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ORIGINAL PAPER

Tree species and management controls on the water storage in forest soil and underlying slope deposits revealed by electrical resistivity tomography

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Abstract

Water is a critical factor in forest production and its sustainable development. In addition, it contributes to the stability of forest ecosystems, essential for the growth and development of individual trees and stands. Electrical resistivity tomography (ERT) is the ideal method for detecting soil moisture among currently available methods. The advantages over other methods are mainly in the non-destructiveness of the measurement, i.e. it does not disturb the soil body. In this work, we deal with the influence of forest management on the dynamics of soil moisture and soil water storage. The measurements were carried out in the core zone of the Dobroč primaeval forest (plots Dobroč 1, Dobroč 2, Dobroč 3), in the buffer zone of the Dobroč primaeval forest with a predominance of European beech (Beech forest) and in the spruce monoculture near the buffer zone (Spruce forest). Measurements were made using ERT using the time-lapse method, while the detected soil resistance was calibrated to soil moisture. To calibrate the spatial variability of moisture, we used the time domain reflectometry (TDR) method to determine the volumetric soil water content. By calibrating between TDR and ERT using calibration equations, we determined the quantity of retained soil water within the measured profile. The results showed that the lowest soil water storage was on the spruce stand plot (53.31 ±9.55 dm^3 m^{-3}). On the contrary, the highest soil water storage was found on the Dobroč 2 plot (133.14 ±5.37 dm^3 m^{-3}). The decrease in soil water storage was the highest in the managed spruce forest. According to the amount of retained soil water, it appears to be the most resistant forest ecosystem of the Dobroč primaeval forest. The trend of soil water storage was more balanced in these ecosystems during the growing season than in areas outside the primaeval forest. Average soil water storage also reached higher values in these plots. The knowledge gained from the study can inform decisions about forest management in Slovakia and contribute to both the mitigation of climate change effects and the adaptation of forests, ensuring that the hydrological functions of forest ecosystems are maintained.

Key words: soil water storage; slope deposits; Norway spruce; European beech; water movement; water uptake

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1. Introduction

Knowledge of the regulation of the water balance of forest ecosystems is currently a high-priority goal of forestry to ensure multifunctionality and climate resistance of the landscape ecosystems (Schwaiger et al. 2018; Jourdan et al. 2020). In addition, the consequences associated with human activities and natural disturbances can have large-scale and long-term impacts on hydrological, landscape and forest ecosystem processes (Ebel & Mirus 2014). Most opinions based on long-term research assume that forests generally tend to reduce the watershed runoff. As a result of evapotranspiration, on the one hand, forests create soil moisture deficits (Lehnardt 1985; Hegg et al. 2004), but on the other hand, the capture and subsequent soil water retention in forest ecosystems is more significant than other areas, where severe storm events occur to the formation of flash floods (Peck & Mayer 1996). Most countries have already invested resources in research on climate change adaptation, including its effects on forests and interactions with water. Nevertheless, many countries still need links between research results and effective forestry policies, which is a topic that needs to be addressed urgently (Nita & Clinciu 2017).

Water availability is becoming a significant factor limiting humanity's ability to satisfy future global food and energy needs (D'Odorico et al. 2018), and water is expected to become an even more strategic resource.

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Human demands for water, energy, and food are projected to increase by 30–50 per cent, with the world facing a 40 per cent global water deficit by 2030 under climate scenarios (The 2030 Water Resources Group 2009; WWAP 2015).

Plant physiological processes are susceptible indicators of stress in extreme environmental conditions. Drought affects plant growth by reducing the water potential in cells, which leads to the subsequent inhibition of cell growth and other negative impacts, up to the inhibition of photosynthesis (Centritto et al. 2011). In mild to moderate drought, stomatal closure is the first response to drought (Cornic 2000; Lawlor & Cornic 2002), while small reductions in soil water availability lead to stomatal closure and osmotic adjustment (Brestič 2002). Centritto et al. (1999) reported that stomatal responses are more closely related to soil moisture content and air humidity than to leaf water status. Kurjak et al. (2012) found that the stems of mature Norway spruce trees function as a water reservoir during shorter periods of drought. The closing of the stomata was controlled by atmospheric conditions, namely by vapour pressure deficit of the air, and not by leaf water potential, which testifies to the adequate protection of spruce during drought. Based on a computer simulation, Hlásny et al. (2011) found that spruce and beech growth in their upper distribution ranges will probably grow while drought-induced production declines at the species' receding edges. At the same time, they determined that beech production seems uncertain and may decrease, while spruce production is likely to increase.

They reduced the diameter of fine roots by adapting the root system of trees to reduce the amount of water in the soil. Several studies (e.g., Bolte & Villanueva 2006; Ostonen et al. 2011; Zang et al. 2011) have investigated the water acquisition strategy, finding that forming thinner and longer fine roots is standard. However, this will remove only moderate land acquisition. Zang et al. (2014a) and Zang et al. (2014b) found that if the soil continues to dry, beech saplings will slow down their satisfactory root growth, and their biomass will decrease due to their mortality. Better acclimatisation of the root system is facilitated by slow drying of the soil rather than short and intense periods of drought (Zang et al. 2021). At the same time, they found that the acclimatisation of the fine roots of saplings is better in the most profound depression of adult trees. Shallow soils and greater competition limit the limitations and conditioning of root systems under conditions of reduced water availability. Montagnoli et al. (2014) found that fine root growth was driven by water and vegetable content, with apparent growth optimum. In a container experiment, Štraus et al. (2014) found that higher soil temperature resulted in higher root biomass, specific root area, and tip density. Mainiero & Kazda (2006) demonstrated that temperature is directly related to root formation, while soil moisture affects root growth to a lesser extent. Železnik et al. (2015) determined that subcanopy precipitation, maximum evapotranspiration, and soil temperatures were significant factors in fine root growth and mortality. Meier et al. (2018) concluded that a persistent decrease in water supply leads to only a tiny adaptive adjustment in the size and structure of the beech root system with a significant change in the depth distribution of some root thickness classes.

The interaction between forest management and its impact on soil water retention is one of the most critical factors of forest ecosystem services. Some works have analysed and compared forest ecosystems and their water-holding capacity using the water balance method with significant results (Zhang et al. 2008; Ma et al. 2017; Zhai et al. 2019). A recent study (Carrière et al. 2020) demonstrated the use of electrical resistivity tomography (ERT) monitoring to detect spatial changes in soil conditions and clarify the relationship of these soil changes with variability in the response of trees to drought. For this purpose, in addition to ERT monitoring, measurements of the water level in the leaves were also collected. The study demonstrated a significant correlation between the percentage change in resistivity (between dry and wet conditions) and biological variables as a functional measure of drought intensity. Similarly, Fäth et al. (2022) used the ERT method in forest ecosystems to monitor soil moisture in space and calibrated it with the time-domain reflectometry (TDR) method.

Previous studies have also demonstrated the use of ERT to assess moisture dynamics in soils with higher soil skeleton content in Mediterranean southern France. ERT showed that plants extracted water from a depth of up to 6 m because the roots penetrate deep into the soil between stones and even into subsoil cracks (Nijland et al. 2010). Also, in this study, they concluded that ERT provides crucial information about soil moisture processes, which is not available using any other currently available measurement method. Monitoring of soil moisture dynamics using ERT on slopes was also dealt with by Hübner et al. (2015). They describe ERT as monitoring soil moisture during the growing season. They found that soil moisture at a depth below 1.5 m is not correlated with torrential rainfall during the summer season, and at the same time, runoff does not form at this depth. On the other hand, soil moisture at a depth below 1.5 m is saturated during the winter period, when incoming water balance components prevail over outgoing ones. In winter, runoff also occurs. In that research, it was found that ERT enables detailed spatial measurement of soil moisture estimates resulting from precipitation and evapotranspiration, so it is particularly suitable for inaccessible soils and detailed spatial analyses where methods based on point measurements with probes or soil sampling lag (de Jong et al. 2020).

In this study, we focus on evaluating the impact of forest management on the water balance dynamics. Our working hypothesis was that tree species composition and forest management affect water storage and its temporal changes in the soil and deep slope deposit layers, also known as cover beds. Due to technical and methodological difficulties, soil hydrology research must often address the latter formations. However, assessing the effect of forests on water storage in deep layers becomes crucial due to limited water availability in shallow layers, which is common in changing climates. We also assumed that water storage would reach maxima and minima at different times in distinct soil and slope deposit layers. The electrical resistivity tomography would capture delays in deeper layers as a non-destructive, high-resolution method.

2. Materials and method

2.1. Site and stand description

The research area was in the Veporské Vrchy mountain range. The geological base consists mainly of compressed granodiorites, schistose granites, and siliceous diorites. The location is humid, with average annual precipitation of 890–960 mm, with rainfall of 515–600 mm in the growing season. The average yearly temperature ranges from 4.5–5.1 °C, which means that the area is humid and relatively cool (Faško & Šťastný 2002; Šťastný et al. 2002). The soil cover consists mainly of Dystric Cambisol according to the WRB classification (2022) with a sandy-loam texture (Fig. 1). The areas in the Spruce Forest and the Beech Forest are undergoing research and were selected within the network of the international project H2020.

Dobroč primaeval forest – core zone

The lowest point of the primaeval forest is 720 m a.s.l. and the highest 1,000 m a.s.l. The territory is dominated by slopes with western and north-western exposure and a slope of 10–20° (Parobeková et al. 2016). In the case of the Dobroč primaeval forest is a multi-storey growth with approximately 200 years and a woody composition on the first floor according to national inventory (https://gis.nlcsk.org/ 2023) mainly of Silver fir (*Abies alba* Mill. – 40%), European beech (*Fagus sylvatica* L. – 30%), Norway spruce (*Picea abies* [L.] H. Karst. – 25%), and Sycamore (*Acer pseudoplatanus* L. – 5%). There were

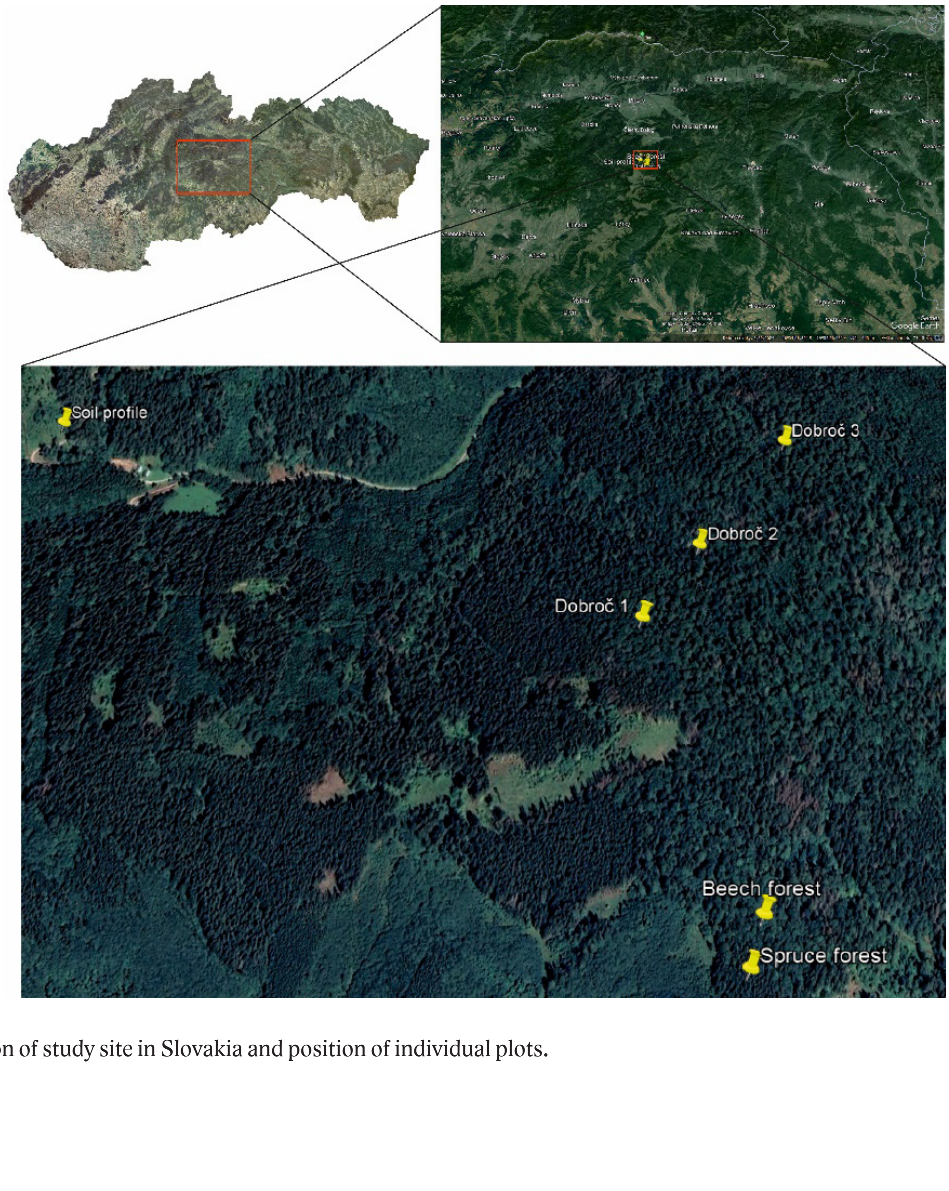

Fig. 1. Location of study site in Slovakia and position of individual plots.

selected three research plots. The first represented the optimum stage (Korpeľ 1989) in the development cycle of the primaeval forest (Dobroč 1 – loamy and sandy-loam soil texture), and the second plot represented the disintegration stage (Dobroč 2 – loamy and sandy-loam soil texture). The third area (Dobroč 3 – loamy and sandy-loam soil texture) represented the ingrowth stage with a high density of dead wood on the soil surface (Fig. 2a).

Spruce forest
These plots represent a managed forest consisting of a Norway spruce monoculture (*Picea abies* [L.] H. Karst. – 100%) aged 70 years. It is located at an altitude of approximately 960 m a.s.l., the area of the stand is 2.45 ha, and the stand density is 0.8. In the Spruce forest, the basal area was 60 m^2 ha^{-1}, aboveground biomass 361 t ha^{-1}, and root biomass in the upper 50 cm 12.3 t ha^{-1}. Granodiorites represent the geological substrate, and the soil type on the plot is Dystric Cambisol, which has a loamy and sandy-loam soil texture. The Beech and Spruce plots are only approximately 100 m apart (Fig. 2b).

Beech forest
On these plots, the geological substrate is also granodiorite, and the soil type is Dystric Cambisol with sandy-loam soil texture. It is located at an altitude of approximately 970 m a.s.l., the stand area is 7.55 ha, and the stand density is 0.55. The age of the forest stand is approximately 145 years. Basal area, aboveground biomass, and root mass in the Beech forest were 48 m^2 ha^{-1}, 467 t ha^{-1}, and 13.8 t ha^{-1} in the upper 50 cm, respectively. In the tree composition, predominate European beech (*Fagus sylvatica* L. – 45%), European ash (*Fraxinus excelsior* L. – 10%) and Sycamore (*Acer pseudoplatanus* L. – 35%) at lower extent Norway spruce (*Picea abies* [L.] H. Karst. – 10%) is also presented (Fig. 2c).

2.2. Field measurements of soil properties

Data on soil water dynamics were recorded in the field based on ERT measurements (Brunet et al. 2010), and data on soil moisture were recorded using the TDR method (Evett 2007). To evaluate the impact of forest management on soil moisture dynamics, we measured four different plots. The original forest represented the area without management practices, where forest management does not disturb the dynamics of soil moisture. The National Nature Preserves buffer zone is a locality managed by close-to-nature forest management. A managed spruce forest represents the area with forest management.

Electrical resistivity measurement
In the research plots, we measured soil electrical resistivity using the electrical resistivity tomography (ERT) method (Reynolds 2011) to monitor soil moisture changes. Monthly measurements were repeated to compare soil moisture's temporal and spatial variability. We used the ARES device (Automatic resistivity system, GF Instruments Brno, Czech Republic) to measure soil resistivity. The soil resistivity measurements took place during the vegetation period in 2021. All areas and individual ERT profiles were firmly fixed in the field, so the profiles were always identical, even during repeated measurements (time-lapse resistivity).

In the Dobroč primaeval's core zone, soil resistivity and moisture variability were measured in 3 study plots. Three parallel ERT profiles were conducted on each plot. The profiles were 78 meters long, and the distance between individual profiles was 5 m, with a unit electrode spacing of 2 m. We performed the measurements with a Wenner-Schlumberger electrode configuration.

We measured shorter transects on the research plots in the Dobroč primaeval forest – buffer zone, the managed spruce forests, and the clear-cutting. On all three plots, four parallel ERT profiles with a length of 31 m with 1 m unit electrode spacing were established. The distance between individual ERT profiles was also 5 m.

Soil water content measurement
To determine soil water storage, we measured volumetric soil water content. The volumetric water content was used to calibrate the soil resistivity, making it possible to decide the water volume over the entire study plot. The Time Domain Reflectometry – TDR method (EasyTest, Lublin, Poland) was used to measure soil water content. TDR probes were installed in two soil profiles near the investigated area approximately 5 m from the beginning and end of the uppermost ERT profile. Volumetric water content was measured at depths from 10 cm to 80 cm with 10 cm increments. Volumetric water content was measured continuously throughout the growing season with a measurement interval of 1 hour. Data on the precipitation amount was determined as throughfall directly on the measured areas, i.e. Spruce forest and Beech forest between ERT profiles 3 and 4. The amount of precipitation from the Beech forest was also used for the regions Dobroč 1–Dobroč 3.

2.3. Data processing and statistical analyses

The measured values of the electrical resistivity of the soil were evaluated in the RES2DINV program (Geotomo Software, Gelugor, Malaysia) to obtain the distribution of values of the apparent resistivity of the soil environment. The resistivity values were recalculated using the soil volume and water content calibration curve. The resistivity values for volumetric soil water content were calibrated in the STATISTICA 12 environment (StatSoft, Inc., Tulsa, USA). The resistivity values measured where the TDR probes are located were fitted to the detected soil moisture from 30 and 80-cm layers.

Two soil depths were selected, considering the sensitivity of the ERT measurement. TDR probes could not be placed in the core zone of the Dobroč primaeval forest due to natural protection. Therefore, the values for this research area were recalculated based on the calibration curve for the buffer zone. By doing so, we created data sets of the location and distribution of volumetric water content expressed as a volumetric percentage for each measured 2D transect. In our case, we focused on data from layers up to a depth of 5 meters, which we considered the depth to which the forest cover can affect soil moisture. On all studied plots, we compared data on the soil water storage at five depths with a step of 1 m, namely 1 m, 2 m, 3 m, 4 m, and 5 m.

To compare the soil water storage and dynamic, it was necessary to calculate the volume of water on the entire investigated plot for individual layers or the whole volume of soil under the ERT profiles. The calculation was made based on the number of datum points in each layer (a datum point is a point between two potential electrodes, where the resistivity of soil is measured), fitted and calculated soil moisture at individual datum points and the soil volume represented by a given datum point. The soil volume for individual datum points was calculated for a depth of up to 1 m, based on the formula for the volume of a cube, and it was necessary to consider the width of the considered soil volume. This was given by the distance of the outer ERT profiles, i.e. for areas in the core zone of primaeval forests, it was 10 m, and for regions in the beech forest and spruce, it was 15 m. Subsequently, the calculated volume was divided by the number of reference points in the layer. The soil volume for individual points was calculated similarly for the soil depth from 1 m to 5 m. Still, due to the decreasing number of datum points in the layers, the formula for the angled pyramid was used for the calculation.

a) b) c) d)

Fig. 2. Experimental sites a) Dobroč 3, b) Spruce forest, c) Beech forest, d) vertical soil profile showing the depth of the slope deposits to determine the soil skeleton (inserted scale is 2 m).

The volume of soil representing one reference point was multiplied by the volumetric soil water content obtained from the recalibrated 2D profiles. Since the depth of the layers in the ERT profiles does not correspond to the depth of the layers for which we evaluated the soil water storage but increases logarithmically, interpolation was necessary for the soil depths considered 1–5 m. These values about the volume of soil water storage were reduced by the volume of the soil skeleton so that the resulting values of the soil water storage were considered for the volume of fine soil. The amount of soil skeleton was determined from the reference soil profile (Fig. 2d) and soil profile near the beginning of ERT profiles according to Folk's (1951) and Alexander's (1982) methodology. Summing up all the points, we obtained information on the soil water storage volume in the studied soil volume for each measurement date. This was converted to a uniform scale in dm m^{-3}, which we compared with each other in subsequent analyses.

We used a generalised linear mixed model that considers repeated measurements within each combination of location (*Loc*) and depth (*Depth*). Time is regarded as a repeated measure with an autoregressive covariance structure. The model includes fixed effects location (*Loc*), depth (*Depth*) and interaction between depth and time (*Depth* × *Time*). The random effects contain a constant value (intercept) for the location through which the model considers the "nested" structure of the data. The dependent variable is the soil water storage. The distribution of the target variable is assumed to be expected, and the model uses an identity linear function. The following equation represents the model:

$$WSup_{ijkl} = \beta_0 + \beta_i(Loc_i) + \beta_j(Depth_j) + \beta_k(Time_k) + \beta_{jk}(Depth \times Time)_{jk} + \epsilon_{ijkl} \quad [1]$$

where $WSup_{ijkl}$ is the soil water storage for the *ith* site, *jth* depth, *kth* time point and *lth* repetition, and β_0 is the intercept. At the same time, $\beta_i(Loc_i)$ is the fixed effect of the with the site, $\beta j(Depth_j)$ is the fixed effect of the *jth* depth, $\beta_k(Time_k)$ is the fixed effect of the *kk* time point, and $\beta_{jk}(Depth \times Time)_{jk}$ the interaction effect between depth and time; ϵ_{ijkl} is the residual error (Salinas Ruíz et al. 2023).

3. Results

From the resistivity and volumetric water content values fitted in this way for each location, except for the Dobroč primaeval forest core zone (Fig. 3), a calibration curve and a calibration equation were created.

On the Dobroč 1 plot in the core zone of the primaeval forest, we observed a decreasing trend in the soil water storage during the 2021 season. In the upper layers up to 3 m, we observe a decrease in the water storage at the beginning of the measurements, followed by an increase in soil water in August. From this period until the end of the measurement season in November, we observe a gradual decrease in the soil water storage in these layers (Fig. 4a). In the soil layers from 4 to 5 m, we observe a decrease in water storage at the beginning of the season until August when the gradual saturation of these layers with soil water occurs. The saturation lasts until October when it reaches its maximum. Until the end of the measuring season, we only observed a decrease in soil water storage (Fig. 4a). The highest soil water storage was recorded on the Dobroč 2 plot in the core zone. The water storage values reached 160–170 dm^3 m^{-3} in the upper layers. Overall, the trend of soil water storage on this plot can be considered balanced during the 2021 season. In the upper soil layers up to 3 m at the beginning of the measurements, there is a decrease in water storage, followed by a more extended period with increasing or balanced soil water storage from July to October. In October, there is a decrease in water storage. Until the end of the measurements in November, we observe a bal-

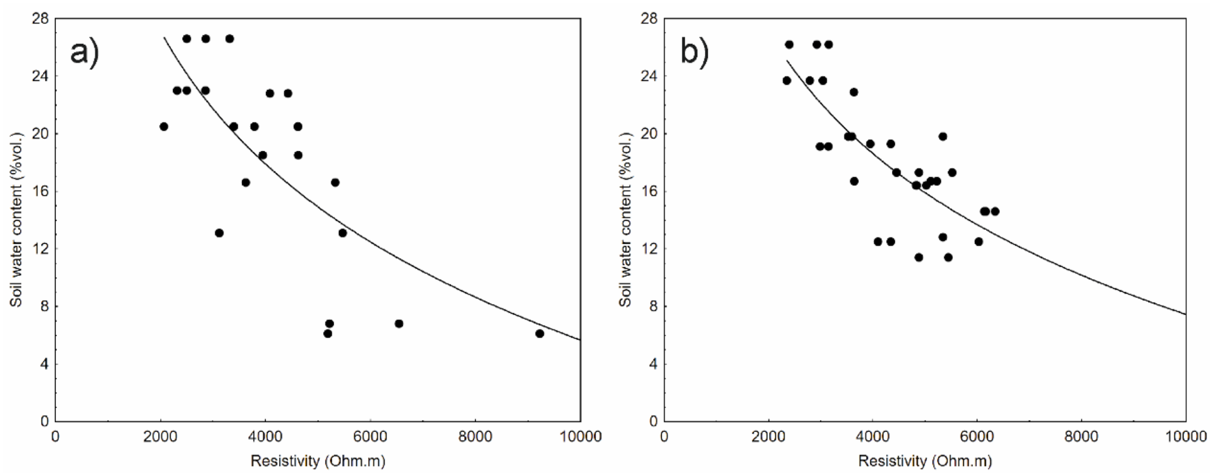

Fig. 3. Soil water content versus electrical resistivity fitted by a decadic logarithm function for a) Beech forest, b) Spruce forest.

anced trend of water storage (Fig. 4b). At the beginning of the season, the lower layers of the soil show a balanced trend of water storage; in August, there is an increase in the amount of soil water. In the following measurement period, in September, there is already a decrease in water storage, while the water storage remains balanced until November (Fig. 4b). The third plot in the core zone of the Dobroč primaeval forest (the Dobroč 3 plot) achieved a balanced trend of soil water storage (mainly layers up to 3 m) in the 2021 season. At the beginning of the measurement in the upper soil layers, the water storage trend was balanced until August; this period was followed by a slow and gradual decrease in the amount of soil water with a minimum in November (Fig. 4c). Deeper layers had more dynamic trend of changes in the amount of soil water. Since the beginning of the measurement in June, a decrease in soil water storage was recorded in July, followed by an increase until September. From this period, it is again possible to observe a decrease in soil water storage with a minimum in November (Fig. 4c).

Significantly lower soil water storage was found in the other experimental areas outside the primaeval forest. In the managed spruce forest, all three soil layers showed a decrease in the amount of soil water during the entire measurement period in the 2021 season, with a maximum in June, a local maximum in August and a minimum in November. The highest values of soil water storage were found in the layer up to 1 m (Fig. 4d). The deeper soil layers had a relatively balanced trend in the 2021 season, even though the values of the water storage were relatively low, only at the level of 50–60 $dm^3 m^{-3}$. In the second half of the measuring season, in September, the soil water storage rose in the 5 m layer and maintained this upward trend until the end of the measurements (Fig. 4d). A similar amount of soil water as in the spruce managed forest was also recorded in the beech forest in the buffer zone of Dobroč primaeval forest, but their seasonal trend was different. The highest water storage was in the 2021 season in the 1 m layer, with a decreasing trend during the measurement season. The maximum was recorded in June and the minimum in November, while there was a temporary increase in the soil water storage in August. The other layers had similar water storage at the beginning of the measurement until August, but their course was different. While the water storage decreased in the 2–3 m layers and rose again in August, the process was the opposite in the 4 and 5 m layers, with an increase in the storage until July, followed by a decrease in the soil water storage. Since August, the storage performance has been significantly different between layers. From September to November, there was a significant saturation of the lower layers of the soil at depths of 4 and 5 m, which exceeded the amount of water in the layers of 2 and 3 m. Compared to the beginning of the measurement season, they maintained a decreasing course of soil water storage until the end (Fig. 4e).

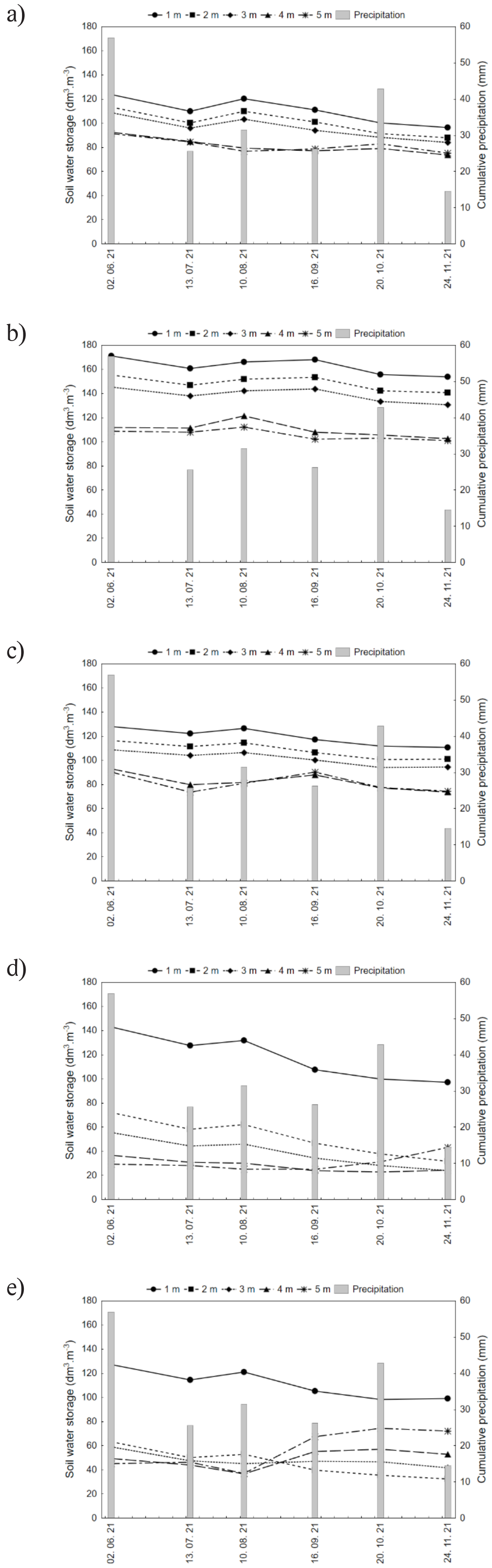

Fig. 4. Soil water storage in individual soil layers on the experimental plots a) Dobroč 1; b) Dobroč 2; c) Dobroč 3; d) Spruce Forest; e) Beech Forest.

In the soil layer of up to 1 m, the Dobroč 2 area had the highest soil water storage. The other areas up to a depth of 1 m had similar soil water storage, with the maximum in June and the minimum in November 2021 (Fig. 5a). In the next layer of soil, at a depth of up to 2 m, we can see the differentiation of areas according to the soil water storage into three groups. The lowest soil water storage was found in the spruce forest and beech forest in the buffer zone of the primaeval forest, followed again by the pair of plots Dobroč 1 and Dobroč 3. The highest values of water storage were again in the area Dobroč 2 in the core zone of the primaeval forest (Fig. 5b). The lowest values were found in November in all areas, and the highest values of the soil water storage were at the beginning of the measurements in June. A similar trend as in the 2 m layer of soil water storage for individual areas was also observed in the 3 m layer. The lowest soil water storage was found again on the spruce and beech areas in the buffer zone, while higher values were on the plot of the Dobroč 1 and Dobroč 3 forests in the core zone of the primaeval forest. The highest values were, similarly to the previous layers, on the Dobroč 2 plot in the Dobroč primaeval forest (Fig. 5c). The lowest soil water storage in the 3 m soil layer was found in November and the highest at the beginning of the measurements in June. The same trend of soil water storage as in the previous layers is also observed in the 4 m layer. The lowest water storage was measured in the beech forest and spruce forest areas, while in the autumn months, we can observe an increase in water storage in the beech forest. The following are the areas in the core zone of the primaeval forest; the highest value of soil water storage was again in the area Dobroč 2. The minimum value of water storage was found in most areas in November, except for beech in the protection zone, where the minimum was in August. The maxima changed during the year individually according to the areas (Fig. 5d). In the deepest layer, in 5 m, we observe a similar development of soil water storage as in the 4 m layer. The lowest soil water storage was measured in spruce, followed by beech forest, while in this area, the soil water storage increased again in the second half of the measurement season up to the level of the areas from the core zone Dobroč 1 and Dobroč 3. The area with the highest values was Dobroč 2 from the core zone of the

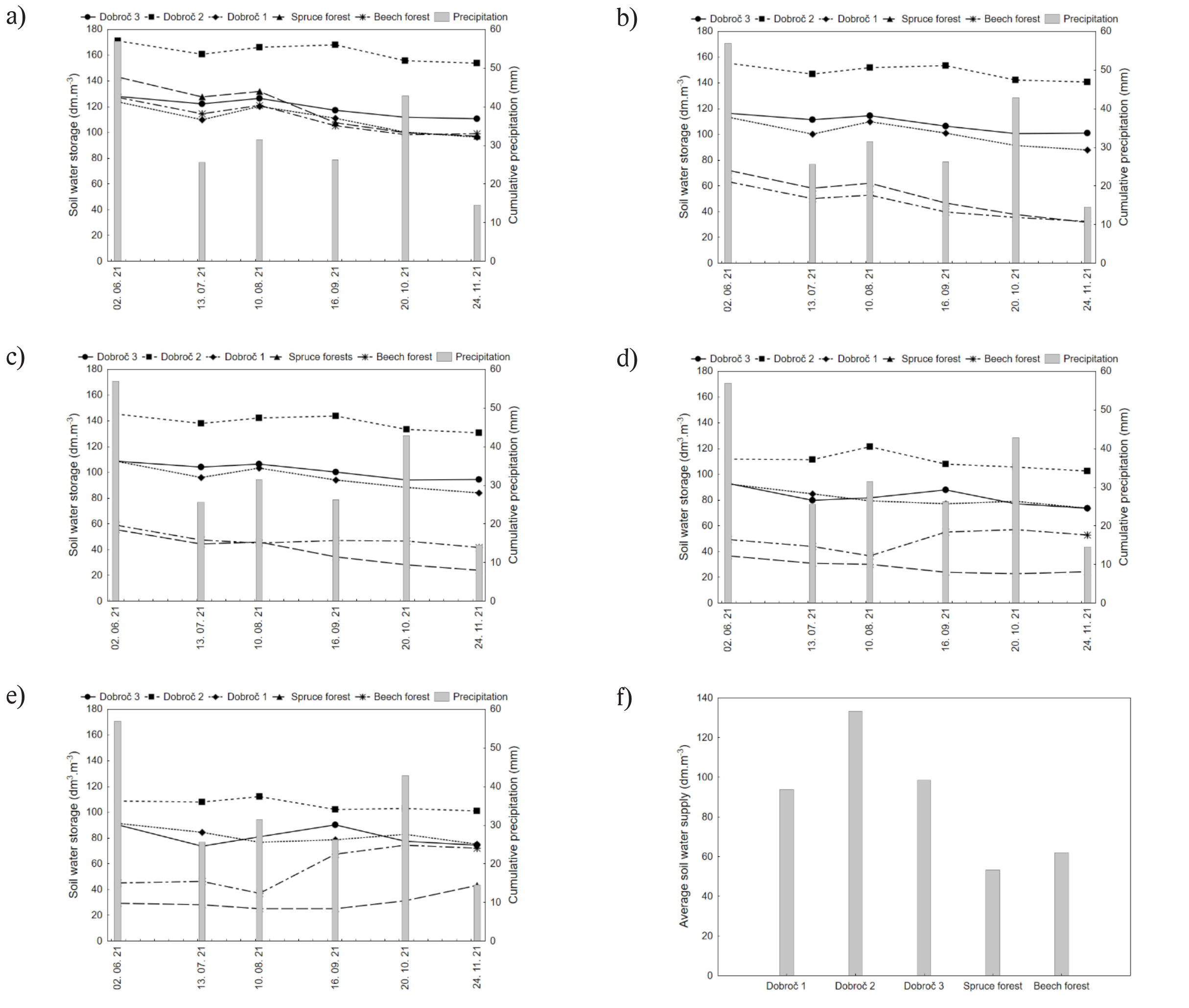

Fig. 5. Soil water storage on individual experimental plots in the soil layer a) 1 m; b) 2 m; c) 3 m; d) 4 m; e) 5 m; f) average soil water storage in all layers.

primaeval forest. At this depth, we can observe, except for the beech area, relatively balanced soil water storage throughout the season in all areas (Fig. 5e). Dobroč 2 plot in the core zone reached the highest average values of soil water storage, followed by the remaining two areas in the core zone, i.e. Dobroč 1 and Dobroč 3. The lowest average value of soil water storage was recorded on the plot with managed spruce forest (Fig. 5f).

3.1. Statistical analyses

The data of soil water storage were evaluated using a generalised linear mixed model. The water storage is significantly influenced by the location (type of forest) and the depth of the layer. The depth significantly influenced the water storage and the order (date) of the measurement. It can be seen from Fig. 4a)–c) that the order of some soil layers and slope deposits changes over time regarding water storage, and the model used showed that these changes are statistically significant. The contribution of the depth of the layer itself is much smaller compared to the influence of the site and the interaction between the depth and the order (date) of the measurement. The contribution of individual factor levels can be positive or harmful to the reference value. A positive effect was found at the Dobroč sites, and a negative impact was found at the site with spruce forests compared to the site with beech stands. The average water storage at the individual locations, as well as factors effects (Tab. 1), clearly illustrate that the three primaeval forest locations form a relatively homogeneous group in terms of water storage with higher storage compared to the pair of locations in the buffer zone (beech), respectively in the managed forest (spruce).

The pairwise comparisons in Table 2 show the differences in average soil water storage between individual sites. In contrast, the pairwise comparison in Table 3 shows the differences in average water storage at all locations between individual depths. The complementary graph in Fig. 4a)–e) indicates the existence of a relatively homogeneous layer in terms of water storage at a depth of 1 m, 2 m, and 3 m and deeper soil layer in 4 m and 5 m.

4. Discussion

From the point of view of the research methodology, the different ages of the trees seem like a problem. However, the stands are similar based on characteristics such as basal area, aboveground biomass, and root biomass. In the case of root biomass, its amount was slightly higher in a beech forest than in a spruce forest. It should be noted that most of the spruce roots are near the soil surface, while the trees in the beech stand mostly have a deep root system, and part of the root biomass may have yet to be captured in the physiological soil profile. In addi-

Table 1. The factor's effects on the water storage according to a generalised linear mixed model.

Source	F	df1	df2	p
Model	7.543	33	116	< 0.001
Locality	12.722	4	116	< 0.001
Depth	18.445	4	116	< 0.001
Depth × Time	4.999	25	116	< 0.001

Table 2. Pairwise comparison of soil water storage by location following the generalised linear mixed model.

Pairwise Contrasts – Locality							
Locality	Contrast Estimate	Std Error	*t*	df	Adj. Sig.	95% Confidence interval	
						Lower	Upper
Dobroč 1 vs Beech	31.142	11.716	2.658	116	0.009	7.936	54.348
Dobroč 1 vs Dobroč 2	–34.185	11.716	–2.918	116	0.004	–57.391	–10.979
Dobroč 1 vs Dobroč 3	2.430	11.716	0.207	116	0.836	–20.776	25.636
Dobroč 1 vs Spruce	40.907	11.716	3.491	116	0.001	17.701	64.113
Dobroč 2 vs Beech	65.327	11.716	5.576	116	1.632×10^{-7}	42.121	88.533
Dobroč 2 vs Dobroč 1	34.185	11.716	2.918	116	0.004	10.979	57.391
Dobroč 2 vs Dobroč 3	36.615	11.716	3.125	116	0.002	13.409	59.821
Dobroč 2 vs Spruce	75.092	11.716	6.409	116	3.268×10^{-9}	51.886	98.298
Dobroč 3 vs Beech	28.712	11.716	2.451	116	0.016	5.506	51.918
Dobroč 3 vs Dobroč 1	–2.430	11.716	–0.207	116	0.836	–25.636	20.776
Dobroč 3 vs Dobroč 2	–36.615	11.716	–3.125	116	0.002	–59.821	–13.409
Dobroč 3 vs Spruce	38.477	11.716	3.284	116	0.001	15.271	61.683
Beech vs Dobroč 1	–31.142	11.716	–2.658	116	0.009	–54.348	–7.936
Beech vs Dobroč 2	–65.327	11.716	–5.576	116	1.632×10^{-7}	–88.533	–42.121
Beech vs Dobroč 3	–28.712	11.716	–2.451	116	0.016	–51.918	–5.506
Beech vs Spruce	9.765	11.716	0.833	116	0.406	–13.441	32.971
Spruce vs Beech	–9.765	11.716	–0.833	116	0.406	–32.971	13.441
Spruce vs Dobroč 1	–40.907	11.716	–3.491	116	0.001	–64.113	–17.701
Spruce vs Dobroč 2	–75.092	11.716	–6.409	116	3.268×10^{-9}	–98.298	–51.886
Spruce vs Dobroč 3	–38.477	11.716	–3.284	116	0.001	–61.683	–15.271

Table 3. Pairwise comparison of water storage by depth following generalised linear mixed model.

Pairwise Contrasts – Depth							
Depth (m)	Contrast Estimate	Std Error	*t*	df	Adj. Sig.	95% Confidence interval	
						Lower	Upper
1.000 vs 2.000	33.323	7.244	4.600	116	1.085×10^{-5}	18.976	47.670
1.000 vs 3.000	39.748	7.244	5.487	116	2.432×10^{-7}	25.400	54.095
1.000 vs 4.000	54.122	7.244	7.472	116	1.619×10^{-11}	39.775	68.469
1.000 vs 5.000	53.033	7.244	7.321	116	3.493×10^{-11}	38.686	67.380
2.000 vs 1.000	–33.323	7.244	–4.600	116	1.085×10^{-5}	–47.670	–18.976
2.000 vs 3.000	6.425	7.244	0.887	116	0.377	–7.923	20.772
2.000 vs 4.000	20.799	7.244	2.871	116	0.005	6.452	35.146
2.000 vs 5.000	19.710	7.244	2.721	116	0.008	5.363	34.057
3.000 vs 1.000	–39.748	7.244	–5.487	116	2.432×10^{-7}	–54.095	–25.400
3.000 vs 2.000	–6.425	7.244	–0.887	116	0.377	–20.772	7.923
3.000 vs 4.000	14.374	7.244	1.984	116	0.050	0.027	28.721
3.000 vs 5.000	13.285	7.244	1.834	116	0.069	–1.062	27.632
4.000 vs 1.000	–54.122	7.244	–7.472	116	1.619×10^{-11}	–68.469	–39.775
4.000 vs 2.000	–20.799	7.244	–2.871	116	0.005	–35.146	–6.452
4.000 vs 3.000	–14.374	7.244	–1.984	116	0.050	–28.721	–0.027
4.000 vs 5.000	–1.089	7.244	–0.150	116	0.881	–15.436	13.258
5.000 vs 1.000	–53.033	7.244	–7.321	116	3.493×10^{-11}	–67.380	–38.686
5.000 vs 2.000	–19.710	7.244	–2.721	116	0.008	–34.057	–5.363
5.000 vs 3.000	–13.285	7.244	–1.834	116	0.069	–27.632	1.062
5.000 vs 4.000	1.089	7.244	0.150	116	0.881	–13.258	15.436

tion, several studies are known in the literature where the parameters of the root system of spruce stands across Europe were evaluated. For example, Ostonen et al. (2011) evaluated fine root foraging of Norway spruce on 12 sites aged 30–140 years and nine soil types. From the point of view of the same geological substratum, soil type and soil texture, we consider the selection of areas to evaluate the water supply.

The results showed a delayed reaction of the lower layers to precipitation and desiccation by tree roots, especially in areas in the primaeval forest (Fig. 4). In the monodominant even-aged stands of the Spruce forest and Beech forest in the buffer zone, the water content in the deeper layers was lower than in the uppermost layer (1 m). At the same time, it also decreased in the leafing phase (Beech forest), respectively, due to the faster active evapotranspiration of the Spruce forest than in the other types of forests. The fastest decrease in water storage was found in the uppermost layer in the Spruce forest. The rapid decline in soil water storage may also be related to the high interception of Norway spruce, which reached the highest values precisely in spruce monocultures, up to 20.5–35.5%, and thus reduced the amount of under-canopy precipitation (Minďaš et al. 2018). The development of the water storage in the deeper layers under the Beech forest, compared to the Spruce forest, in 2021 reflected a decrease in evapotranspiration at the end of summer and beginning of autumn associated with a higher amount of water available for percolation into deeper layers. Water saturation after the spring and summer drought in 2021 in all depths was faster and more uniform in Dobroč forests (Dobroč 1–Dobroč 3) than in Beech and Spruce forests, where a distinct increase was manifested only in the uppermost layer, while the water content in deeper layers fluctuated due to the amount of soil water availability for infiltration from the central vadose zone. The determined differences in the temporal changes of water storage at different depths were tested depending on soil depth and time of measurement and their interaction. The generalised linear mixed model showed a high statistical significance of the measurement time and its interaction with depth.

Based on our results of changes in water storage in time in the individual measured layers, we hypothesise that the central root zone was 3.0 m, except for the Spruce forest. In Spruce forest, we recorded the most significant changes in soil water storage at a depth of 1.0 m. We observed a close relationship of soil water storage in soil layers 1.0–3.0 m in all locations. Based on this, we concluded that the layers to a depth of 3.0 m represent the direct (deduction) and indirect effect (through the moisture potential gradient) of the root system of trees. Therefore, the most significant changes in soil water storage can occur there. Similar results were also found in the work of Fäth et al. (2022), where they found a markedly different time delay in the process of water saturation and drying of soil to a depth of 3 m. While in the winter, the water infiltration proceeded relatively slowly and continuously, in the summer, sudden drying began in the upper three meters of the measured ERT profiles. Furthermore, the authors stated that dry periods also occurred in the deeper half of the ERT profiles (3–6 m), especially in the last years of the research period (2018, 2019, 2020). Although these depths seemed less critical for the direct water source for the forest trees, one should still consider the increasing resistivity values even in the deeper parts of the measured profiles, which means an annual decrease in the water content.

Similar results with the ERT method used in the forest ecosystem were also achieved in a recent study by Rieder & Kneisel (2023), where they showed that the top layer of the soil dries significantly from summer to autumn to a depth of about 3 m. Still, during the winter period, an increase in water content and a decrease in soil resistivity can be observed at a depth of more than 3 m. The most significant changes in resistivity and temporal variations were found in layers from 1 to 3 m, corresponding to the main root zones of most forest sites. The temporal variation of resistivity values corresponds well to changes in soil moisture up to a depth of 3 m. Since mean values from single-point TDR measurements were also used in classical soil moisture estimations or for hydrological modelling in forest ecology, calibration of the spatial resistivity model using functional correlation obtained from mean TDR soil moisture values, is considered acceptable, at least for the depth range considered in similar studies (Fäth et al. 2022).

Kuhr (2000) found that more giant trees tended to grow roots to greater depths, but at the same time, the total biomass of beech fine roots decreased with increasing stand age (Finér et al. 2007). According to Lüttschwager & Jochheim (2020), young beech trees have few coarse roots and finer ones in shallower layers, but the opposite was found in older trees. Therefore, it can be assumed that suppressed trees mainly take water from the upper layers of the soil, while dominant trees may be able to receive water from deeper layers of the soil. According to Le Goff & Ottorini's (2001) study, dominant beech trees put relatively more biomass into coarse roots than trees with lower social status. Grote et al. (2016) reported that beech trees in the lower tree layer increased the density of fine roots near the surface, resulting in trees not having access to water from deeper parts of the soil, especially in the precipitation deficiency. On the other hand, trees on the upper tree layer had the opportunity to draw from soil water stored in deeper soil layers. Kodrík & Kodrík (2002) indicate that the rooting depth for beech is up to 1.2 m. According to Büsgen et al. (1929), the most excellent rooting depth of beech on the fresh, shaly, stony ground was found to be 1.23 meters, and a beech standing on moist, fine-grained diluvial formations reached a depth of 1.80 meters. The mentioned authors divided the trees according to the shape and depth of the root system into three groups: spruce in the group with the surface root system, beech in the group with the heart root system, and fir in the group with the taproot system. Based on a literature review, Fan et al. (2017) indicate the mean rooting depth: spruce 0.74 ±0.47 m, beech 0.83 ±0.46 m and fir 1.30 ±0.67 m. Karizumi (1979) gives the most excellent rooting depth of spruce at 2.30 m in Japan; for beech, Kalisz et al. (1987) have a maximum rooting depth of 1.35 m.

Our results corresponded with findings that slope deposits affect water movement, e.g., they slow it down or change its direction. Buchter (1986, 1997) detected both vertical and lateral (at depths of 30 cm and 110 cm) movement of tracer substances with a speed of 1 to 25 cm per day by applying chloride and bromide solutions in the Rendzic soil type under a 130-year-old beech forest. Other authors, e.g., Caballero et al. (2002), also used tracers. While a relatively homogenous soil on the plateau can think under certain conditions with a direct proportionality of rainfall and tracer penetration depth (Jury & Roth 1990), dislocation caused by solifluction leads to hydraulic anisotropy, as a result, that water can flow into soil material also laterally, while vertical movement is limited and a lateral (slope or hypodermic) flow occurs (Kleber & Schellenberger 1998). Periglacial slope deposits thus played a crucial role in the hydrology of slopes regarding the mentioned properties and their wide distribution in the European mountains. Because of the high spatial variability of their soil physical properties, their hydraulic properties showed high variability (Moldenhauer et al. 2013).

5. Conclusions

Our study aimed to test the applicability of the time-lapse electrical resistivity tomography method, a non-destructive method for determining soil moisture, for measuring the water supply in undisturbed soil in stands with different tree compositions and in forestry. The calibration of resistivity and volumetric water content, measured by the reflectometry method in the time domain, made it possible to compare the changes in water storage in the soil during the growing season. Statistical analysis using a generalised linear mixed model showed statistically significant differences between areas and a substantial effect of depth and time on soil water retention. The decrease in soil water reserves was the fastest in the spruce forest among all plots. At the same time, the lowest soil water supply was also found in this plot. In plots Dobroč 1–Dobroč 3, the trend of soil water retention in the growing season was more balanced than in areas outside the primaeval forest. The average soil water supply also reached the highest values in these areas. According to the amount of soil water reserves, the plots in the Dobroč forest show the highest level of ecosystem resistance to dry weather conditions.

The study results support knowledge about Norway's spruce's inefficiency in using soil water and its high susceptibility to drought. At the same time, it cannot replenish the water deficit for physiological needs from the deeper soil layer. Based on the study's results, growing Norway spruce in a tree mixture with deep root systems such as silver fir and common beech appears to be a suitable planting strategy. At the same time, however, it should be remembered that the mentioned study results are primarily valid for the investigated location, and it is not possible to generalise them for stands on other geological subsoils and with different slope deposits or soil thicknesses. Electrical resistivity tomography proved to be a suitable method for monitoring the movement and accumulation of water in undisturbed soil. It represents an advantageous alternative to point soil sampling or soil moisture measurements, which are usually extrapolated to larger soil volumes or areas with significant estimation error due to variability in soil properties, including soil depth.

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