

The water absorbability of beech (*Fagus sylvatica* L.) and fir (*Abies alba* Mill.) organic matter in the forest floor

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Abstract. The organic horizons of forest soils are characterised by double capillarity: between particles and inside them. It has been hypothesized that the time required to fill the internal capillarity of organic particles depends on their botanical origin and the degree of their decomposition. The aim of the present study is to determine the time of water absorption by organic matter that is part of the O1 and Ofh horizons of selected beech (*Fagus sylvatica* L.) and fir (*Abies alba* Mill.) stands. The present research on water absorbability lasted for 14 days and consisted in measuring the absorption time in organic particles from the moment of immersion of an air-dry sample in water until the particles soaked in water exceeded the density of 1.0 g·cm⁻³. It was found that in fir organic matter the time of water absorption decreases with the advancement of decomposition. In beech stands, progressing decomposition processes result in a longer water absorption time. The dynamics of water absorption of organic matter indicates that no single rainfall is able to entirely fill the internal capillarity of organic particles, whereby the organic horizons of forest soils can maintain the ability to retain water even in long-term rainfall.

Keywords: forest hydrology, forest soils, water absorbability, organic matter, *Fagus sylvatica* L., *Abies alba* Mill.

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Introduction

The process of rainfall infiltration through the forest environment into the soil was compared by Suliński (1993) to filling 4 containers: (i) the tree surface, (ii) the surface of plants of the forest floor, (iii) the forest litter horizon and (iiii) the capillary spaces in the mineral soil horizon. Each of these containers is characterised by a specific water storage capacity and a specific mechanism of filling, which can occur simultaneously or with a certain delay. As the highest soil horizon, the forest litter retains both rainwater and water flowing down the tree stem (Putuhena & Cordery 1996). It has a positive effect on the water content in the near-surface soil horizon and keeps moisture in soil for longer periods after rainfall (Sharafatmandrad et al. 2010). Litter plays an important role in water infiltration into the soil profile, prevents erosion, slows down stemflow and limits evaporation from deeper soil horizons (Onda & Yukawa 1994, Tamai et al. 1998, Greiffenhagen et al. 2006). Its water storage capacity depends not only on the quantitative share of individual litter components, such as leaves, needles and branches, but also on the bulk density, total porosity and species composition of the stand (Laurén & Mannerkoski 2001, Zhang et al. 2006, 2009, Ilek et al. 2015, 2017).

In the water exchange between the atmosphere, the stand and the soil, an important role is played not only by litter but by entire organic soil horizons. Depending on the advancement of organic matter decomposition processes, apart from litter (Ol), consisting of less decomposed organic debris with preserved tissue structure, the following subhorizons are distinguished in the organic horizons of forest soils (Dziadowiec et al. 2004): (i) detritus (Ofh) - composed of highly fragmented and discoloured material as well as mineral particles, (ii) fermentation (Of) - composed of highly fragmented and discoloured material and (iii) epihumus (Oh) - containing mainly

macro- and microscopically amorphous humus as well as a significant admixture of mineral material.

The organic horizons of forest soils are formed under the influence of vegetation and the processes of organic matter decomposition. They mainly include fallen leaves and needles as well as other dead parts of plant and animal origin. The thickness of organic horizons depends on climate, vegetation, topography, soil type and human activity (Walsh & Voigt 1977). While in litter the water is retained mainly on the surface of its constituent organic particles, inside the tissues and in the spaces between individual particles (Suliński 1993), along with the advancement of organic matter decomposition and its fragmentation in the Of, Oh and Ofh horizons it is capillary spaces that play an increasingly greater role in retaining water. As soil horizons containing organic particles are characterised by double capillarity: between and inside particles (Kucza 2007), the dynamics of rainwater retention through these horizons is a complex process that is relatively poorly understood. Considering the influence of the species composition of a stand and the degree of organic matter decomposition on the physical and retention properties of the organic horizons of forest soils (Ilek et al. 2015, 2017), it is necessary to take into account the different time periods necessary to fill the internal capillarity of organic matter particles in various states of transformation. Therefore the present study inspects the hypothesis that the filling of the internal capillarity of organic particles depends on their botanical origin and the degree of their decomposition. The aim of the present research is to determine: (i) the dynamics of water absorbability, (ii) the average time of water absorption and (iii) the minimum time required to fill with water the internal capillarity of organic matter that is part of the litter (Ol) and detritus (Ofh) horizons of selected beech (*Fagus sylvatica* L.) and fir (*Abies alba* Mill.) stands in southern Poland.

Materials and methods

Research area and sampling

The research on the water absorbability of organic matter covered the O1 litter horizons and the Ofh detritus horizons in 9 beech stands and 10 fir stands, whose general characteristics are given in Table 1. The stands are located in the Złoty Potok catchment area and the Proszków stream catchment, located within the area of the Makowski Beskid Mts in southern Poland (Fig.1). The soils of all examined stands were classified as Dystric Cambisols (IUSS Working Group WRB 2015).

The research material was obtained in November 2014. In each of the stands, a transect with a length of 100 m was designated, where



Figure 1 Location of the study area

samples of O1 and Ofh horizons were collected at every 20 m. Water absorbability and the degree of organic matter decomposition were tested using averaged samples, obtained as a result of mixing the material sampled from a given transect. In the case of O1 horizons in fir and beech stands, water absorbability was tested only in needles and leaves, as they constituted the largest part of the litterfall produced annually by these stands (Švidenko 1980, Małek 2006, Niewinna 2010, Jonczak 2013).

Laboratory tasks

When measuring the water absorbability of organic matter, it was assumed that the water-soaked organic particles reach the state of internal capillarity filling once their density exceeds $1.0 \text{ g}\cdot\text{cm}^{-3}$. This method of water absorbability measurement was adopted after Kucza & Urbaś (2005) and Kucza (2007). It consists in measuring the soaking time of organic matter from the moment of immersion of an air-dry sample in distilled water at $20^\circ\text{C} (\pm 2^\circ\text{C})$, until the moment of its sinking to the bottom of the beaker, i.e. until the water-soaked particles exceed the density of $1.0 \text{ g}\cdot\text{cm}^{-3}$. The soaking time of the organic matter was examined for 14 days; the particles that had sunk to the bottom were removed at least once a day, dried at

Table 1 Basic characteristics of the sampling sites

Characteristics	Variable	Vegetation type		
		<i>Abies alba</i>	<i>Fagus sylvatica</i>	
Topography	Altitude [m]	430-810	520-765	
	Exposure	N, NW, NE	S, SW, SE	
	Slope [°]	10-22	5-25	
Stand characteristics	Age [years]	30-120	10-115	
	DBH [cm]	10-51	24-102	
	Humus form	moder	moder	
	Height [m]	8-31	5-32	
	Thickness [cm]	O1	0.2-1.0	0.4-1.0
		Ofh	0.6-2.8	0.6-3.4

105°C and weighed. The removal of particles was accompanied by the exchange of water in the beakers. In the Ofh horizons, often containing a significant amount of mineral particles, the weight of individual fractions of a sample that had sunk to the beaker bottom after a given soaking time was reduced by the share of the weight of mineral particles by incinerating the samples at a temperature of 550°C. For that reason, the results of the present research refer only to the organic matter present in these horizons. The calculation of the content of organic matter took into account the share of ash parts remaining in a given sample after incineration. The following relationships were used for the conversions: 100% of fir organic matter = 97.5% loss on ignition and 100% of beech organic matter = 96.6% loss on ignition (Ilek et al. 2015). The method of conducting the experiments made it possible to divide the organic matter contained in the Oi and Ofh horizons into: (i) sinkable matter, capable of reaching a density greater than 1.0 g·cm⁻³, and (ii) unsinkable matter, unable to achieve the desired absorbability even after 14 days of soaking.

The mean time T_A of water absorption by the organic matter from the Oi and Ofh horizons of the beech and fir stands was calculated as the weighted average mass of particles that had sunk to the bottom after a given soaking time, in relation to the total weight of the particles sinkable in water.

The minimum time (t_{min}) needed to fill the internal capillarity of the sinkable organic matter being part of the Oi and Ofh horizons as well as the entire organic horizons O was determined on the basis of the cumulative percentage of organic particles that sank after a given soaking time. This percentage was determined jointly for all samples from individual horizons of the fir stands and for all samples obtained from the beech stands. The time after which 75% of the organic matter from a given horizon reaches a density greater than 1.0 g·cm⁻³ was adopted as the moment of filling the internal capillarity.

The content of organic carbon C in individ-

ual soil horizons was determined by the Tiurin method while the total content of nitrogen N was determined by the Kjeldahl method in the Kiej-Fos automatic 16210 kit. The degree of decomposition was expressed using the decomposition index of organic matter W_{NC} in the following form (Kucza & Urbaś 2005):

$$W_{NC} = 1000 \cdot (NC) \quad (1)$$

Results

The share of unsinkable organic matter

The distribution of variability of the percentage of unsinkable organic matter S_{NS} in the Oi and Ofh horizons under the beech and fir stands is shown in Figure 2. The Ofh horizons in both stands are characterised by a higher share of unsinkable organic matter than the Oi horizons, with the highest share of S_{NS} found in the Ofh horizons of the beech stands (average $28.6 \pm 5.3\%$). The average share of S_{NS} in beech litter and in the Oi and Ofh horizons under the fir stands is: 6.1 ± 1.1 , 0.2 ± 0.1 and $9.3 \pm 1.6\%$ respectively.

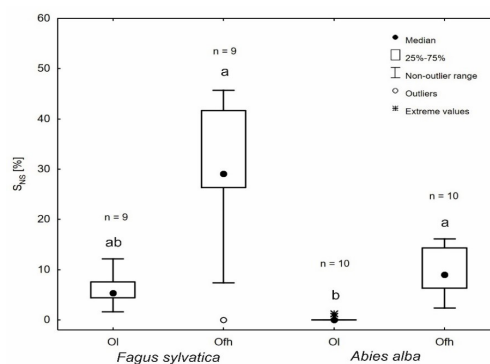


Figure 2 The range of variability of the percentage of unsinkable organic matter S_{NS} in the Oi and Ofh horizons of the beech and fir stands. Different letters indicate the significance of differences between individual horizons (Kruskal-Wallis test, $p < 0.05$) and n is the sample size

The dynamics of water absorbability of organic matter

The dynamics of water absorbability of organic matter, presented in Figure 3, differs between the two species. In the case of beech litter, most of the organic matter sank during the first 24 hours of soaking, and an average of 89% of the matter sank after 2 days. In the case of fir litter, only 8% of organic matter sank during the first 24 hours while most of it (25%) sank between the first and the second day of soaking. The largest amount of organic matter from the Ofh horizons of both species sank within the first 24 h; in the case of beech stands it was an average of 19% while in the case of fir stands 46%. An average of 21% of the organic matter of the beech Ofh horizons and 69% of the organic matter of the fir Ofh horizons sank after 2 days.

The mean water absorption time

The mean time T_A of water absorption by organic matter being part of beech litter is 0.94 ± 0.11 days (Fig. 4a) and is more than three times lower than the mean time T_A reached

by the organic matter of fir litter (3.17 ± 0.34 days). The mean time T_A reached by the organic matter of the beech Ofh horizons (3.22 ± 0.29 days) is almost twice higher than time T_A reached by the Ofh horizons of fir stands (1.73 ± 0.21 days). Comparing the mean time of water absorption with the advancement of disintegration processes in the organic matter of individual horizons in the analysed stands (Fig. 4b), it can be concluded that in the case of fir ectohumus, time T_A decreases with the growth of the W_{NC} index, i.e. with the increase in the degree of organic matter decomposition. On the other hand, in beech ectohumus, the advancement of organic matter decomposition results in prolonging the time of water absorption by organic matter.

Time of filling the internal capillarity of organic matter

Figure 5 shows the cumulative percentage of organic matter sinking during the 14 days of soaking, and belonging to the Ol and Ofh horizons and the entire ectohumus O, determined jointly for a total of 9 beech and 10 fir research plots. The percentage was used to determine the minimum soaking time t_{min} necessary to fill the internal capillarity of organic matter.

In the case of beech litter, time t_{min} amounted to 1.2 days, by which it was over 3 days shorter than time t_{min} reached by fir litter. The largest minimum time needed to fill the internal capillarity (8.6 days) characterises the organic matter of the beech Ofh horizons. This time is over 7 times greater than time t_{min} of the beech litter and 5.5 days longer than time t_{min} reached by the organic matter of the Ofh horizons in fir stands. Time t_{min} reached by organic matter in the entire beech ectohumus is only 1.4 days lower than time t_{min} of fir ectohumus (Fig. 5).

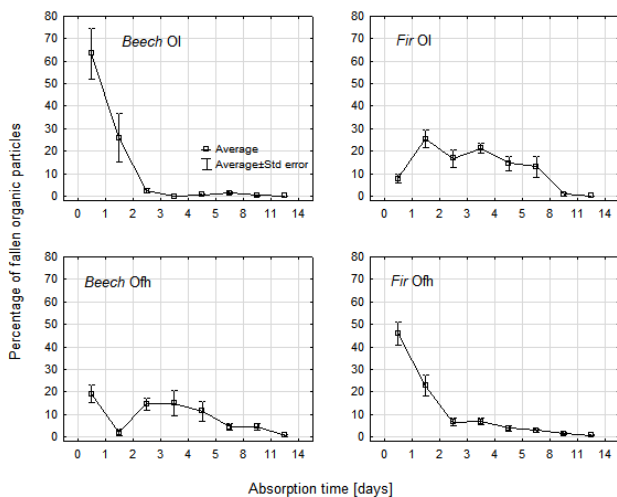


Figure 3 The dynamics of water absorbability of the sinkable organic matter being part of the Ol and Ofh horizons of the beech and fir stands

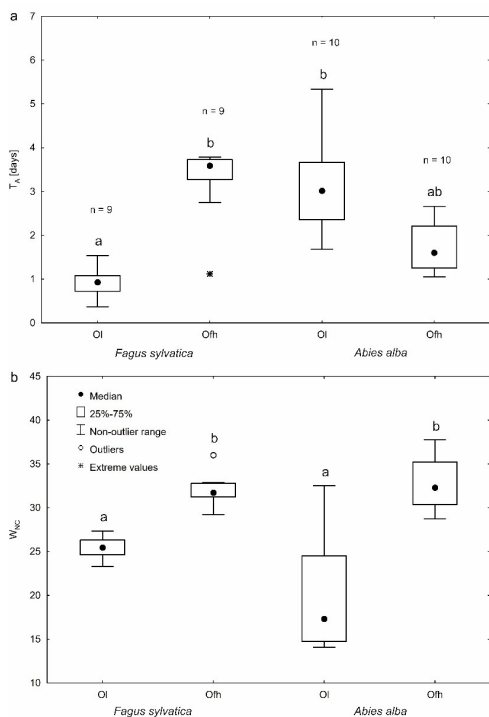


Figure 4 The range of variation of: a) the T_A mean water absorption time and b) the W_{NC} index of decomposition of the organic matter being part of the Ol and Ofh horizons in beech and fir stands. Different letters indicate the significance of differences between particular horizons (Kruskal-Wallis test, $p < 0.05$) and n is the sample size

Discussion

In their research on water absorbability in spruce stands (*Picea abies* (L.) H. Karst), Kuczka & Urbaś (2005) stated that the mean time of water absorption by the organic matter of the Ol, Of and Oh horizons amounts to 2.6, 1.7 and 0.9 days, respectively. They expressed the view that the time of water absorption can be a measure of the current state of organic matter decomposition. On the one hand, that thesis is confirmed by the results obtained in fir stands; on the other hand, it is undermined by the re-

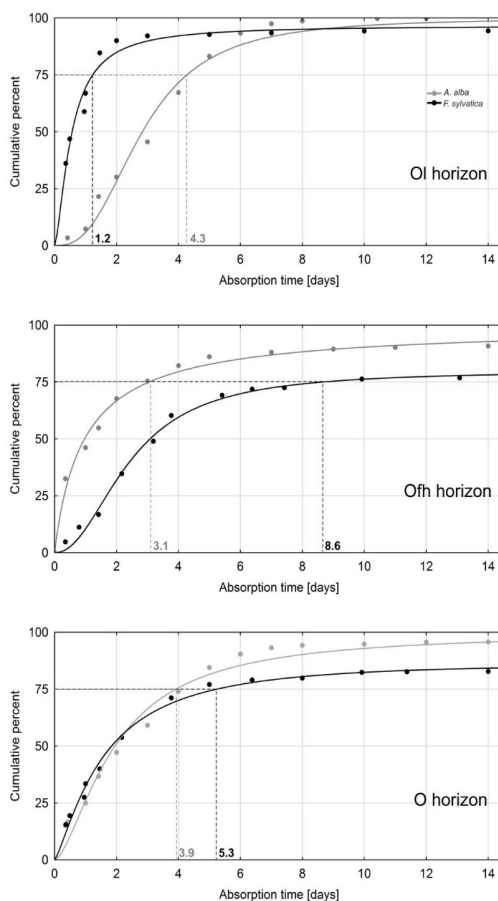


Figure 5 The cumulative percentage of organic matter sinking within 14 days of soaking along with the minimum time needed to fill the internal capillarity of the organic matter being part of the Ol and Ofh horizons and the entire organic horizons O of beech and fir stands

sults obtained in beech stands (Fig. 4). Despite a lack of differences between the values of decomposition index W_{NC} in the Ol horizons of the fir and beech stands, water absorption processes in the organic matter of the litter of both species proceed in a different way. A similar pattern applies to the Ofh horizons (Fig. 3-5). This suggests that the water absorbability of organic matter is affected not only by the degree of decomposition itself but also by the

accompanying multidirectional changes in the chemical composition of litterfall, and thus by the quality of organic matter.

The chemical composition of living plants translates into the quality of the litter they form (Berg & McLaugherty 2008). Litter consists of plant remains containing various kinds of compounds soluble and insoluble in water. In general, these remains contain 15-40% cellulose, 10-43% hemicellulose, 25-40% lignins, 1-10% waxes and lipids and 1-15% protein (Schulze et al. 2005). Lignin is the most complex component of leaves, resistant to microorganisms (Gołab 1978). According to Tomczuk (1975), beech leaves contain over 20% lignins while fir needles contain about 23%. Apart from the higher lignin content, fir litter is also characterised by a lower content of cellulose and hemicellulose than beech litter (Hobbie et al. 2006). The quality of litter translates into the rate of organic matter decomposition, dependent, among others, on the initial content of N, Ca, lignins as well as on the ratios: C:N, C:P and lignins to N (Fogel & Cromack 1977, Jacob et al. 2010). Rutigliano et al. (1996) found different dynamics of lignin distribution in beech leaves and fir needles. In an early phase, lignin decomposed faster in beech than in fir whereas at a later stage the decomposition of lignin was faster in fir than in beech. The variation in the litter decomposition rate among different plant species is often positively correlated with the initial nitrogen content and negatively correlated with the initial lignin content (Hobbie et al. 2006). Comparing the rate of decay of beech and hornbeam leaves (*Carpinus betulus* L.), Gołab (1978) found that the slower rate of beech leaf decomposition is related to a slower decomposition of hemicelluloses and lignins contained in them while the different resistance of these components to biological decomposition in both types of leaves results from differences in their chemical structure. A different rate of decomposition of individual components of litter makes its quality change over time, which continuously affects the course of the decomposition process

(Fioretto et al. 2005). The change in the quality of organic matter during the decomposition is indicated by the share of unsinkable organic matter (Fig. 2). While in fir stands the difference in the share of SNS between the O1 and Ofh horizons amounts to 9.1% on average, an increase in the average share of unsinkable organic matter from 6.1% (O1 horizon) to 28.6% (Ofh horizon) in beech stands indicates that the decomposition of beech organic matter produces compounds that are clearly hydrophobic, which results in a significant prolongation of the water absorption time (Fig. 4).

Differences in water absorption time between beech and fir litter may also result from differences in the age of needles and leaves that are its constituents. In beech stands, where leaves account for over 80% of the total litterfall in non-seed years and over 47% in seed years (Jonczak 2013), 80-90% of the total annual litterfall occurs in October and November (Małek et al. 1998). Švidenko (1980) states that in fir stands 50-60% of litterfall are needles, which fall throughout the year with varying intensity: around 59% of needles fall in autumn, 18-23% in winter, 8-10% fall in spring and 9-13% in summer. Considering that fir needles remain on shoots from 2 to 11 years (Boratyński 1983) and that their falling lasts the whole year, the O1 horizons of fir stands may even contain needles from the last several years of litterfall, while in beech stands litter is composed of one-year-old leaves, fallen in a given year. As shown by Tomczuk (1975), the content of lignin in fir needles increases with the ageing of needles: in one-year-old needles it is 22.8% while in 3-year-old ones it is 25.9%. The content of lignin in pine needles is also not uniform during the year: it is the highest in spring and the lowest in winter. Changes that occur in leaves during the growing season affect their wettability (Klamerus-Iwan & Błońska 2017, Klamerus-Iwan & Kraj 2017).

A different course of the dynamics of water absorbability of beech and fir organic matter can also be associated with the anatomical structure of the leaves of both species. The

thickness of the cuticle, the amount of epicuticular and internal wax and the amount of pectin in the leaves are not only different in each plant species but also variable within a single plant itself, depending on its age, growth conditions and the side of a leaf (Hejnowicz 2002). The cuticle is a layer that is poorly permeable to water and air. It covers the whole epidermis, and the only breaks in the cuticle occur in places of the pores of stomata (Malinowski 1987), which after the death and fall of a leaf may be natural ways for water to enter the leaf interior. The stomata may be on the same level as other epidermis cells, but they may also be recessed below that level. The size and density of stomata depend on many factors, such as genetic conditions, age of needles/leaves and trees, and insolation (Franich et al. 1977, Hejnowicz 2002). Hypostomatic beech leaves have elliptical stomata (Cho et al. 2014), and their average size is 23.5 μm (Denk 2003). According to Sweeney (2014), the width of stomata depends on the tree species; in *Pinus sylvestris*, *Picea abies* and *Abies alba* it is: 24.6, 33.1 and 25.9 μm , respectively. In fir, the stomata are recessed and the stomatal pores are covered with a wax crust (Bačić et al. 2005). The opening of the stomata is caused by an increase in turgor pressure in the stomatal cells which are penetrated by water. They have a mechanism that regulates the opening of pores depending on CO_2 concentration and turgor inside the green organ (Hejnowicz 2002). While the mechanisms of stomata opening and closing are quite widely described in the literature, little is known about what happens to the stomata at the time of leaf fall. Considering that water scarcity causes a turgor decrease in stomatal cells and the closing of the stomata (Malinowski 1987), it may be expected that in the falling leaves/needles the stomata are closed. Nevertheless, as shown in Figure 6, presenting sample photographs of needle and leaf stomata from the Ol and Ofh horizons in both of the studied stands, the stomata of leaves in beech litter are open

(Fig. 6c) while in fragments of leaves from the Ofh horizons, the stomata are closed (Fig. 6d). Although at this stage of the research it is difficult to indicate the reason for these differences, the closed stomata in leaves from the Ofh horizon may impede the penetration of water into the leaf interior, which partly explains the prolongation of absorption time T_A and time t_{min} along with the advancement of the degree of decomposition of beech organic matter (Fig. 4-5). On the other hand, the wax that covers needles (Fig. 6a), and presumably makes it more difficult for water to penetrate the interior of undecomposed needles, undergoes degradation with progressing decomposition (Fig. 6b), which probably affects the acceleration of the water absorption rate and the decrease in time T_A and t_{min} along with an increase in the degree of decomposition of fir organic matter.

Due to the large macroporosity of litter, depending on the size of organic particles in its composition (Ilek et al. 2017), water retention in this horizon occurs mainly through the

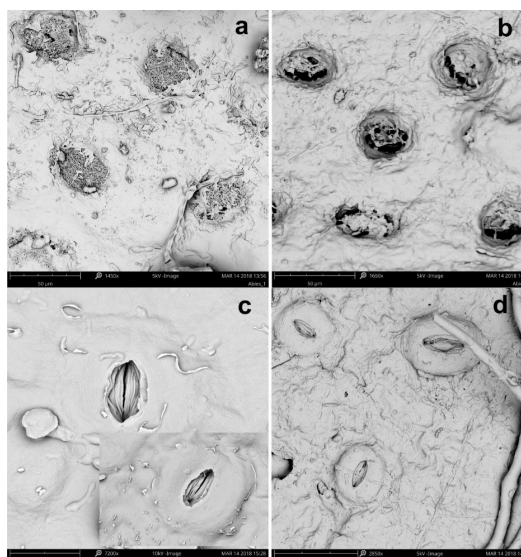


Figure 6 Sample photographs of *Abies alba* Mill. needle stomata covered with wax (a-b) and *Fagus sylvatica* L. leaves (c-d) collected from the Ol (a and c) and Ofh (b and d) horizons.

adsorption and absorption of water through undecomposed organic matter. Zhang et al. (2006) found that the rate of water absorption by undecomposed litter of various types of stands decreases rapidly in the first 6 hours of soaking; and in the first 8 hours in the case of partially decomposed litter. In both cases, most of the water was absorbed in the initial period of soaking, and the influence of the type of stand on the absorption rate was hardly noticeable. Similar results were obtained by Zhang et al. (2009) and Chen et al. (2018). Considering that in those studies the absorption rate was examined for 20 or 24 h of soaking the samples in water, those results may mainly reflect the process of filling the outer capillarity (between particles), retaining water on the surface of organic particles, and only partially the process of filling their internal capillarity. This is indicated by the dynamics of water absorbability shown in Figure 3. While the majority of organic particles of beech litter and the Ofh horizons of fir stands soak within the first 48 hours, the dynamics of water absorbability of organic particles of fir litter and beech Ofh horizons is more spread over time. The fact of reaching a density greater than $1 \text{ g} \cdot \text{cm}^{-3}$ by organic particles does not mean the end of the absorption process, but only the moment of achieving a certain high degree of saturation of internal capillarity of particles (Kucza 2007). The period of internal capillarity filling is of great importance in the dynamics of water retention by organic horizons of forest soils. The minimum time t_{min} , presented in Figure 5, indicates that despite the high porosity and low bulk density of the organic horizons of forest soils (Ilek et al. 2015), they can maintain the ability to retain water even in long-term rainfall. It should also be noted that despite the different dynamics of absorbability and different t_{min} values of in the Ol and Ofh horizons of the examined stands (Fig. 3 and 5), the cumulative percentage of organic matter sinking within 14 days, as determined for the O horizon, is similar in both stand types.

Conclusions

The research on water absorbability of beech and fir organic matter has shown that filling the internal capillarity of organic particles with water is a complex process that depends on many factors. It has been confirmed that water absorbability is influenced by the botanical origin of organic particles and the degree of their decomposition. In fir stands, the time of water absorption decreases with an increase of the decomposition index, while in beech stands an increase in the advancement of decomposition processes results in a prolonged time of water absorption by organic matter. A similar pattern applies to the minimum time necessary to fill internal capillarity. The dynamics of water absorption of organic matter, distributed over time, indicates that no single rainfall is able to entirely fill the internal capillarity of organic particles, whereby the organic horizons of forest soils can maintain the ability to retain water even in long-term rainfall. The knowledge of the influence of species composition on retention properties of the organic horizons and the dynamics of their rainwater retention may contribute to better management of the forest environment and to an awareness of how to affect it, thereby increasing the retention abilities of a catchment.

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