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ON THE SPECIFIC WATER HOLDING CAPACITY OF LITTER FOR THREE FOREST ECOSYSTEMS IN THE EASTERN FOOTHILLS OF THE ALPS

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Abstract

Forest ecosystems typically have a large leaf-area index both within the crown level and on the ground as litter, making interception a very important element of the forest water balance. Broad information exists about crown interception, but relatively few data are available regarding litter interception. The litter layer is able to change the quantities of water available for soil infiltration and runoff, so the water holding capacity of the litter is an important parameter for hydrological modelling. In this study the water holding capacity of the litter for three species (spruce, beech, sessile oak) was determined under field conditions in the eastern foothills of the Alps. Litter data were produced through a collection of about 450-500 samples over two years (2003-2005). Although the litter oven-dry weights of the forest stands were different, the specific water holding capacities [litres per kg oven-dry weight] of the litter were near-identical for needle-leaf and broad-leaf forest ecosystems. According to our measurements, the specific water holding capacity of the litter is about 2.0 – 2.1 litres kg^{-1} oven-dry weight, regardless of the tree species.

Keywords: interception, water holding capacity, litter, forest

1. Introduction

Rainfall arriving at forest stands reaches first the canopy level where tree crowns retain varying portions of it. Only a reduced amount of rainfall (stand precipitation) reaches the forest litter layer which can store and also evaporate significant amounts of water. A further portion of the rain passes through the litter at varying speeds depending on the litter morphology. While in the canopy only the surfaces of the leaves are wetted, within the litter water storage can also take place inside the tissues of the dead leaves. The speed of infiltration through the litter layer can further regulate the amount of the retained water in the forest litter.

Gerrits et al. (2007) considers interception as the portion of the rainfall volume over a given time period which is retained on the wetted surface after which it evaporates back to the atmosphere. Therefore, this process equals the change in interception storage (S_{int}) plus the evaporation (E_{int}) from that storage over the time period.

Interception is a very important term in the forest water balance, amounting to 15-50% of the total rainfall (Gerrits et al. 2010) even if it is not always considered as a significant process in hydrological models (De Groen and Savenije, 2006). It is true that interception can be negligible during large rainfall events leading to floods, but it can also strongly influence antecedent soil moisture conditions which is a very important factor for the generation of floods (Savenije, 2004).

Interception research generally concentrates on canopy interception, but interception by the forest floor and understorey vegetation can be of similar magnitude or sometimes even higher

(Gerrits et al., 2007). Between canopy and forest floor interception there are two main differences: a) the canopy has a larger evaporative potential than litter due to its better exposure to winds and enhanced surface roughness conducive to more effective transport of moisture into the air; b) canopy interception capacity is relatively small compared to that of the forest floor (Baird and Wilby, 1999).

Litter interception depends mostly on the litter mass per unit area but thickness, composition of litter, and the frequency of wetting/drying periods also have an influence on the process. The first three properties determine the storage capacity while the rainfall distribution (wetting/drying frequency) affects the evaporation of the stored water amount in the litter. Therefore, the water holding capacity is one of the most important variables for interception modelling.

Many studies have focused on the connection of litter and canopy interception (Helvey, 1964; Führer, 1992, 1994; Sitkey, 2006; Osuch et al., 2009; Gerrits 2010; Tsiko, 2012; Bullock and Jewitt 2012a), but fewer dealt with the moisture content of the litter with respect to surface runoff (Guevara-Escobar et al., 2007; Kim et al., 2014), flammability and fire spreading (Viney-Hatton, 1990; Cseresnyés and Csontos, 2007; Dimitrakopoulos-Papaioannou, 2001), litter decomposition and microbial activity (Schimel et al., 1999; Nagy et al., 2002).

Forest litter is able to store more water than its own dry weight (Juhász, 2002) up to its specific water holding capacity which cannot be exceeded even under long-duration rainfall events. Gerrits et al. (2010) analysed forest litter interception processes using field measurements while Sato et al. (2004) employed a laboratory approach, both evaluating the water holding capacity of the litter layer.

In this study the litter layer characteristics of three forest stands were examined and compared with the aim of deriving their specific water holding capacity values. This study in contrast to previous research, relies on sustained measurements, covering a period of several years employing a systematic sampling procedure with a large number of samples. These samples collected at the same time in three different tree species make a reliable comparison possible.

2. Materials and methods

For litter collection the approach of Helvey's (1964) methodology was followed. The litter sampling period started in October 2003 and ended in November 2005 at Hidegvíz Valley of Hungary at northern latitudes 47°35'08'' – 47°39'06'' and eastern longitudes 16°25'31'' – 16°28'15'' (WGS 84 datum) within the Sopron Hills of the eastern flanks of the Alps (*Fig. 1*). Three forest stands were selected for the present study: beech (*Fagus sylvatica* L., 1753), spruce (*Picea abies* (L.) Karsten, 1881) and sessile oak (*Quercus petraea* (Mattuschka) Liebl., 1784).

The general characteristics of the stands are listed in *Table 1*. The breast height diameter of the trees was manually measured on a 20 × 20 m sample area (the total number of measured trees for sessile oak, beech, and spruce were 76, 34, 92, respectively). Canopy closure and undergrowth density were estimated in the same sample area location. The leaf area index was determined by a manual method. The height and age of the forest stands were derived from the Hungarian Forestry Database. The average litter thickness was determined by taking undisturbed samples.

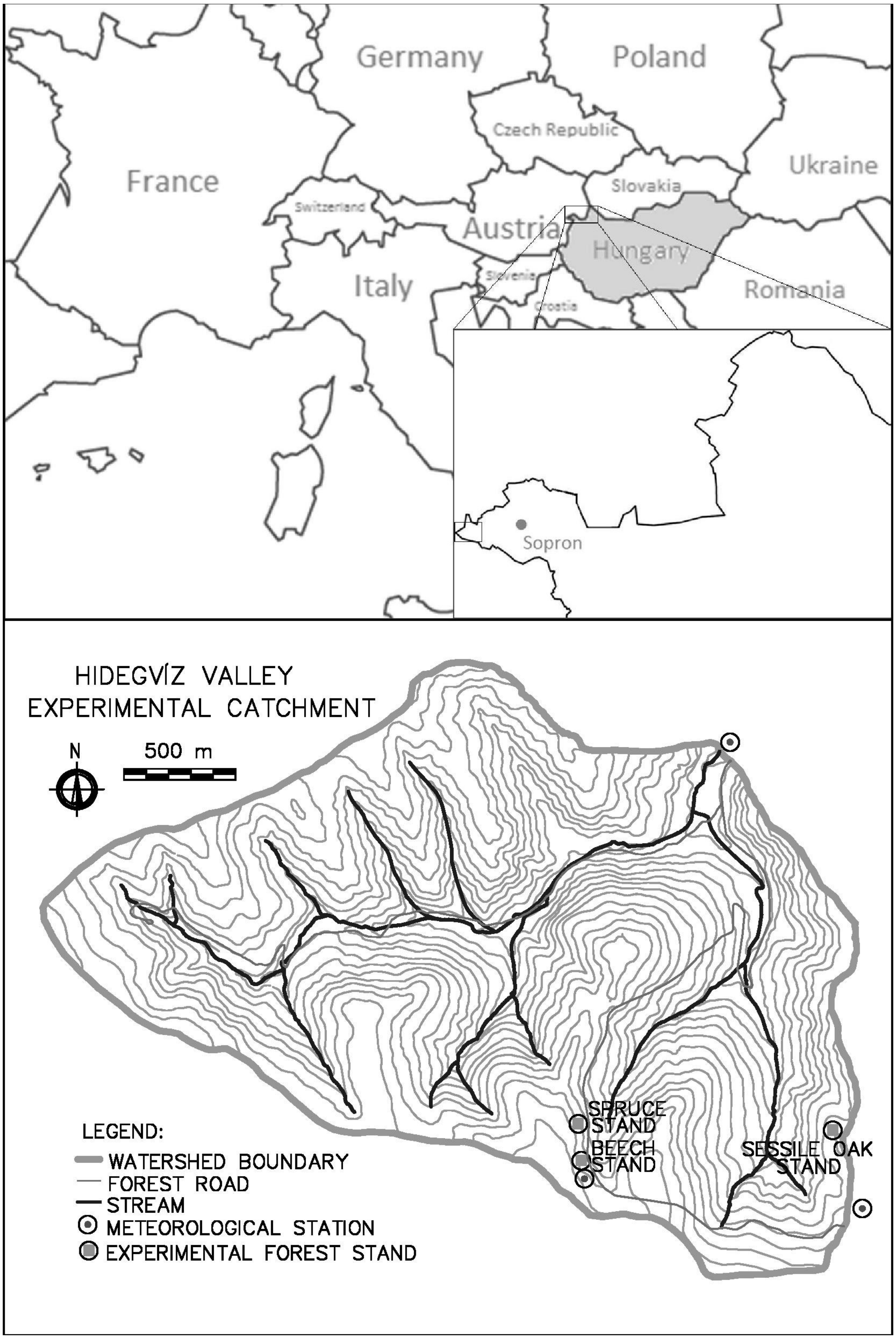


Fig. 1. Location of the study area

The area has a sub-alpine climate with daily mean temperatures of 19 °C in July, and -2 °C in January, and with an annual precipitation of 750 mm/year. Late spring and early summer are the wettest and fall is the driest season (Marosi and Somogyi, 1990; Dövényi, 2010).

Gross precipitation values were registered by an automatic rain gauge (Lat.: 47°39’21.16”, Lon.: 16°27’16.28”, 515 m a.s.l.), located about one km from the oak interception garden.

Table 1. General parameters for beech, spruce and sessile oak stands

	Mean tree height (m)	Mean breast height diameter (cm)	Age in 2003 (year)	Leaf Area Index	Under-growth*	Canopy closure (%)	Average litter thickness (mm)
Beech	17	17 ± 4.1	44	8	sparse	95	14 ± 6.0
Spruce	17	14 ± 4.9	33	11	-	100	16 ± 5.1
Oak	14	15 ± 3.5	37	6	rare	80	18 ± 4.3

*undergrowth means vegetated forest floor
±: standard deviation

2.1. Rainfall characteristics

The magnitude and distribution of rainfall events influence the water content of the litter, it is therefore necessary to briefly review the precipitation distribution over the sampling period (see *Table 2*). A total of 1,510 mm rainfall was measured between September 1, 2003 and November 10, 2005 within the study area (Zagyvainé, 2012) from altogether 340 rainfall events. It is worth noting that events smaller than 2 mm do not typically pass through the canopy (Kucsara, 1996). More than half of all the rainfall events (179) fell into this category, but their total sum barely exceeded 80 mm. On the contrary, there were only 10 relatively large (i.e., greater than 20 mm) rainfall events. Annual precipitation in the 2003 calendar year (493 mm/year) was far below the long-term average (so it was a very dry year) while 2005 (737 mm/year) was the wettest out of the three years the study period fell into. The annual precipitation in 2004 (683 mm/year) was closer to the 2005 than to the 2003 rainfall sum. Compared to the general climatic conditions of the region, the sampling period was altogether drier than normal.

Table 2. Distribution of the precipitation events during the sampling period (September 1, 2003 - November 10, 2005)

	Number of rainfall events	*Total sum (mm)*
0-2 mm	179	83.6
2-5 mm	56	185.7
5-10 mm	51	367.2
10-20 mm	44	607.1
20 mm -	10	266.7
Grand total	340	1510.3

2.2. Forest litter samples

Litter samples were collected from ten 40cm × 40cm plots along a time-varying baseline that was parallel to the contour lines (*Fig. 2*) under each forest stand. The distance between the samples was 1 m in each baseline provided it did not coincide with the location of a tree. Each consecutive baseline was set parallel with the previous one for every new sampling. The consecutive baselines were not affected by earlier sampling locations. The distance of the baselines was varied between 0.5 - 2 m. We found no significant differences in moisture content of the litter samples with regard to their distance to the tree trunks (Zagyvaine et al., 2013) within a given forest stand. It should be noted that our litter samples contained both un-decomposed and decomposed, but still recognizable, plant parts, and thus the reported values apply to such type of litter samples.

Sampling --depending on weather conditions-- have occurred weekly in the growing season. In the dormant season sampling was not so regular, due mostly to snow cover and frost effect.

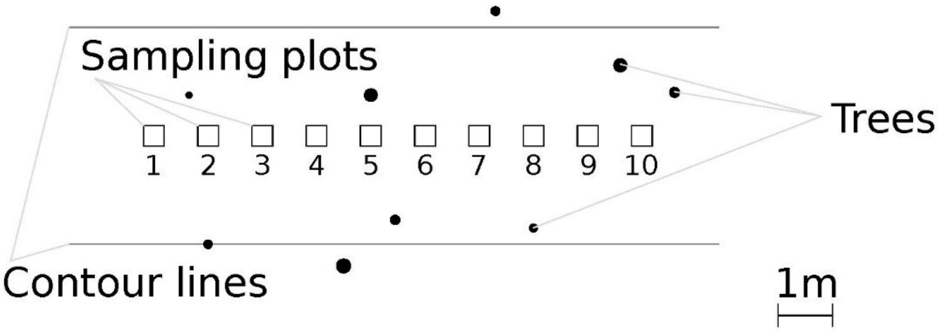


Fig. 2. Sampling layout (horizontal lines symbolize contour lines)

Only the non-biodegraded parts of the leaves and twigs thinner than 0.5cm were included in the samples. The soil, mull humus and branches thicker than 0.5cm were excluded. The samples were put into Ziplock plastic bags to prevent evaporation before weighing. After measuring field weight, the sample was oven-dried to a constant weight at 105°C and it was reweighed. Retained water amount was determined as the difference between field weight and oven-dry weight (representing 450-480 pairs of data for each forest stand). Oven-dry litter does not occur naturally, only air-dry one. The average difference between air- and the oven-dry moisture content was between 12-14% in our measurements (determined in the laboratory).

2.3. Statistical methodology

About five hundred samples per stand were collected for the analysis of litter water content. The analysis has been performed by the free R statistical software (R Core Team, 2012). Beside descriptive statistics and box-plot figures for a general analysis, a linear regression model was also employed for determining the specific water holding capacity.

The regression lines specify the maximum retained amount of water as a function of the litter oven-dry weight per unit area. The general equation of the straight lines is

$$w_{maxi} = \beta_0 + \beta_1 \bullet m_i + \varepsilon_i \tag{1}$$

where w_{max} is the maximum retained amount of water, i.e., water holding capacity [mm] as a response variable, β_0 is the intercept [mm], β_1 is the slope of the regression line [mm kg^{-1} m^2 or litres kg^{-1}], m is the litter oven-dry weight [kg m^{-2}] as a predictor variable, ε is the standard error of the regression (in the root mean-square-error sense) [mm], and index i denotes the i^{th} observation. Note that the slope, β_1, of the maximum water content line is called the specific water holding capacity.

Determination of the upper envelops for the water content values included the following steps. The data pairs were divided into bins of litter oven-dry weight with bin-widths of 100 g m^{-2} for sessile oak and beech, and 250 g m^{-2} for spruce. For each bin a data pair was derived representing the upper 5 percentile for both, the weight and water content, values separately (large circles in *Figs. 5-7*). For bins where the number of data pairs did not reach 20, no pairs of data were selected for regression. A linear regression line was then fit over the resulting data pairs for each stand using Eq. 1.

In Eq. *1.* β_0 was assumed to be zero from physical considerations as zero weight of forest litter has zero depth of retained water. Moreover, from a statistical viewpoint the fitted β_0 values were not significantly different from zero for any species. It may be noted that a bare soil surface (when there is no litter at all on the surface) can exert nonzero interception but that scenario is very different from the present situation.

For further examination of seasonal changes, monthly groups were created from the data taken after the 21th of October, 2003, the date the sampling protocol had been established. The aim of the monthly examination is to check if the distributions of the monthly data are identical or not. For samples with a normal distribution the choice of ANOVA would be appropriate, but the distribution of the samples is not normal (for several months there are outlier elements or significant skewness).

Based on the assumption of independent samples, monthly values were compared employing the Kruskal–Wallis test by ranks to see if they represent the same distribution. This statistical method was purposefully chosen for comparison because of the outliers and kurtosis as well as skewness found in the monthly distributions (Conover-Iman, 1979). The non-parametric Conover-Iman (1979) test with the Bonferroni correction was further employed for pairwise comparison of the monthly median values as the Kruskal-Wallis test failed (i.e., the monthly distributions are not identical at the chosen significance level).

3. Results

3.1. Oven-dry weight of forest litter

As a first step of the analysis, the oven-dry weight of litter samples were examined. The distribution of the oven-dry weights (kg m^{-2}) are displayed in *Fig. 3* as box-plots. The median weight of spruce litter was 1.89 kg m^{-2} with a standard deviation of 0.56 kg m^{-2}. Samples with extremely large litter weight, i.e., more than 4 kg m^{-2} (maximum: 4.34 kg m^{-2}) have also occurred. These samples were collected near to decaying tree trunks and emerging roots where litter accumulates naturally.

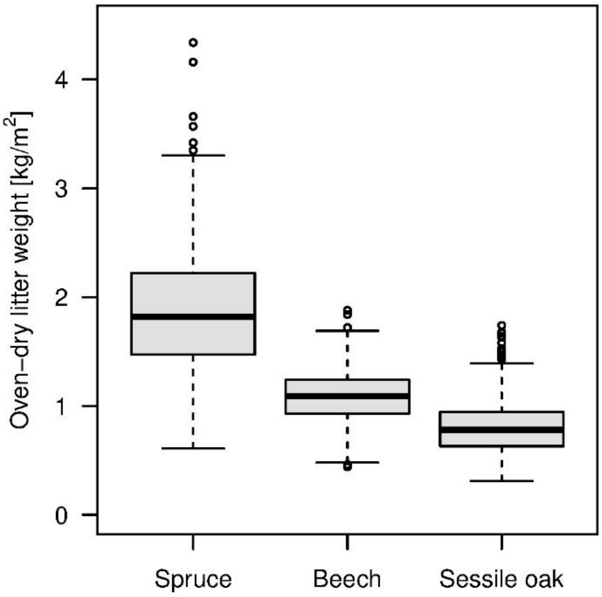
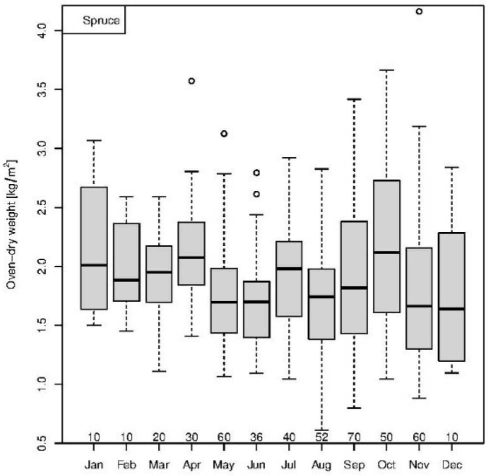


Fig. 3. Box-plots of oven-dry weight values for spruce, beech and sessile oak litter samples

The median weight of beech litter was 1.09 kg m^{-2} with a standard deviation of 0.24 kg m^{-2}. The maximum values of the samples were around 1.8 kg m^{-2}.

The sessile oak litter samples can be characterized by the lowest values of oven-dry weight, not exceeding 1.74 kg m^{-2}. The median value of the samples is only 0.81 kg m^{-2} with a standard deviation of 0.25 kg m^{-2}.

As seen, there is a significant difference between the tree species. Spruce litter has the largest oven-dry weight, almost twice as large as beech, and more than twice as much as oak stands. By comparing coefficients of variation (spruce: 0.30; beech: 0.22; oak: 0.31) the oven-dry weights of beech litter seems to be the most homogenous while spruce and oak litter samples were similarly variable.



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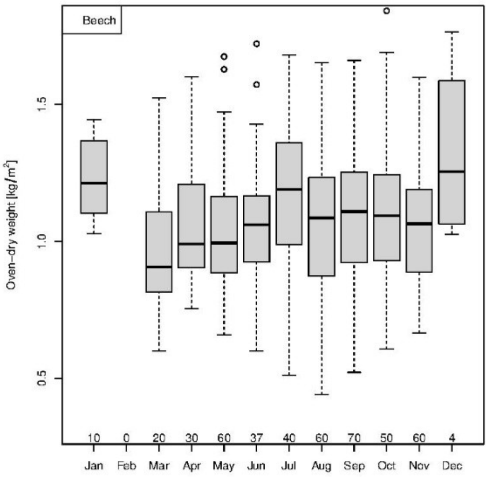

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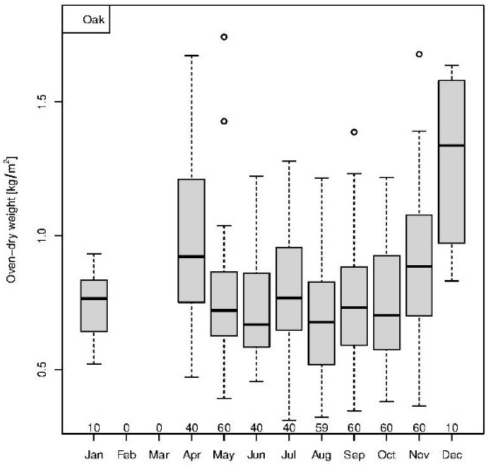

c.

Figure 4. Monthly boxplot of litter oven-dry weights from three stands (a. spruce, b. beech, c. oak)

Seasonal changes in the oven-dry weights are displayed in Fig 4. The possible seasonal change in oven-dry weights (representing storage capacity) cannot be regarded as a time series. The main reason is that the destructive, rowing sampling along the contour lines yields independent samples for each time step. The monthly data are visualised as box-and-whiskers plots for each forest stands (Fig. 4). The median lines of the boxplots in Figure 4 illustrate that there is no dominant seasonal variation in the oven-dry weight (which represents also storage capacity). This is probably so because additional new leaves during the end of the growing season do not represent a significant amount of mass change in comparison with earlier settled litter on the forest floor. Although not a dominant seasonal cycle, some increases appear in the broadleaved species, especially oak, at the beginning of the dormant season. Based on the results of the Kruskal-Wallis test ($p_{max} = 0.0028$), the distribution of at least one month differs for each species, so the null hypothesis of the Kruskal-Wallis test of identical distributions among months can be rejected at a 99% confidence level. Even though the distributions of the monthly oven-dry weights may not be identical for each month, the Conover-Iman test concludes that the median values of the months cannot be rejected to be identical at a 99% confidence level (even in April, November, December for oak and March, July for beech).

For the present analysis it therefore can be concluded that the differences between monthly dry weights are not significant, especially when inherent difficulties of the sampling process (e.g., huge variability of litter layer thickness) are also taken into consideration.

3.2. Water content of forest litter

The scatter plots (*Figs. 5-7*) display the water content (mm) as a function of leaf litter dry-weight per unit area. The data-clouds display significant differences between species in both, oven-dry weight and water content, values during the two years of investigation, but the upper envelopes (denoted by large circles) of the weight vs water content relationship, representing the maximum water content, look very similar in their slopes, even though their maximum observed values are quite different. This difference in maximum water content is most visible between the spruce and the other two, deciduous stands. While for sessile oak and beech stands the measured maximum water content did not exceed 4 mm, for spruce even a 5-7 mm water retention could be achieved. Points below the large circles in the scatter plots represent those events where the rain depth was less than the maximum water holding capacity of the litter.

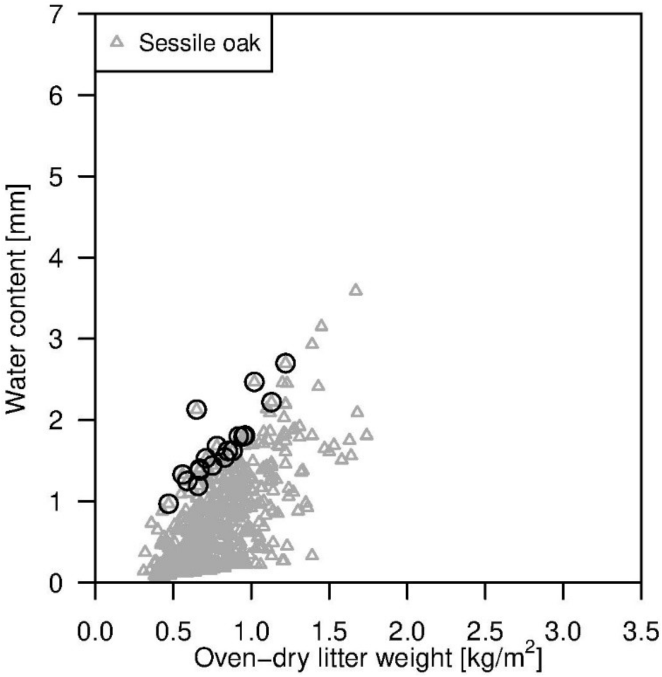

Fig. 5. Water content of sessile oak litter samples as a function of the oven-dry weight. Large circles indicate the upper envelope points (upper 5-percentile of water content)

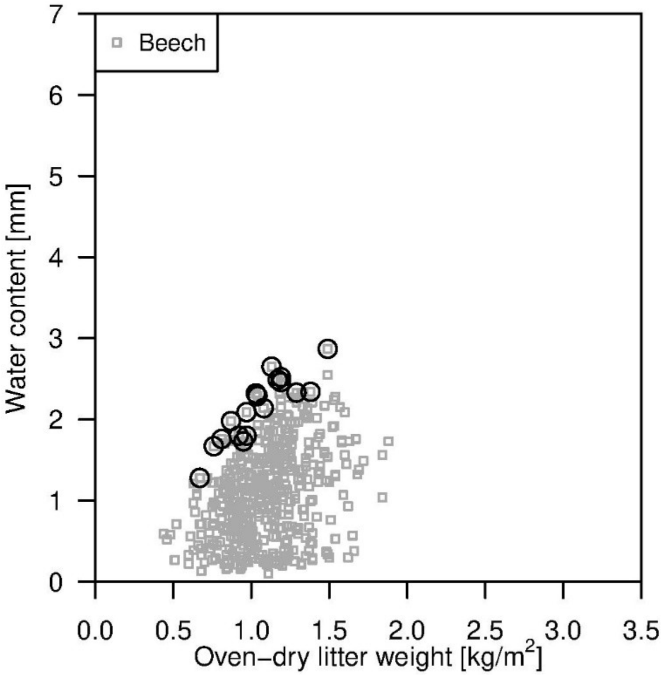

Fig. 6. Water content of beech litter samples as a function of the oven-dry weight. Large circles indicate the upper envelope points (upper 5-percentile of water content).

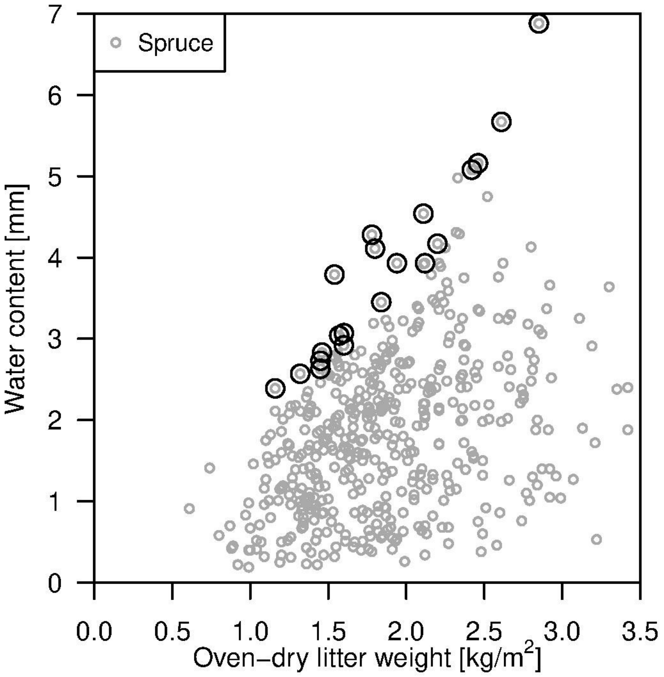

Fig. 7. Water content of spruce litter samples as a function of the oven-dry weight. Large circles indicate the upper envelope points (upper 5-percentile of water content)

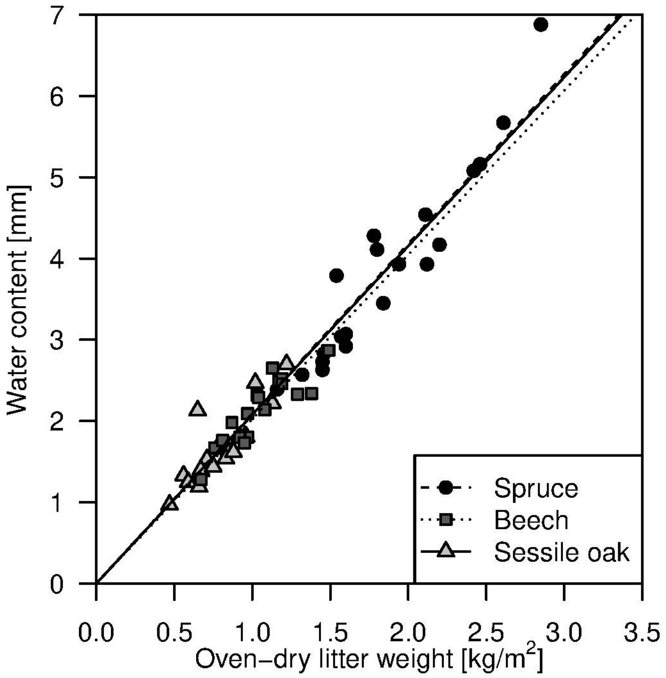

Fig. 8. Maximum observed water content for sessile oak, beech and spruce litter samples as a function of litter oven-dry weight per unit area

As seen in *Fig. 8*, the slopes (β_1) are practically identical: for spruce and sessile oak 2.09 and 2.08 litres kg^{-1}, respectively, slightly different from that of beech: 2.02 litres kg^{-1} (Table 3). The claim by Sato et al. (2004) that coniferous litter has a larger specific water holding capacity than deciduous litter is not confirmed by our data.

Table 3. Regression parameters for beech, spruce and sessile oak stands

	Estimate (β_1) [l/kg]	**Std. Error (ε) [mm]**	**R^2**
Beech	2.02	0.04555	0.9915
Spruce	2.09	0.04581	0.9910
Sessile oak	2.08	0.06646	0.9819

Note: ε in Eq.1. is represented by the Std. Error.

The practically identical β_1 values tell us that there is no significant difference in the specific water holding capacities between the tree species, at least in this forest. Thus the water holding capacity of forest litter depends only on the oven-dry weight of litter per unit area, independent of the type of leaves (i.e., needle- or broad-leaved) it is composed of. The oven-dry weight per unit area in turn depends on tree species, age, climate and other conditions, thus indirectly influencing the water holding capacity.

Water holding capacity of a forest stand can be calculated by multiplying the oven-dry litter weight and the specific water holding capacity. Comparing water holding capacities of our ecosystems (Table 4.) it can be stated that sessile oak litter has the lowest value, i.e., 1.66 l/m^2. Beech litter water holding capacity is more than 30 % higher than that of oak litter. Spruce litter has the highest water holding capacity, which is more than 2.4 times higher than the value for oak litter.

Table 4. Summary of litter mass and water holding capacity values

	Oven-dry weight of litter (kg m^{-2})	**Standard deviation of oven-dry weight of litter (kg m^{-2})**	**Sampling number (pcs)**	**Specific water holding capacity (litres kg^{-1})**	**Water holding capacity (mm)**
Beech	1.09	0.24	457	2.02	2.20
Spruce	1.89	0.56	473	2.09	3.95
Sessile oak	0.81	0.25	479	2.08	1.66
Average	1.26		469	2.06	2.60

4. Discussion

According to our measurements one kilogram of leaf litter can store 2.02-2.09 litres of precipitation equalling 200-210% of its own weight. This finding is supported by Helvey (1964), who characterized the maximum water content of forest litter as a percentage of dry weight and found it between 210-215% for a mixed deciduous stand. Blow (1955) published a similar value (225%) for the specific water holding capacity of litter for an oak forest. Schaap and Bouten (1997) measured forest floor evaporation with a weighing lysimeter (containing 30 cm soil and undisturbed forest floor above it) in a 30-year old Douglas fir stand in the Netherlands. From their data the specific water holding capacity of a representative 5cm thick forest floor can be estimated as 200%.

Several authors have estimated the water holding capacity of forest litter under laboratory conditions. Lowdermilk (1930) estimated it for pine and mixed pine-cedar stands using saturation experiments. According to his measurements, the average water holding capacity is 180% of the air-dry weight of litter. By converting the air-dry weight to oven-dry weight, his result of 195-215% matches our measurements. In laboratory experiments Sato et al. (2004) measured much lower values of average water holding capacity (for *Lithocarpus edulis* and *Cryptomeria japonica*), but they examined largely the upper, relatively un-decomposed litter layer (the decomposed litter was removed from the samples). Otherwise, in their Fig. 5 the upper envelopes (defined as SD over the average) of the specific water holding capacities indicated similar values for lower litter mass (below 1.5 kg) as in our experiment. Their two forest types had equal specific water holding capacity under fully saturated conditions, and the values of storage capacities expressed a linear relationship with the litter mass regardless of the thickness of the forest floor. Kim et al. (2014) determined similarly low (via typically higher litter weights) values in a long-lasting (24 hours) saturation experiment. However maximum water storage capacity values below 1 kg litter weight was very similar to that determined in our field experiment. The water holding capacity was obtained by them through linear relationships (similar to ours) for different tree species, however, their equations display (due to a non-zero intercept value) water retention even for the absence of litter. Guevara-Escobar et al. (2007) determined the water holding capacity of litter by a short-duration (i.e., six hours) experiment. Their rainfall simulation lasted for a combined three hours (i.e. three times one hour) with two rain breaks (one and two hours) in between. By longer rain events to bring the litter to full saturation their values might have approached the results of the present study. Bullock and Jewitt (2012a) measured litter interception with only forest-floor filled lysimeters combined with tipping bucket rain gauges in three different forests (representative dominant tree species were Eucalyptus grandis, Acacia mearsnsii and Pinus patulata) in South Africa. They determined litter storage capacity of representative samples using a saturation experiment in a laboratory (Bullock and Jewitt, 2012b). Employing their data of litter mass significantly different specific water holding capacities can be calculated for the different species (E. grandis 113%, A. mearnsii 75%, P. patulata 135%). Zagyvainé (2012) determined the forest litter water holding capacity of the same forest stands described in Table 1 during a short duration (one hour) saturation experiment in a laboratory. The following specific water holding capacities were obtained: sessile oak 128%, beech 124%, spruce 78%.

It seems that the specific water holding capacities determined in a laboratory during a short time experiment are significantly lower than those measured in a field experiment. The main cause of this relatively large underestimation can be the shorter time-span of saturation in the laboratory experiments. During field conditions water probably also moves inside the tissues of the dead leaves,-thus enhancing the storage capacity. The adsorbed water inside these dead plant tissues may be the cause that the specific water storage capacity of the litter is not considerably different by the tree species. The specific surface of the different litter species may be different, but there is no significant difference in the density of leaf tissue (Redding et al., 2005).

There can also be an effect of snow cover on litter maximum storage capacity. As Gerrits et al. (2010) note if snow events occur, the leaves are flattened due to the snow weight, causing a smaller storage capacity, but if no snow occurs, the leaves retain their original shape, with larger storage capacity. Therefore snow events can have a strong influence on storage capacity if thick and longer lasting snow cover appears. During our sampling period only rare and thin snow cover happened in our experimental catchment, therefore snow could not significantly influence water holding capacity of the forest litter in the forest stands. Due to climate change projections more rain and less snow will be more likely during winter therefore the effect of snow cover will be increasingly less significant in lower elevations of Central Europe. Nevertheless, for higher elevation sites and for forest ecosystems at higher latitudes the effect of snow on litter storage capacity needs further evaluation.

Conclusions

In the present study the oven-dry weight and water content of forest litter and their relationship were analysed via field experiments for three tree species: sessile oak, beech and spruce. A large number of litter samples were collected over a two-year sampling period between 2003 and 2005. It was found that spruce had the largest litter mass per unit area (1.9 kg m^{-2}) followed by beech (1.1 kg m^{-2}), and sessile oak (0.8 kg m^{-2}).

No significant difference was found for the specific water holding capacity of litter between the examined tree species (beech: 2.02 litres kg^{-1}, spruce: 2.09 litres kg^{-1}, oak: 2.08 litres kg^{-1}), thus water holding capacity depends solely on the litter oven-dry weight (*Table 4*), making it simple to estimate. From a detailed study of literature on field investigations, it can be established that different authors in almost every case have already demonstrated (although may have been unbeknownst to them) the conclusion of the present article that the specific water holding capacity of the leaf litter is independent from tree species.

This result is well suited for numerical models because once the weight of the litter is known, the water holding capacity of the litter can be estimated immediately without further knowledge on the percent composition of the litter by tree species. Water holding capacity of our forest stands were significantly different (beech: 2.2 mm, spruce: 3.95 mm, oak: 1.68 mm) because dry weights of litter also varied.

Based on our results the average value of the specific water holding capacity of 2.06 litres kg^{-1} (Table 4) can be recommended for the estimation of litter water holding capacity for forest ecosystems in temperate zones, provided there is no significant snow compaction effect.

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