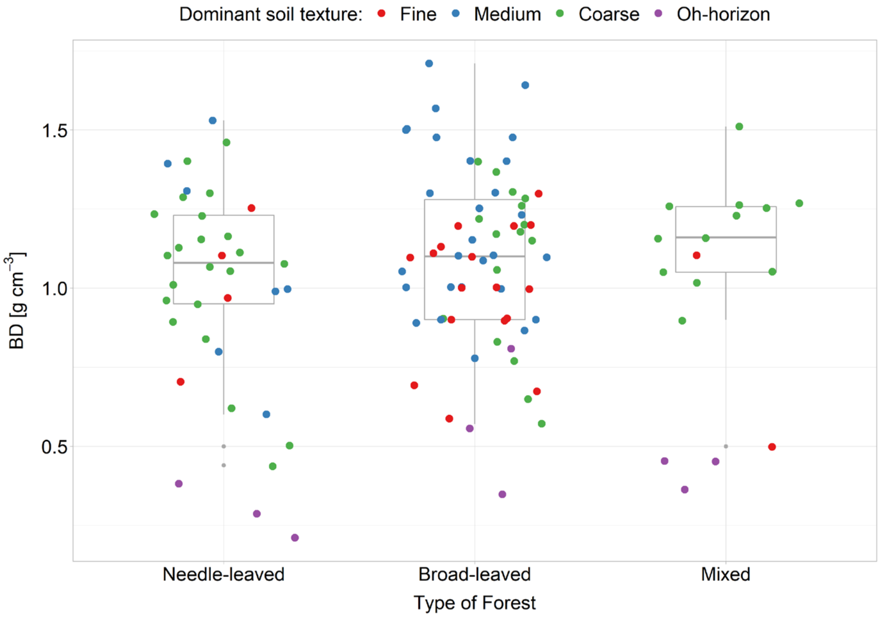

Figure 4. Descriptive statistics of the top mineral soil bulk density for dataset B in terms of forest type and soil texture: fine (clay-dominated), medium (mostly loamy), and coarse (mostly sandy). Scattered points represent the individual values between 0 and 30 cm soil depth, including the Oh-horizon. Grey points indicate the outliers.

Table 5. Topsoil bulk density and hydraulic conductivity values in terms of forest type, filtered by soil texture. Letters C, M, and F stand for soils with coarse (mostly sandy), medium (mostly loamy), and fine (clay-dominated) soil texture, respectively, between 0 and 30 cm soil depth. In the case of bulk density, the letter Oh represents the values for the Oh-horizon.

Bulk Density (g cm^{-3})	**Needle-Leaved**				**Broad-Leaved**				**Mixed**			
Soil texture	C	M	F	Oh	C	M	F	Oh	C	M	F	Oh
mean values	1.04	1.09	1.01	0.29	1.08	1.20	1.00	0.57	1.18	-	0.80	0.42
n	22	7	4	3	16	28	17	3	12	-	2	3
max	1.46	1.53	1.25	0.38	1.40	1.71	1.30	0.81	1.51	-	1.10	0.45
min	0.44	0.60	0.70	0.21	0.57	0.78	0.59	0.35	0.90	-	0.50	0.36
Hydraulic Conductivity (cm d^{-1})	**Needle-Leaved**				**Broad-Leaved**				**Mixed**			
Soil texture	C	M	F	Oh	C	M	F	Oh	C	M	F	Oh
mean values	204	261	875	-	242	286	1225	-	464	320	64	-
n	13	2	2	-	17	5	2	-	14	1	1	-
max	567	468	1200	-	751	1096	1400	-	1201	-	-	-
min	17	53	550	-	35	12	1050	-	27	-	-	-

For needle-leaved and broad-leaved forests, the highest mean values for bulk density were observed in forest stands with a loam-dominated soil texture, whereas the lowest were found in sites with a fine soil texture. Overall bulk density in the Oh-horizon were in the order: broad-leaved > mixed > needle-leaved, with a limited number of values reported in the screened articles (Table 5). Moreover, it was often difficult to identify whether the soil density values corresponded to the mineral layer or the organic layer. Therefore, it is possible that there is a bias in the values reported in our study due to a lack of detail in terms of the depth of measurements.

3.3. Soil Saturated Hydraulic Conductivity

Figure 5 and Tables 3–5 summarise all the information regarding the topsoil saturated hydraulic conductivity obtained from the reviewed articles. Analogous to the bulk density, dataset A comprises 59 values, while dataset B contains 46 values. Between the two datasets, no change in the mean values in terms of forest type was noticeable: mixed > broad-leaved > needle-leaved (Table 3, Figure 5). Furthermore, no statistical effect of forest type on the soil hydraulic conductivity of the topsoil was observed (p-values > 0.05, Table 3).

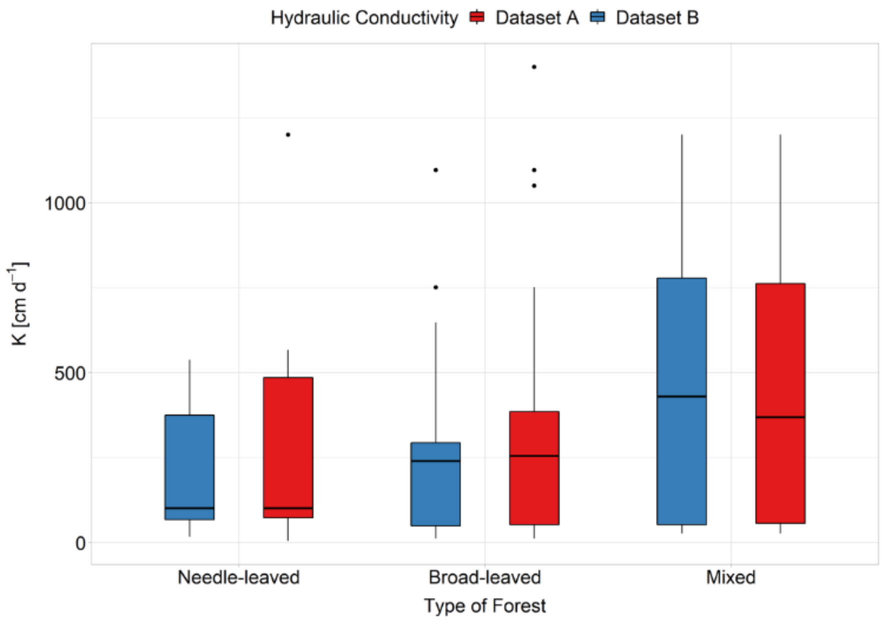

Figure 5. Descriptive statistics of topsoil hydraulic conductivity in terms of forest type considering two datasets: dataset A containing all values found and dataset B containing filtered values based on available information on tree age and soil particle size. All values refer to the topsoil (0–30 cm depth). Black dots represent the outliers.

For needle-leaved forests, most studies concentrated on the young stage, whereas the old stages of broad-leaved forests dominated the screened studies (Table 4, Figure 6). For mixed forests, there were no data on hydraulic conductivity at the young stage, while most studies occurred in the stands of the mature age (Figure 6). In the case of needle-leaved forests, the order of the mean values of hydraulic conductivity recorded was: mature > old > young, differing from that under broad-leaved forests: young > old > mature. However, the number of studies in the mature and old stages of needle-leaved forests was extremely low and therefore did not allow any statistical comparison.

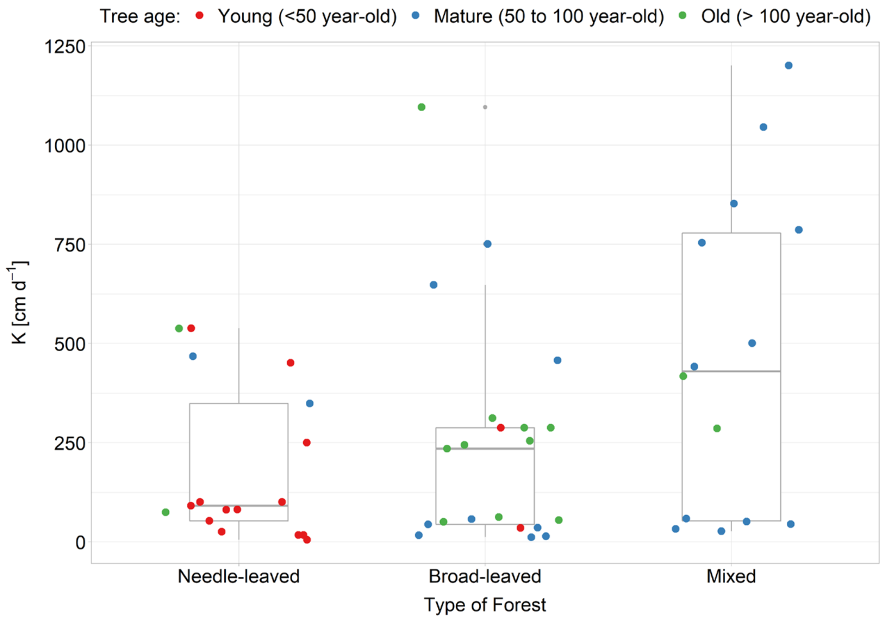

Figure 6. Descriptive statistics of top mineral soil hydraulic conductivity for dataset B in relation to tree age and forest type. Scattered points represent the individual values classified by the different forest stages considered in this study. Values correspond to the 0–30 cm soil depth. Grey points represent the outliers.

Figure 7 and Table 5 describe the statistical distribution for dataset B with regard to the saturated hydraulic conductivity in relation to forest type and soil texture. Most of the reviewed studies with information on soil texture were conducted in broad-leaved forests and study sites were dominated by a coarse soil texture.

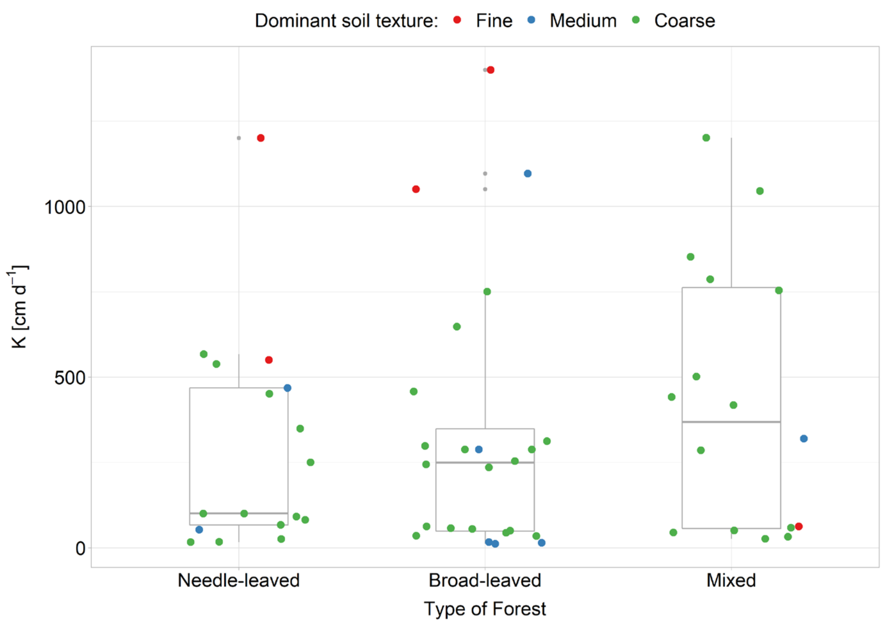

Figure 7. Descriptive statistics for dataset B top mineral soil hydraulic conductivity in terms of forest type and soil texture: fine (clay-dominated), medium (mostly loamy), and coarse (mostly sandy). Grey points represent the outliers.

Under needle-leaved and broad-leaved forests, the order of magnitude of hydraulic conductivity was comparable between the coarse and medium soil textures, whereas soil dominated by fine texture presented higher values (Table 5). It has to be noted that the number of studies carried out in all forest types with regard to hydraulic conductivity in stands with fine-textured soils was very low.

4. Discussion

Our literature review revealed that with respect to water retention characteristics of soils under forests, only limited information is available, with fewer than 20 studies reporting values (Table 2). Thus, the reported information does not allow any conclusion on the influence of tree species and age on water retention characteristics (which are part of SHP) for different site conditions (i.e., soil texture, tree species). Moreover, the reported studies differ in the applied methodology and experimental design, which allows only limited comparability among the studies. Dedicated studies such as Wahren et al. [17] and Julich et al. [16] indicate that for sites influenced by stagnant soil water conditions, differences in SHP for stands of different tree types and age can be expected. However, the transferability of those findings needs to be tested by more experiments on sites with different site conditions.

With respect to bulk density as an important indicator of soil structure, more information in the screened literature is available (Tables 1, 3, 4 and 5). Bulk density varies together with the changes in forest structure. Bakhshandeh-Navroud et al. [51] observed a soil bulk density of 1.33 g cm^{-3} in a broad-leaved monoculture, whereas a higher value was observed when eight different broad-leaved tree species were mixed (1.48 g cm^{-3}). Jost et al. [37] found a higher soil bulk density in a broad-leaved forest in contrast to a needle-leaved forest (1.13 vs. 0.97 g cm^{-3}). Błońska et al. [33] observed higher values in a broad-leaved forest (range: 0.35–0.81 g cm^{-3}) compared to needle-leaved stands (range: 0.21–0.28 g cm^{-3}), and in a mixed forest (0.36 g cm^{-3}); however, it has to be considered that in this study, the organic layer instead of the top mineral layer was sampled. This emphasizes the need for a clear description of the sampled depth and horizon. Moragues-Saitua et al. [52] reported a higher bulk density under needle-leaved forests (1.06 g cm^{-3}) and in broad-leaved forests (0.67 g cm^{-3}) in contrast to the beforementioned studies. The results of the presented literature review suggest an effect of forest type (tree species) on soil bulk density (Table 3a, p-value < 0.05). Moreover, it is not only soil texture that has been described in the literature as a factor that might explain variations in soil bulk density but tree age as well. Polláková et al. [53] observed that bulk density was higher (1.15 and 1.01 g cm^{-3}) in mature needle-leaved forests with comparable characteristics (110 years old, sandy soil), in contrast to old forests. Furthermore, they noticed that bulk density was higher in a silty soil young forest (50 years old, 1.31 g cm^{-3}). Rosenkranz et al. [54] reported that a 100-year-old mature needle-leaved forest presented a soil bulk density of 0.82 g cm^{-3}, but when mixed with a three-year-old broad-leaved tree species, it was reduced to 0.64 g cm^{-3}. Baldocchi et al. [43] found that soil bulk density was 1.05 g cm^{-3} in a 250-year-old needle-leaved forest with sandy soil, while Link et al. [55] reported lower values (0.8 g cm^{-3}) in an older forest (450 years old) containing needle-leaved tree species. Frêne et al. [29] observed a higher bulk density in a 110-year-old needle-leaved forest in contrast to an old (350/400 years old) mixed forest (0.77 vs. 0.44 g cm^{-3}, respectively); however, information on soil texture was not provided.

Regarding soil hydraulic conductivity, our literature review suggests that there is no apparent effect of forest type on soil hydraulic conductivity (Table 3). However, there are studies concluding that this parameter not only varies in terms of tree species, but also that site characteristics play a relevant role. Bauwe et al. [22] reported lower infiltration capacity under needle-leaved stands (349 cm d^{-1}) in contrast to broad-leaved forests (both with mature tree stands). Bens et al. [21] observed the highest hydraulic conductivity in mixed forests (76-year-old pine with 34-year-old beech) with 1045 cm d^{-1}, whereas needle-leaved and broad-leaved forests presented 57% and 38% lower infiltration rates, respectively. Similarly, Wahl et al. [7,8] reported the highest infiltration rates in mixed forests and the lowest in needle-leaved forests, both presenting comparable sandy soil. Julich et al. [16] reported a higher amount of well-connected macropores for a 170-year-old broad-leaved forest, and higher infiltration capacities, in contrast to a young 25-year-old needle-leaved forest, probably influenced by their deep-developed rooting system. Moreover, Frey et al. [56] found higher hydraulic conductivity in a mixed forest with loamy soil (320 cm d^{-1}) in contrast to a mixed forest with loamy soil but containing a much higher clay content (63 cm d^{-1}).

As reported by these authors, soil hydraulic conductivity is sensitive to other soil properties; still, many authors describe this parameter under varying conditions. For instance, Archer et al. [20] considered a wide range of parameters to assess the water infiltration rates such as the soil particle size, tree ages, and measurements at different depths. However, results were not able to be derived on the influence of such parameters since all forests differed in age and soil texture. They considered two mature stages (160/180 years old) and one old (500 years old) stage with broad-leaved stands and a young stage (~50 years old) with needle-leaved tree species. The sites differed in soil texture. In young needle-leaved forests the range was 82–101 cm d^{-1} (mean 90.9 cm d^{-1}), in mature broad-leaved sites the ranges were 12–17 cm d^{-1} (mean 14.3 cm d^{-1}) and 245–312 cm d^{-1} (mean 280.2 cm d^{-1}), and the range in the old broad-leaved site was 235–288 cm d^{-1} (mean: 258.3 cm d^{-1}). Similarly, Bens et al. [21] and Wahl et al. [7,8] reported higher values (648, 458, and 751 cm d^{-1}, respectively, by author) in broad-leaved forests in contrast to needle-leaved stands (451, 251, and 538 cm d^{-1}, respectively, by author). However, the study considered a young (<40 years old) needle-leaved and a mature (91 years old) broad-leaved forest, which also differed in terms of soil texture.

5. Conclusions

The various soils under forests present an extensive assortment of site conditions: i.e., soil texture, porosity, biotic activity (in particular that of the meso- and macrofauna), amount and vertical distribution of soil organic matter, and tree species and ages, among many others. Nevertheless, in our literature review we found considerable limitations in assessing the effect of forest type on soil hydraulic properties, which led us to the following conclusions:

- We found hardly any articles addressing SHP and describing an appropriate number of site parameters simultaneously in the reviewed studies, which made it difficult to determine the impact of forest type and age on soil hydraulic properties.
- The main purpose of many of the screened articles was not specifically to assess the SHP, which were measured as additional information; possibly one of the reasons why many parameters of interest for our analysis were poorly detailed.
- The great variability in results in the reviewed studies underlines the belief that SHP can be sensitive to a wide range of site parameters. Due to an incomplete description of the study site's conditions and differences in methodologies applied for each author (different measuring devices, diversity of sampling design, and inappropriate comparisons), there is not enough evidence to draw sophisticated conclusions in terms of the influence of specific forest characteristics (type and age) on SHP.
- Due to the large gap of knowledge in the literature and the abovementioned arguments, we were neither able to accept nor reject our hypothesis.

We suggest that the effect of forest type on soil water dynamics should be assessed based on studies with comparable site parameters to avoid overlooking the high sensitivity of SHP. For this reason, a much higher number of systematic studies following standardised methods is clearly needed. Such studies should include a minimum of information on tree age, mixture rate, depth of measurement, and soil texture in order to make future studies comparable and to create an understanding of the influence of forest type and forest structure on SHP under different site conditions.

Author Contributions: Conceptualisation S.J. and V.V.-R.; literature review, data analysis and writing-original draft preparation V.V.-R.; writing-review and editing S.J. and K.-H.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the scholarship programme of the Graduate Academy for the Promotion of Early-Career Female Scientists at the TU Dresden.

Data Availability Statement: The author, upon request, can provide information regarding the reviewed papers.

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

References

1. Allen, C.D.; Breshears, D.D.; McDowell, N.G. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere* **2015**, *6*, 129. https://doi.org/10.1890/ES15-00203.1.
2. Allen, C.D.; Macalady, A.K.; Chenchouni, H.; Bachelet, D.; McDowell, N.; Vennetier, M.; Kitzberger, T.; Rigling, A.; Breshears, D.D.; Hogg, E.H.; et al. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *For. Ecol. Manag.* **2010**, *259*, 660–684. https://doi.org/10.1016/j.foreco.2009.09.001.
3. European Commission, Eurostat. Forestry in the EU and the World: A Statistical Portrait 2011. Available online: https://data.europa.eu/doi/10.2785/13022 (accessed on 20 October 2021).
4. Lindner, M.; Maroschek, M.; Netherer, S.; Kremer, A.; Barbati, A.; Garcia-Gonzalo, J.; Seidl, R.; Delzon, S.; Corona, P.; Kolström, M.; et al. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *For. Ecol. Manag.* **2010**, *259*, 698–709. https://doi.org/10.1016/j.foreco.2009.09.023.
5. Pretzsch, H.; Steckel, M.; Heym, M. Stand growth and structure of mixed-species and monospecific stands of Scot pine (*Pinus sylvestris* L.) and oak (*Q. robur* L., Quercus petraea (MATT.) LIEBL.) analysed along a productivity gradient through Europe. *Eur. J. For. Res.* **2020**, *139*, 349–367. https://doi.org/10.1007/s10342-019-01233-y.
6. Seiwa, K.; Kunii, D.; Masaka, K.; Hayashi, S.; Tada, C. Hardwood mixture enhances soil water infiltration in a conifer plantation. *For. Ecol. Manag.* **2021**, *498*, 119508. https://doi.org/10.1016/j.foreco.2021.119508.
7. Wahl, N.A.; Bens, O.; Schäfer, B.; Hüttl, R.F. Impact of changes in land-use management on soil hydraulic properties: Hydraulic conductivity, water repellency and water retention. *Phys. Chem. Earth* **2003**, *28*, 1377–1387. https://doi.org/10.1016/j.pce.2003.09.012.
8. Wahl, N.A.; Wöllecke, B.; Bens, O.; Hüttl, R.F. Can forest transformation help reducing floods in forested watersheds? Certain aspects on soil hydraulics and organic matter properties. *Phys. Chem. Earth* **2005**, *30*, 611–621. https://doi.org/10.1016/j.pce.2005.07.013.
9. Tor-Ngern, P.; Oishi, A.C.; Uebelherr, J.M.; Palmroth, S.; Tarvainen, L.; Ottoson-Löfvenius, M.; Linder, S.; Domec, J.C.; Näsholm, T. Ecophysiological variation of transpiration of pine forests: Synthesis of new and published results. *Ecol. Appl.* **2017**, *27*, 118–133. Available online: http://www.jstor.org/stable/44132586 (accessed on 11 October 2021).
10. Meusburger, K.; Trotsiuk, V.; Schmidt-Walter, P.; Baltensweiler, A.; Brun, P.; Bernhard, F.; Gharun, M.; Habel, R.; Hagedorn, F.; Köchli, R.; et al. Soil-plant interactions modulated water availability of Swiss forests during the 2015 and 2018 droughts. *Glob. Chang. Biol.* **2022**, *28*, 5928–5944. https://doi.org/10.1111/gcb.16332.
11. Schmidt-Walter, P.; Trotsiuk, V.; Meusburger, K.; Zacios, M.; Meesenburg, H. Advancing simulations of water fluxes, soil moisture and drought stress by using the LWF-Brook90 hydrological model in R. *Agric. For. Meteorol.* **2020**, *291*, 108023. https://doi.org/10.1016/j.agrformet.2020.108023.
12. Assouline, S.; Or, D. Conceptual and parametric representation of soil hydraulic properties: A review. *Vadose Zone J.* **2013**, *12*, 1–20. https://doi.org/10.2136/vzj2013.07.0121.
13. Weninger, T.; Bodner, G.; Kreiselmeier, J.; Chandrasekhar, P.; Julich, S.; Feger, K.-H.; Schwärzel, K.; Schwen, A. Combination of measurement methods for a wide range description of hydraulic soil properties. *Water* **2018**, *10*, 1021 https://doi.org/10.3390/w10081021.
14. Archer, N.A.L.; Otten, W.; Schmidt, S.; Bengough, A.G.; Shah, N.; Bonell, M. Rainfall infiltration and soil hydrological characteristics below ancient forest, planted Forest and Grassland in a Temperate Northern Climate. *Ecohydrology* **2016**, *9*, 585–600. https://doi.org/10.1002/eco.1658.
15. Chandler, K.R.; Stevens, C.J.; Binley, A.; Keith, A.M. Influence of tree species and forest land use on soil hydraulic conductivity and implications for surface runoff generation. *Geoderma* **2018**, *310*, 120–127. https://doi.org/10.1016/j.geoderma.2017.08.011.
16. Julich, S.; Kreiselmeier, J.; Scheibler, S.; Petzold, R.; Schwärzel, K.; Feger, K.H. Hydraulic properties of forest soils with stagnic conditions. *Forests* **2021**, *12*, 1113. https://doi.org/10.3390/f12081113.
17. Wahren, A.; Schwärzel, K.; Feger, K.H. Potentials and limitations of natural flood retention by forested land in headwater catchments: Evidence from experimental and model studies. *J. Flood Risk Manag.* **2012**, *5*, 321–335. https://doi.org/10.1111/j.1753-318X.2012.01152.x.
18. Liu, Y. A numerical study on hydrological impacts of forest restoration in the southern United States. *Ecohydrology* **2011**, *4*, 299–314. https://doi.org/10.1002/eco.178.
19. Bogunovic, I.; Viduka, A.; Magdic, I.; Telak, L.J.; Francos, M.; Pereira, P. Agricultural and forest land-use impact on soil properties in Zagreb periurban area (Croatia). *Agronomy* **2020**, *10*, 1331. https://doi.org/10.3390/agronomy10091331.

20. Archer, N.A.L.; Bonell, M.; MacDonald, A.M.; Coles, N. A Constant Head Well Permeameter Formula Comparison: Its Significance in the Estimation of Field-Saturated Hydraulic Conductivity in Heterogeneous Shallow Soils. *Hydrol. Res.* **2014**, *45*, 788–805. https://doi.org/10.2166/nh.2014.159.
21. Bens, O.; Wahl, N.A.; Fischer, H.; Hüttl, R.F. Water infiltration and hydraulic conductivity in sandy cambisols: Impacts of forest transformation on soil hydrological properties. *Eur. J. For. Res.* **2007**, *126*, 101–109. https://doi.org/10.1007/s10342-006-0133-7.
22. Bauwe, A.; Koch, M.; Kallweit, R.; Konopatzky, A.; Strohbach, B.; Lennartz, B. Tree-ring growth response of Scots pine (*Pinus sylvestris* L.) to climate and soil water availability in the lowlands of north-eastern Germany. *Balt. For.* **2013**, *19*, 212–225. Available online: https://www.researchgate.net/publication/260435722 (accessed on 20 October 2021).
23. Gebauer, T.; Horna, V.; Leuschner, C. Canopy transpiration of pure and mixed forest stands with variable abundance of European beech. *J. Hydrol.* **2012**, *442–443*, 2–14. https://doi.org/10.1016/j.jhydrol.2012.03.009.
24. Meinzer, F.C.; Woodruff, D.R.; Eissenstat, D.M.; Lin, H.S.; Adams, T.S.; McCulloh, K.A. Above- and belowground controls on water use by trees of different wood types in an eastern US deciduous forest. *Tree Physiol.* **2013**, *33*, 345–356. https://doi.org/10.1093/treephys/tpt012.
25. Aranda, I.; Forner, A.; Cuesta, B.; Valladares, F. Species-Specific Water Use by Forest Tree Species: From the Tree to the Stand. *Agric. Water Manag.* **2012**, *114*, 67–77. https://doi.org/10.1016/j.agwat.2012.06.024.
26. Knutzen, F.; Meier, I.C.; Leuschner, C. Does reduced precipitation trigger physiological and morphological drought adaptations in European beech (*Fagus sylvatica* L.)? Comparing provenances across a precipitation gradient. *Tree Physiol.* **2015**, *35*, 949–963. https://doi.org/10.1093/treephys/tpv057.
27. Wang, Y.; Dong, X.; Wang, H.; Wang, Z.; Gu, J. Root trip morphology, anatomy, chemistry and potential hydraulic conductivity vary with soil depth in three temperate hardwood species. *Tree Physiol.* **2015**, *36*, 99–108. https://doi.org/10.1093/treephys/tpv094.
28. Christiansen, J.; Vesterdal, L.; Callesen, I.; Elberling, B.; Schmidt, I.K.; Gundersen, P. Role of six European tree species and land-use legacy for nitrogen and water budgets in forests. *Glob. Chang. Biol.* **2010**, *16*, 2224–2240. https://doi.org/10.1111/j.1365-2486.2009.02076.x.
29. Frêne, C.; Dörner, J.; Zúñiga, F.; Cuevas, J.G.; Alfaro, F.D.; Armesto, J.J. Eco-hydrological functions in forested catchments of Southern Chile. *Ecosystems* **2020**, *23*, 307–323. https://doi.org/10.1007/s10021-019-00404-7.
30. Hansson, K.; Olsson, B.A.; Olsson, M.; Johansson, U.; Kleja, D.B. Differences in soil properties in adjacent stands of Scots pine, Norway spruce and Silver birch in SW Sweden. *For. Ecol. Manag.* **2011**, *262*, 522–530. https://doi.org/10.1016/j.foreco.2011.04.021.
31. Norman, J.S.; Barrett, J.E. Substrate and nutrient limitation of ammonia-oxidizing bacteria and archaea in temperate forest soil. *Soil Biol. Biochem.* **2014**, *69*, 141–146. https://doi.org/10.1016/j.soilbio.2013.11.003.
32. Schiff, S.L.; Devito, K.J.; Elgood, R.J.; McCrindle, P.M.; Spoelstra, J.; Dillon, P. Two adjacent forested catchments: Dramatically different NO_3^- export. *Water Resour. Res.* **2002**, *38*, 28-1–28-13. https://doi.org/10.1029/2000WR000170.
33. Błońska, E.; Klamerus-Iwan, A.; Lasota, J.; Gruba, P.; Pach, M.; Pretzsch, H. What characteristics of soil fertility can improve in mixed stands of Scots pine and European beech compared with monospecific stands? *Commun. Soil Sci. Plant Anal.* **2018**, *49*, 237–247. https://doi.org/10.1080/00103624.2017.1421658.
34. Kopler, I.; Burg, D.; Wittenberg, L.; Malkinson, D. Differences in soil moisture in two middle eastern oak forests: Comparing the effects of trees and soil composition. *Hydrol. Process.* **2019**, *33*, 86–100. https://doi.org/10.1002/hyp.13313.
35. Maes, S.L.; Blondeel, H.; Perring, M.P.; Depauw, L.; Brümelis, G.; Brunet, J.; Decocq, G.; den Ouden, J.; Härdtle, W.; Hédl, R.; et al. Litter quality, land-use history, and nitrogen deposition effects on topsoil conditions across European temperate deciduous forests. *For. Ecol. Manag.* **2019**, *433*, 405–418. https://doi.org/10.1016/j.foreco.2018.10.056.
36. Farahnak, M.; Mitsuyasu, K.; Jeong, S.; Otsuki, K.; Chiwa, M.; Sadeghi, S.M.M.; Kume, A. Soil hydraulic conductivity differences between upslope and downslope of two coniferous trees on a hillslope. *J. For. Res.* **2019**, *3*, 143–152. https://doi.org/10.1080/13416979.2019.1590967.
37. Jost, G.; Schume, H.; Hager, H.; Markart, G.; Kohl, B. A hillslope scale comparison of tree species influence on soil moisture dynamics and runoff processes during intense rainfall. *J. Hydrol.* **2012**, *420–421*, 112–124. https://doi.org/10.1016/j.jhydrol.2011.11.057.
38. Lange, B.; Germann, P.F.; Lüscher, P. Greater abundance of Fagus sylvatica in coniferous flood protection forests due to climate change: Impact of modified root densities on infiltration. *Eur. J. For. Res.* **2013**, *132*, 151–163. https://doi.org/10.1007/s10342-012-0664-z.
39. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; The Prisma Group. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Int. J. Surg.* **2010**, *8*, 336–341. https://doi.org/10.1016/j.ijsu.2010.02.007.
40. Bittner, S.; Talkner, U.; Krämer, I. Modeling stand water budgets of mixed temperate broad-leaved forest stands by considering variations in species specific drought response. *Agric. For. Meteorol.* **2010**, *150*, 1347–1357. https://doi.org/10.1016/j.agrformet.2010.06.006.
41. Grant, R.F.; Zhang, Y.; Yuan, F.; Wang, S.; Hanson, P.J.; Gaumont-Guay, D.; Chen, J.; Black, T.A.; Barr, A.; Baldocchi, D.D.; et al. Intercomparison of techniques to model water stress effects on CO_2 and energy exchange in temperate and boreal deciduous forests. *Ecol. Model.* **2006**, *196*, 289–312. https://doi.org/10.1016/j.ecolmodel.2006.02.035.

42. Metzger, J.C.; Wutzler, T.; Valle, N.D.; Filipzik, J.; Grauer, C.; Lehmann, R.; Roggenbuck, M.; Schelhorn, D.; Weckmüller, J.; Küsel, K.; et al. Vegetation impacts soil water content patterns by shaping canopy water fluxes and soil properties. *Hydrol. Process.* **2017**, *31*, 3783–3795. https://doi.org/10.1002/hyp.11274.
43. Baldocchi, D.D.; Law, B.E.; Anthoni, P.M. On measuring and modeling energy fluxes above the floor of a homogeneous and heterogeneous conifer forest. *Agric. For. Meteorol.* **2000**, *102*, 187–206. https://doi.org/10.1016/S0168-1923(00)00098-8.
44. Dusek, J.; Vogel, T. Hillslope hydrograph separation: The effects of variable isotopic signatures and hydrodynamic mixing in macroporous soil. *J. Hydrol.* **2018**, *563*, 446–459. https://doi.org/10.1016/j.jhydrol.2018.05.054.
45. Almahayni, T.; Houska, T. Towards dynamic and process–based modelling of radionuclides cycling in terrestrial radioecology. *J. Environ. Radioact.* **2020**, *225*, 106380. https://doi.org/10.1016/j.jenvrad.2020.106380.
46. Duarte, H.F.; Raczka, B.M.; Ricciuto, D.M.; Lin, J.C.; Koven, C.D.; Thornton, P.E.; Bowling, D.R.; Lai, C.; Bible, K.J.; Ehleringer, J.R. Evaluating the Community Land Model (CLM4.5) at a coniferous forest site in northwestern United States using flux and carbon-isotope measurements. *Biogeosciences* **2017**, *14*, 4315–4340. https://doi.org/10.5194/bg-14-4315-2017.
47. Kirchen, G.; Calvaruso, C.; Granier, A.; Redon, P.O.; Van der Heijden, G.; Bréda, N.; Turpault, M.P. Local soil type variability controls the water budget and stand productivity in a beech forest. *For. Ecol. Manag.* **2017**, *390*, 89–103. https://doi.org/10.1016/j.foreco.2016.12.024.
48. Leuschner, C. Water extraction by tree fine roots in the forest floor of a temperate Fagus-Quercus forest. *Ann. For. Sci.* **1998**, *55*, 141–157. https://doi.org/10.1051/forest:19980109.
49. Curiel, J.; Janssens, I.A.; Carrara, A.; Ceulemans, R. Annual Q_{10} of soil respiration reflects plant phenological patterns as well as temperature sensitivity. *Glob. Chang. Biol.* **2004**, *10*, 161–169. https://doi.org/10.1111/j.1529-8817.2003.00727.x.
50. Schwärzel, K.; Menzer, A.; Clausnitzer, F. Soil water content measurements deliver reliable estimates of water fluxes: A comparative study in a beech and a spruce stand in the Tharandt forest (Saxony, Germany). *Agric. For. Meteorol.* **2009**, *149*, 1994–2006. https://doi.org/10.1016/j.agrformet.2009.07.006.
51. Bakhshandeh-Navroud, B.; Abrari, V.K.; Pilehvar, B.; Kooch, Y. The interactions between tree-herb layer diversity and soil properties in the oriental beech (Fagus Orientalis Lipsky) stands in Hyrcanian forest. *Environ. Monit. Assess.* **2018**, *190*, 425. https://doi.org/10.1007/s10661-018-6809-x.
52. Moragues-Saitua, L.; Arias-González, A.; Gartzia-Bengoetxea, N. Effects of biochar and wood ash on soil hydraulic properties: A field experiment involving contrasting temperate soils. *Geoderma* **2017**, *305*, 144–152. https://doi.org/10.1016/j.geoderma.2017.05.041.
53. Polláková, N.; Šimanský, V.; Jonczak, J. Characteristics of physical properties in soil profiles under selected introduced trees in the nature reserve Arboretum Mlyňany, Slovakia. *Folia Oecologica* **2017**, *44*, 78–86. https://doi.org/10.1515/foecol-2017-0010.
54. Rosenkranz, P.; Dannenmann, M.; Brüggemann, N.; Papen, H.; Berger, U.; Zumbusch, E.; Butterbach-Bahl, K. Gross rates of ammonification and nitrification at a nitrogen-saturated Spruce (*Picea abies* (L.) Karst.) stand in southern Germany. *Eur. J. Soil Sci.* **2010**, *61*, 745–758. https://doi.org/10.1111/j.1365-2389.2010.01274.x.
55. Link, T.E.; Flerchinger, G.N.; Unsworth, M.; Marks, D. Simulation of water and energy fluxes in an old-growth seasonal temperate rain forest using the simultaneous heat and water (SHAW) model. *J. Hydrometeorol.* **2004**, *5*, 443–457. https://doi.org/10.1175/1525-7541(2004)005<0443:SOWAEF>2.0.CO;2.
56. Frey, B.; Niklaus, P.A.; Kremer, J.; Lüscher, P.; Zimmermann, S. Heavy-machinery traffic impacts methane emissions as well as methanogen abundance and community structure in oxic forest soils. *Appl. Environ. Microbiol.* **2011**, *77*, 6060–6068. https://doi.org/10.1128/AEM.05206-11.