*Acta hydrotechnica* **31/54 (2018)**, Ljubljana
ISSN 1581-0267

***Open Access Journal***
***Odprtodostopna revija***

UDK/*UDC*: 551.578.1:582.091(497.4)
Izvirni znanstveni članek – *Original scientific paper*

Prejeto/*Received:* 30.11.2017
Sprejeto/*Accepted:* 23.01.2018

# SPATIAL VARIABILITY OF THROUGHFALL UNDER SINGLE BIRCH AND PINE TREE CANOPIES

# PROSTORSKA SPREMENLJIVOST PREPUŠČENIH PADAVIN POD KROŠNJAMA BREZE IN BORA

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## Abstract

The influence of tree characteristics and meteorological variables on spatial variability of throughfall under a single silver birch and black pine tree was evaluated. During the year 2016 throughfall was measured at 11 points under each tree canopy. For 30 analysed events total throughfall under the birch tree accounted for 73% and under the pine tree 56% of the rainfall in the open. The coefficient of variation of point throughfall was 30% and 40% for the birch and pine tree, respectively. In case of the birch tree both the distance from the stem and canopy coverage influenced throughfall spatial variability, which also showed different patterns during leafed and leafless periods. Additionally, the amount of rainfall and its microstructure influenced the spatial variability of throughfall under the birch tree. However, among the considered tree characteristics only canopy coverage was recognized as a parameter influencing spatial variability of throughfall under the pine. Furthermore, its spatial patterns were specified by meteorological variables, namely the amount of rainfall and its intensity.

**Keywords:** rainfall interception, throughfall, spatial variability, spatial distribution, *Betula pendula*, *Pinus nigra*.

## Izvleček

Obravnavali smo vpliv lastnosti dreves in meteoroloških spremenljivk na prostorsko spremenljivost prepuščenih padavin pod drevesnima krošnjama navadne breze in črnega bora. Delež prepuščenih padavin smo merili leta 2016 v 11 točkah pod krošnjama. Za 30 dogodkov, ki smo jih vključili v analizo, je delež prestreženih padavin pod brezo znašal 73 %, pod borom pa 56 % padavin na prostem. Koeficient variacije točkovno izmerjenih prepuščenih padavin je znašal 30 % v primeru breze in 40 % v primeru bora. Na prostorsko spremenljivost prepuščenih padavin pod brezo sta vplivali tako oddaljenost od drevesnega debla kot tudi pokritost s krošnjo. V obdobjih olistane krošnje in v obdobju mirovanja je razporeditev prepuščenih padavin pod krošnjo breze tvorila drugačne vzorce. Poleg tega sta na prostorsko porazdelitev prepuščenih padavin pod brezo vplivali tudi količina padavin in njihova mikrostruktura. Ne glede na to, pa je med obravnavanimi lastnostmi dreves na razporeditev prepuščenih padavin pod borom vplivala le pokritost s krošnjo. Na te prostorske vzorce sta vplivali še količina padavin in njihova intenziteta.

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https://doi.org/10.15292/acta.hydro.2018.01

**Ključne besede:** prestrežene padavine, prepuščene padavine, prostorska spremenljivost, prostorska porazdelitev, *Betula pendula*, *Pinus nigra*.

## 1. Introduction

The researchers have been studying the process of rainfall interception for quite some time (e.g. Hoppe, 1896; Horton, 1919) as it was recognised as an important part of the hydrological cycle, influencing surface runoff, ground water recharge, the nutrient cycle, soil modification, and leaching of agrochemical products (Gómez et al., 2002). Precipitation falling above the canopy is distributed into three main components: throughfall, stemflow, and rainfall interception. Rainfall interception evaporates back into the atmosphere and does not reach the ground, and therefore contributes neither to surface runoff nor to groundwater recharge. The remaining precipitation captured by vegetation eventually reaches the ground as throughfall (falling through the gaps between leaves and branches or dripping from them) or stemflow (flowing down the stem). Rainfall redistribution has been broadly researched for various types of vegetation such as agricultural plants (e.g. Parkin and Codling, 1990; Frasson and Krajewski, 2011; Bäse et al., 2012; Ma et al., 2015), bushes (Martinez-Meza and Whitford, 1996; Garcia-Estringana et al., 2010; Zhang et al., 2016) and most commonly trees in forests (Iroume and Humer, 2002; Dietz et al., 2006; Šraj et al., 2008a; Muzylo et al., 2012; Pérez-Suárez et al., 2014; Vilhar et al., 2015; Sun et al., 2017) or single trees (Xiao et al., 2000; Gómez et al., 2002; Guevara-Ecobar et al., 2007; Šraj et al., 2008b; Livesley et al., 2014, Zabret and Šraj, 2015; Zabret et al., 2017).

Throughfall largely varies in space and in time (Keim et al., 2005; Staelens et al., 2006; Nanko et al., 2011). This has potential effects on ion loading, trace gas fluxes, and solute leaching (Hansen, 1995), distribution of water content in the soil (Raat et al., 2002), atmospheric depositions (Zirlewagen and von Wilpert, 2001; Kowalska et al., 2016), the composition of vegetation species in undergrowth (Falkengren-Grerup, 1989), surface runoff generation and soil erosion (Nanko et al., 2010). It also influences sampling strategies and the interpretation of throughfall data (Carlyle-Moses et al., 2004; Zimmermann et al., 2007; Fang et al., 2015; Voss et al., 2016). The spatial variability of throughfall is the consequence of lateral translocation of the intercepted rainfall in the tree canopy (Frischbier and Wagner, 2015). However, the translocation itself depends on many different parameters, described by tree properties (Zabret, 2013) and rainfall characteristics. Carlyle-Moses et al. (2004) reported the influence of different tree characteristics (canopy and understory cover fraction, vegetation area index, distance to nearest stem, the basal area and height of the tree) on the spatial variability of throughfall for rainfall events with less than 5 mm, Gómez et al. (2002) observed consistent throughfall patterns for high rainfall events, and Keim and Link (2018) measured that at locations with high throughfall values throughfall had intensities similar to rainfall. However, the influence of tree characteristics is more often addressed. Gerrits et al. (2010) recognised as an influential parameter the seasonal patterns of tree canopies, and similarly Staelens et al. (2006) assigned spatial heterogeneity of throughfall ions to leaves in the growing period and to branches in the leafless period. Additionally, Dohnal et al. (2014) reported increasing the throughfall amount with decreasing crown closure, whereas specific canopy characteristics were emphasised by Nanko et al. (2011), who observed that throughfall spatial variability is connected to the canopy shape and position of branches. Fang et al. (2015) noticed increased concentration of throughfall at the canopy edge due to down-facing branches inducing the edge effect, and Shachnovich et al. (2008) observed a downward curving branch above the point that consistently received more throughfall.

Spatial variability of throughfall was mainly addressed on study plots in forests (e.g. Konishi et al., 2006; Shachnovich et al., 2008; André et al., 2011; Kato et al., 2013; Dohnal et al., 2014; He et al., 2014; Siegert et al., 2016; Keim and Link, 2018), whereas studies run under single tree canopies are quite rare (Gómez et al., 2002;

Staelens et al., 2006; Guevara-Escobar et al., 2007; Nanko et al., 2011; Fang et al., 2015), and as far as we know none have been conducted in an urban area. Trees in urban areas have an important role, as they reduce surface runoff due to rainfall interception (Armson et al., 2013; Livesley et al., 2014; Zabret and Šraj, 2015), influence the evaporation and infiltration of retained water (Berland and Hopton 2014), improve the air quality, reduce atmospheric CO2, and help reduce energy consumption (McPherson et al. 2005). The results of studies from the forest varied according to the meteorological characteristics at the study plot, properties of the observed trees, and also the type of forest (deciduous or coniferous). Significant differences between coniferous and deciduous trees were observed in mixed forests (Kowalska et al., 2016). Therefore the main aims of this study are: (i) to evaluate the influence of tree characteristics and meteorological conditions on the spatial variability of throughfall under a single canopy, and (ii) to address the differences in throughfall spatial variability for deciduous and coniferous tree.

## 2. Materials and methods

The experimental plot is situated in the city of Ljubljana, Slovenia (46.04° N, 14.49° E; 292 m above sea level). It covers approximately 600 $m^2$ of lawn with two groups of trees in the western part. A group of black pine trees (*Pinus nigra* Arnold) grows on the north-west part of the plot and a group of silver birch trees (*Betula pendula* Roth) on the south-west part. The climate in the study area is subalpine, with subcontinental and maritime influences. The average long-term (1986–2016) annual temperature is 11 °C, with the average monthly temperature ranging from –3 °C to 24 °C. The average annual rainfall amounts 1380 mm, with the maximum monthly precipitation mainly recorded in autumn with a mean monthly value of 146 mm (ARSO, 2017).

Rainfall in the open was measured on the clearing in the north-east part of the experimental plot with a tipping bucket (0.2 mm/tip) rain gauge (RG2-M, Onset Computer Corp., Bourne, MA, USA) equipped with an automatic data logger (HOBO Event, Onset Computer Corp., Bourne, MA, USA). Additionally, rainfall microstructure (drop velocity and diameter, number of drops) was measured with a disdrometer (OTT Parsivel, OTT Hydromet, Loveland, CO, USA) positioned on the rooftop of the nearby two-storey building. The measuring area of the disdrometer is 54 $cm^2$, measuring drop velocity from 0.05 m/s to 20.8 m/s and drop diameter from 0.312 mm to 24.5 mm. Data on other meteorological variables (air pressure, air temperature, relative humidity, wind direction, and wind speed) were obtained from the nearest Slovenian Environment Agency's meteorological station Ljubljana-Bežigrad, located 3 km northeast from the experimental site.

Throughfall was measured under each single tree species. Two steel trough gauges with an area of 0.75 $m^2$ were positioned from the stem to the edge of the canopy. One was connected to 10-litre and 50-litre containers, which were emptied regularly. Another one was equipped with a tipping bucket flow gauge (Unidata 6506G, Unidata Pty Ltd, O'Connor WA, Australia) and an automatic data logger (HOBO Event, Onset Computer Corp., Bourne, MA, USA). Under the part of the isolated canopy (without the influence from the buildings or overlapping with other canopies) of each tree species 11 manually-read funnel-type gauges with 1-litre capacity and a 0.008 $m^2$ catch area were placed 1 m above ground in a concentric pattern (Figure 1).

The main characteristics of the trees were evaluated using several approaches (Table 1). Tree height, crown area, and branch inclination were estimated from the photos, and the diameter at breast height (DBH) was measured on site. The bark storage capacity was determined in the laboratory, where three bark samples for each tree were first soaked in water for 24 hours and then dried at 40 $^0$C until their weight stopped declining (Pérez-Harguindeguy et al., 2013). Leaf area index (LAI) was measured with LAI-2200C Plant Canopy Analizer (LI-COR Inc., Lincoln, Nebraska, USA). During the periods of leaf-growth and leaf-fall LAI measurements were taken daily, while during the leafed and leafless periods LAI was measured monthly. For each tree measurements with 90° lens shutter were taken above and below the canopy in four repetitions. Measurements were adjusted according to the canopy profiles using FV2200 software (LI-COR Biosciences, 2010). The LAI values measured for pine trees were corrected for clumping and non-leafy materials (Jonckheere et al., 2005).

Also four vegetation periods were determined, namely the leafed period, leaf-fall period, leafless period, and leafing period. The start and end date of each period were determined based on the observations of the leaf conditions in the birch tree canopy and according to the measured LAI values. Above the throughfall measurement points network (Figure 1) the canopy cover (percentage of sky covered with branches and leaves) was calculated from the photographs, taken with Sony DSC-RX100M2 camera in 1.4-times magnification parallel to the floor above each funnel-type throughfall gauge during the leafed period. Photographs were cropped using ImageJ software (Schneider et al., 2012) to a size of 2200 x 3080 pixels and converted into 1-bit pictures. Based on the ratio between black and white pixels the canopy cover over each throughfall measurement point was estimated (Table 2).

The rainfall events were defined based on at least a 4-hour dry period between the end of the previous and the beginning of the next rainfall event. For each event the disdrometer's raw data were used to evaluate average rainfall microstructure. Data was analysed using R, a software environment for statistical computing and graphics (R Core Team, 2015). The data of throughfall spatial distribution for each event was visualized on heatmaps for better understanding and interpretation of the measured values in the real situation. The heatmaps were compiled using package lattice (Sarkar, 2017) in R software. The similarities between the patterns of throughfall spatial distribution presented on the heatmaps were searched using the Orange software suite (Demsar et al., 2013), which clustered heatmaps using a hierarchical clustering approach with Ward's method and cosine distance. For each cluster the meteorological variables of the assigned events were analysed in order to see their influence on throughfall spatial distribution and its patterns. To analyse the influence of the vegetation parameters, which do not change with the rainfall event but with the measurement point, decision trees were used that were constructed using the "rpart" package (Therneau et al., 2017). The relationship between throughfall and the variables was tested with linear regression.

***Figure 1:** Location of the funnel-type throughfall gauges, marked with red points (left birch tree, right pine tree). Black lines indicates the position of through gauges.*

***Slika 1:** Lokacije točkovnih merilnikov prepuščenih padavin, označenih z rdečimi točkami (levo – breza, desno – bor). Črni okvirji označujejo postavitev merilnih korit.*

***Table 1:*** *Characteristics of groups of birch and pine trees.*

***Preglednica 1:*** *Značilnosti skupine dreves navadne breze in črnega bora.*

| | Average height [m] | Average DBH [cm] | Total crown area [m$^2$] | Bark storage capacity [mm] | Average branch inclination [°] | LAI - leafless period | LAI - leafed period |
|---|---|---|---|---|---|---|---|
| Birch trees | 15.7 ± 1.0 | 17.9 ± 0.4 | 42.3 | 0.7 | 51 | 0.87 ± 0.30 | 2.30 ±0.46 |
| Pine trees | 12.6 ± 0.6 | 19.0 ± 2.3 | 22.7 | 3.5 | 98 | 3.47 ± 0.52 | 4.37 ±0.52 |

***Table 2:*** *Canopy cover above the throughfall measurement points for each tree species.*

***Preglednica 2:*** *Pokritost s krošnjo nad točkami merilnikov prepuščenih padavin za obe drevesni vrsti.*

| Point | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Birch tree | 76.6% | 82.6% | 69.9% | 79.2% | 83.0% | 80.4% | 73.7% | 83.2% | 74.8% | 73.5% | 83.9% |
| Pine tree | 90.5% | 85.5% | 92.7% | 90.3% | 85.9% | 87.8% | 83.2% | 85.5% | 89.9% | 87.4% | 87.2% |

## 3. Results

### 3.1 Rainfall and throughfall

Rainfall in the open and throughfall as a percentage of rainfall in the open reaching the ground under the trees were measured from 1 January to 31 December 2016. During the analysed period 113 rainfall events were detected, delivering a total of 1139 mm of rainfall. The amount of rainfall per event varied between 0.2 mm and 93 mm. The majority of rainfall events the (72) occurred in the leafed period, delivering 698.6 mm of rainfall. During the leafless period 35 rainfall events were detected, during leafing 2, and during leaf-fall 4 events. The rainfall events lasted on average 9.7 (± 12.3) hours, with the longest rainfall event lasting for almost 3 days (67 hours). Rainfall intensity was on average 1.8 (± 3.3) mm/h.

Throughfall under the birch tree was measured during 90 events and in total delivered 831.6 mm of rainfall. On average per event it was equal to 51% (± 32%) of rainfall in the open with significant differences between vegetation periods: 65% (± 29%) in the leafless period and 45% (± 31%) in the leafed period. Under the pine tree throughfall occurred during 77 events and accounted for 639.2 mm. Throughfall amounted 26% (± 26%) of rainfall in the open on average per event with noticeable differences in the leafless (33 ± 25%) and leafed (23 ± 27%) periods.

Spatial variability of throughfall was analysed for 30 rainfall events with complete data of rainfall in the open with at least 5 mm of rainfall and throughfall measurements at 11 points under both considered tree species. The events extended over all vegetation periods: 18 events were detected during the leafed period, 1 event during the leaf-fall period, 9 events during the leafless period, and 2 events during the leafing period. Due to the small number of events in transitional periods, they were assigned to the leafed or leafless period according to the values of LAI at that time. Selected events delivered 738.8 mm of rainfall, which varied between 5.6 mm and 93 mm per event. The intensity of the events was between 0.4 mm/h and 7.3 mm/h and the average duration was 16.1 (± 13.7) hours. The average wind speed per event ranged from 0.7 m/s to 3.4 m/s and the event's average temperature ranged from 2.8 °C to 23.9 °C. Additionally, rainfall microstructure was measured, resulting in average event drop velocity of 3.85 m/s (± 0.37 m/s), drop diameter of 0.69 mm (± 0.14 mm), and the number of drops at 3,143 (± 2,999) per cm$^2$. For selected rainfall events average throughfall under the birch tree varied between 24% and 92% of rainfall in the open and on average accounted for 71% (± 15%), whereas under the pine tree ranged from 9% to 97% and was on average equal to 48% (± 23%) of rainfall in the open.

To evaluate spatial variability of throughfall under birch and pine trees, throughfall was measured at 11 points under each tree species canopy (Figure 1). The coefficient of variation (CV) of the event point throughfall decreases with the amount of rainfall (Figure 2). The average value of CV for birch tree was 31%, varying between 12% for events in the leafed period and 59% for events in the leafless period. The values of CV of throughfall under the pine tree varied between 15% and 68%, both measured in the leafless vegetation period, with an average value of 42%.

The average point throughfall increases with rainfall amount and stabilizes at larger rainfall amounts of more than 28 mm for both considered trees (Figure 3, Figure 4). For the birch tree the percentage of throughfall for events with more than 28 mm depends on vegetation period, as it on average equals 70% of rainfall in the open in the leafed and 85% in the leafless period. The rainfall depth of 46.2 mm differs from the general tendency in the case of both trees as measured throughfall was quite low for that rainfall amount (Figure 4). For the birch tree the amount of throughfall exceeds the amount of rainfall in the open during 19 events with more than 10 mm of rainfall. Throughfall of more than 100% of rainfall in the open under pine tree was observed during 4 events with at least of 16.8 mm of rainfall (Figure 3). The overall throughfall performance in relation to rainfall depth varies among the tree species. Throughfall is lower for the pine tree, with minor differences among measuring points, and rarely exceeds 100% of rainfall in the open (Figure 3). For the birch tree, however, the percentage of throughfall at measurement points extends from 12% up to 250% of rainfall in the open and is especially scattered for events between 20 mm and 40 mm of rainfall (Figure 3).

## 3.2 The influence of tree characteristics

The influence of canopy coverage and distance from the tree stem on spatial variability of throughfall was analysed. The tree characteristics were determined for each throughfall measurement point (Figure 1, Table 2).

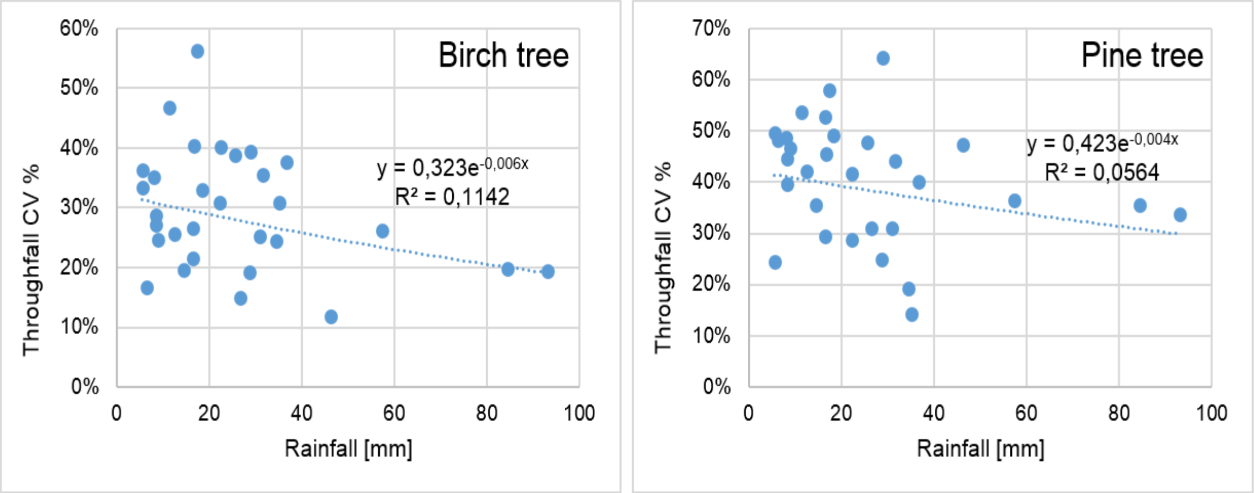

**Figure 2:** *Event point throughfall CV according to the event's amount of rainfall.*

**Slika 2:** *Koeficient variacije točkovnih vrednosti prepuščenih padavin za vsak dogodek glede na pripadajočo količino padavin.*

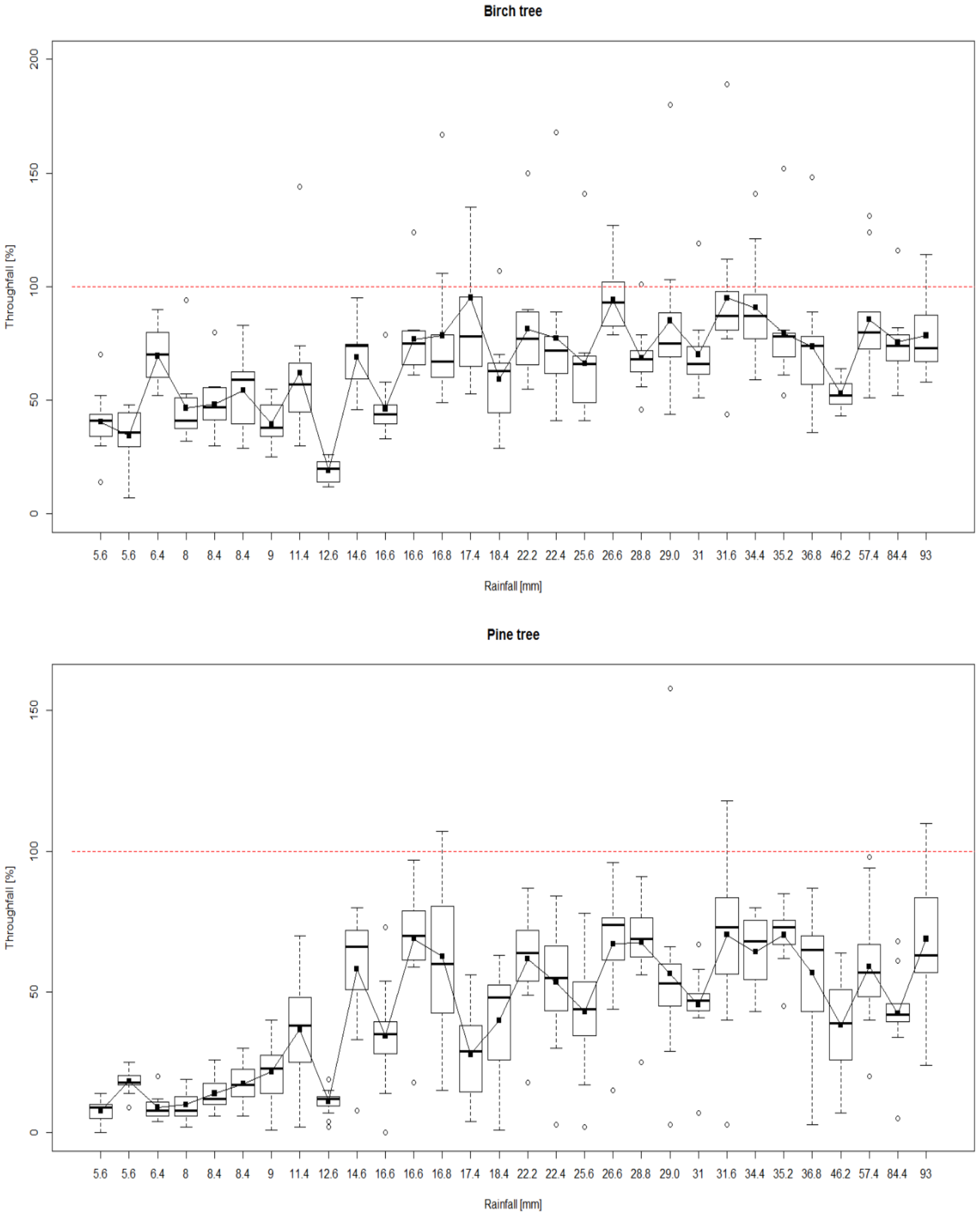

***Figure 3:** Box and whisker plots of throughfall as a percentage of rainfall in the open. The black square in the box represents the mean value and the black bold line the median value; the box height includes the upper and the lower quartile values, while the bars represent the highest and the lowest values. The red line indicates throughfall equal to 100% of rainfall in the open.*

***Slika 3:** Škatla z ročaji za prepuščene padavine kot delež padavin na prostem. Črn kvadratek v škatli označuje povprečno vrednost, črna črta mediano, višina škatle predstavlja zgornje in spodnje vrednosti kvartilov, ročaji pa označujejo največje in najmanjše vrednosti. Rdeča črta označuje prepuščene padavine, enake 100 % padavin na prostem.*

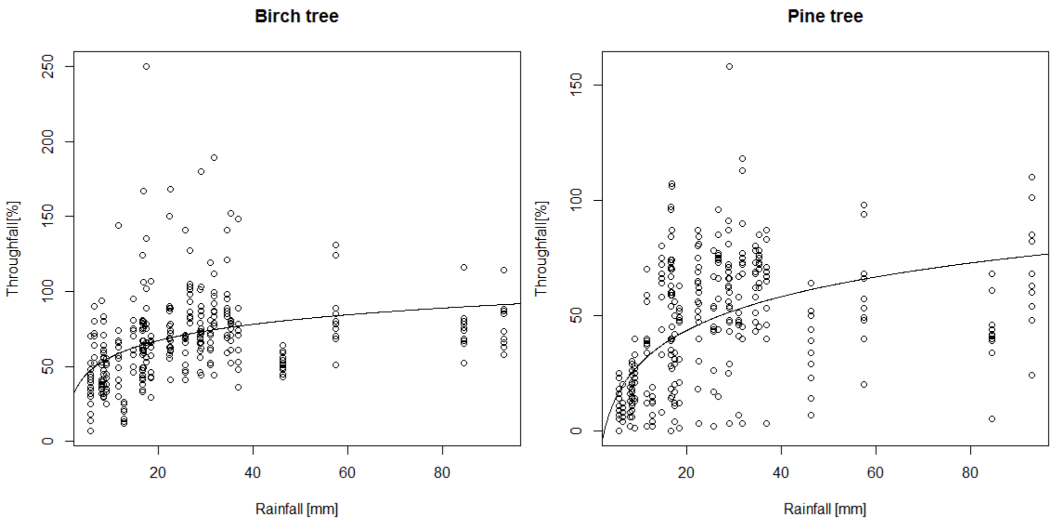

***Figure 4:** Scatterplots of throughfall as a percentage of rainfall in the open measured at each of the 11 points against corresponding rainfall depth and logarithmic fit.*

***Slika 4:** Graf raztrosa prepuščenih padavin, izraženih kot delež padavin na prostem, izmerjenih v vsaki izmed 11 merilnih točk, glede na pripadajočo količino padavin in logaritemska ustrezna funkcija.*

The most influential characteristic for the birch according to the regression tree is the distance from the tree stem (Figure 5). The measurement points were divided into three groups according to the radius of the line on which they were positioned (Figure 1). The highest throughfall on general was observed at measurement points situated closest to the tree stem (points 1, 2 and 3). On average, throughfall measured in this points was equal to 74% (± 42%) of rainfall in the open. At measurement points placed in the middle circle (points 4, 5, and 6) on average 62% (± 26%) of throughfall was measured. Additionally, throughfall amounts measured at the points of outer circle depends also on the coverage of the canopy (Figure 5). Two points in the middle of outer circle (8 and 11) had higher canopy coverage and on average received slightly lower amount of throughfall (65% ± 21% of rainfall in the open) comparing to other three points with lower canopy coverage (67% ± 18% of rainfall in the open).

The spatial variability of throughfall under the pine tree depends on canopy coverage only, whereas distance from the stem does not play any significant role (Figure 6). At measurement points with canopy coverage larger than 87.3% of the sky, throughfall was on average lower (38% ± 27% of rainfall in the open) than at measurement points with lower canopy coverage (50% ± 28% of rainfall in the open).

The vegetation periods and LAI values also influences the spatial variability of throughfall under the tree species (Figure 7). The hot spot for the birch tree, receiving the highest amounts of throughfall in the leafed and leafless vegetation periods, was point 3. In the leafless period the amount of throughfall measured at this point was on average 141% of rainfall in the open, whereas during the leafed period it was on average 96% of rainfall in the open. Also the lowest throughfall under the birch tree was detected at point 1 in both periods, 51% in the leafless and 46% in the leafed period. However, in the leafed period lower amounts of throughfall were in general measured close to the stem (points 1 and 2) and on the left side of the measurement network at points 6 and 11 (green colour, Figure 7a), whereas in the leafless period lower throughfall was detected on the right side and in the middle at points 4, 5, 7, and 10 (yellow colour, Figure 7b).

The points with the highest and lowest measured throughfall under the pine tree were the same in the leafed and in the leafless period too. At point 11 throughfall of 70% and 51% of rainfall in the open was measured on average, whereas at point 3 20% and 8% of throughfall was measured on average in the leafless and in the leafed period, respectively. In the leafed period the measured amounts of throughfall were lower, but with similar distribution to the leafless period: lower values were observed at points 3, 6, and 9 (turquois colour, Figure 7c; dark green colour, Figure 7d) and higher values at points 1, 2, and 11 (light green colour, Figure 7c; yellow colour, Figure 7d).

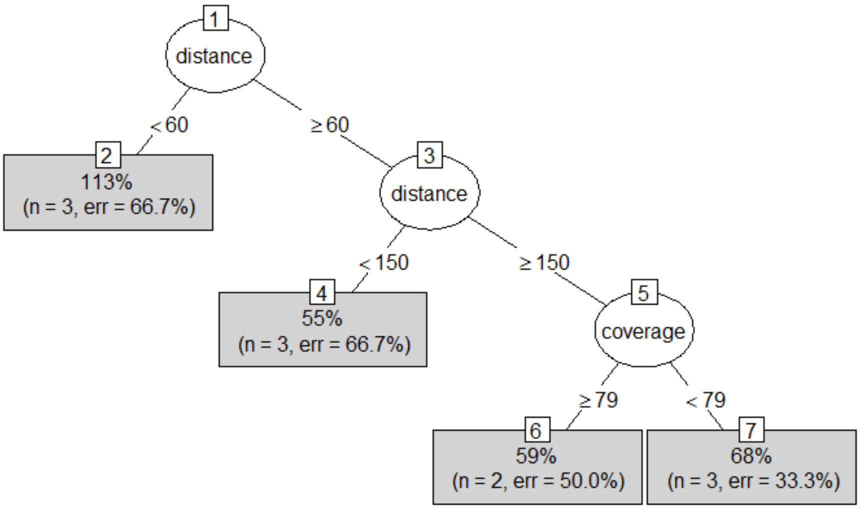

***Figure 5:*** *Regression tree indicating the influence of distance from the stem and canopy coverage on throughfall spatial variability under the birch tree (results on the final nodes are presented as: estimated TF [%], n = number of cases assigned to the node, err = error of estimated TF).*

***Slika 5:*** *Regresijsko drevo, ki prikazuje vpliv oddaljenosti od drevesnega debla in pokritosti s krošnjo na prostorsko spremenljivost prepuščenih padavin pod brezo (rezultati na zadnjih listih so prikazani kot: ocenjeni delež prepuščenih padavin [%], n = število primerov, pripisanih listu, err = napaka ocenjenega deleža prepuščenih padavin).*

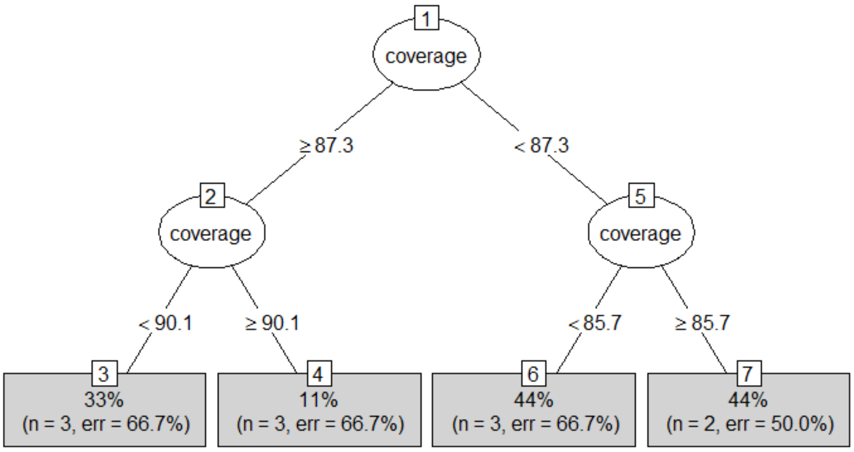

***Figure 6:*** *Regression tree indicating the influence of distance from the stem and canopy coverage on throughfall spatial variability under pine tree (results on the final nodes are presented as: estimated TF [%], n = number of cases assigned to the node, err = error of estimated TF).*

***Slika 6:*** *Regresijsko drevo, ki prikazuje vpliv oddaljenosti od drevesnega debla in pokritosti s krošnjo na prostorsko spremenljivost prepuščenih padavin pod borom (rezultati na zadnjih listih so prikazani kot: ocenjeni delež prepuščenih padavin [%], n = število primerov, pripisanih listu, err = napaka ocenjenega deleža prepuščenih padavin).*

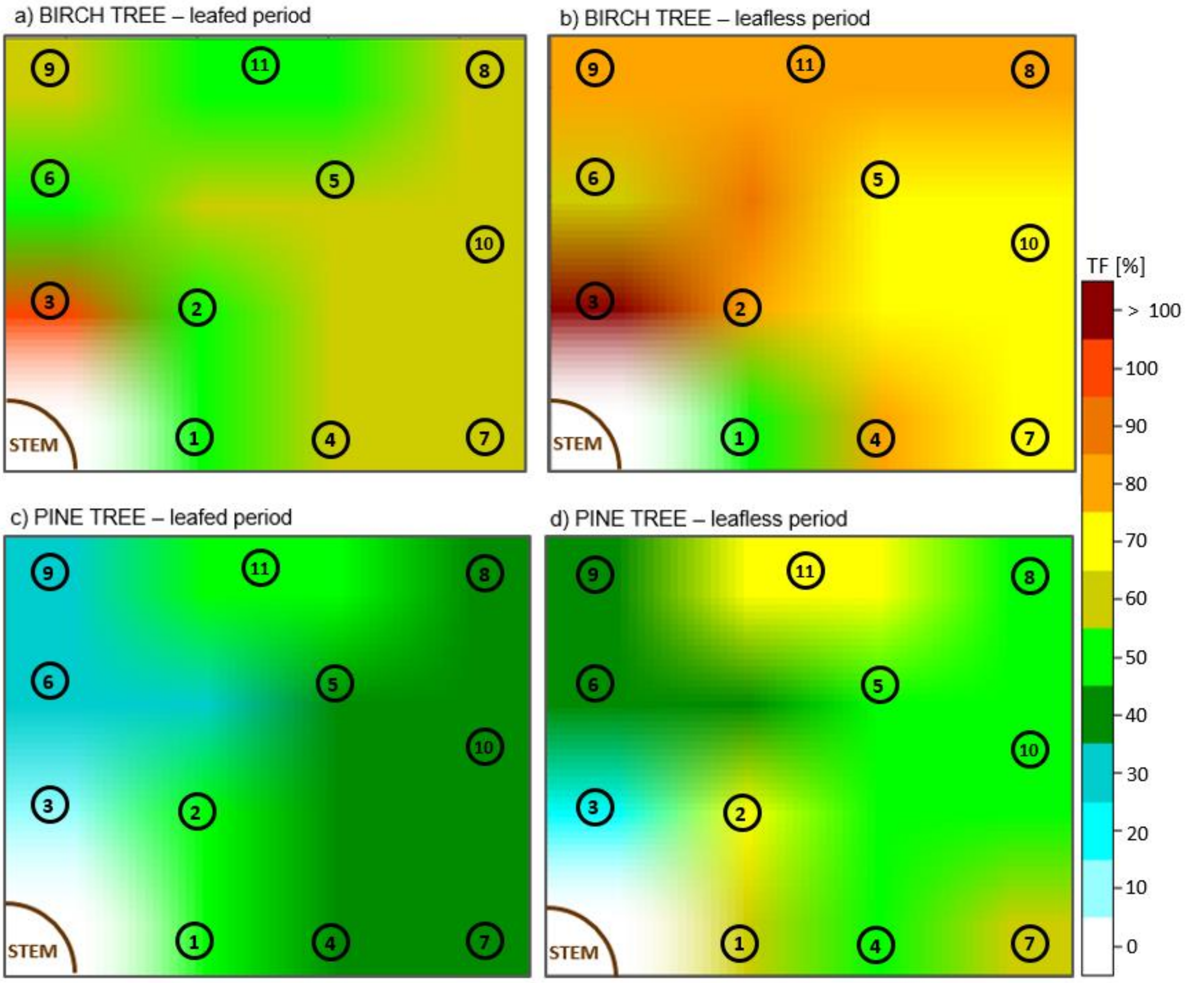

***Figure 7:** Average spatial distribution of throughfall as a percent of rainfall in the open under the birch and pine tree in the leafed and leafless vegetation period.*

***Slika 7:** Povprečna prostorska porazdelitev prepuščenih padavin, izraženih kot delež padavin na prostem, pod brezo in borom v obdobju olistane krošnje in v obdobju mirovanja.*

### 3.3 The influence of meteorological parameters

The spatial distribution of throughfall under the canopies was visualized for each event (Figure 8). Figures were analysed with hierarchical clustering using Orange (Demsar et al., 2013). According to the similarities in the patterns they were grouped in clusters using Ward’s method. The meteorological properties of events in each cluster were examined.

Throughfall events, measured under the birch, were grouped into 6 clusters (Table 3). Only one event (17 August 2016) was assigned to the first cluster. Throughfall during this event was significantly lower than during all the other events, as it did not exceed 30% of rainfall in the open at any of the measuring points. However, this event was neither small (12.6 mm of rainfall) nor light (3.4 mm/h). Four events from the leafed vegetation period were grouped in cluster 2. These events delivered small amount of rainfall, as neither exceeded 20 mm of rainfall, with light intensity (less than 1.5 mm/h) and small rainfall drops (with MVD less than 2 mm). However, the measured amount of throughfall was high, with more than 75% on average and exceeding 100% at point 3 during two of the assigned events. Relatively short rainfall events with a low amount of precipitation (5.6 – 9 mm) were assigned to cluster 3. Throughfall was low (less than 68% on average per event) and at every point during all considered events it remained lower than the amount of rainfall in the open. Contrary to that, throughfall measured at point 3 exceeded the rainfall amount during almost all events grouped in cluster 4. These events were also quite heavy, as all delivered more than 20 mm of rainfall in less than 15.5 hours. The majority of the events measured during the leafless period were assigned into cluster 5. The amount of rainfall, the event's duration, and the event's intensity differ significantly between the events; however, the throughfall amount was quite high and at certain points exceeded 100% of rainfall during all events. Although events assigned to cluster 6 had various rainfall amounts (17.4 – 93 mm), durations (3.7 – 21.5 h), and intensities (1.3 -7.3 mm/h) their raindrops were the largest (median volume diameter (MVD) of more than 1.6 mm). Throughfall during these events exceeded rainfall in the open at more than one measuring point.

Throughfall events measured under the pine tree were assigned to five clusters (Table 4). The vegetation period did not play a significant role in this hierarchical clustering. Events with lowest measured throughfall were assigned to cluster 1. Their throughfall values at measurement points reached only up to 30%. However also the amount of rainfall was low (less than 13 mm) and intensities were light. The events with the highest average throughfall were grouped in cluster 2. Although the intensities of those events were the heaviest (between 2 and 7.3 mm/h) and raindrops the largest (MVD up to 3.4 mm), throughfall remained lower than 100% at all measurement points. Events assigned to clusters 3 and 4 were both characterized by a large amount of rainfall (between 16.6 and 93 mm). However, events in cluster 3 were shorter, had heavier intensities (up to 4.3 mm/h), had and larger raindrops (MVD up to 2.5 mm), which was reflected in higher amounts of throughfall. All events in which throughfall exceeded the amount of rainfall in the open were also grouped in cluster 3. Events in cluster 4 were longer, with moderate intensity (up to 2.8 mm/h) and smaller raindrops (MVD up to 1.5 mm) compared to the events in cluster 3. This was also reflected in lower amounts of throughfall, which on average reached up to 75% at a single measurement point per event. The last three events with low average throughfall amount were grouped in cluster 5. According to rainfall amount they were quite similar to the events assigned to cluster 2; however, maximal measured throughfall values at single points were lower than 65%.

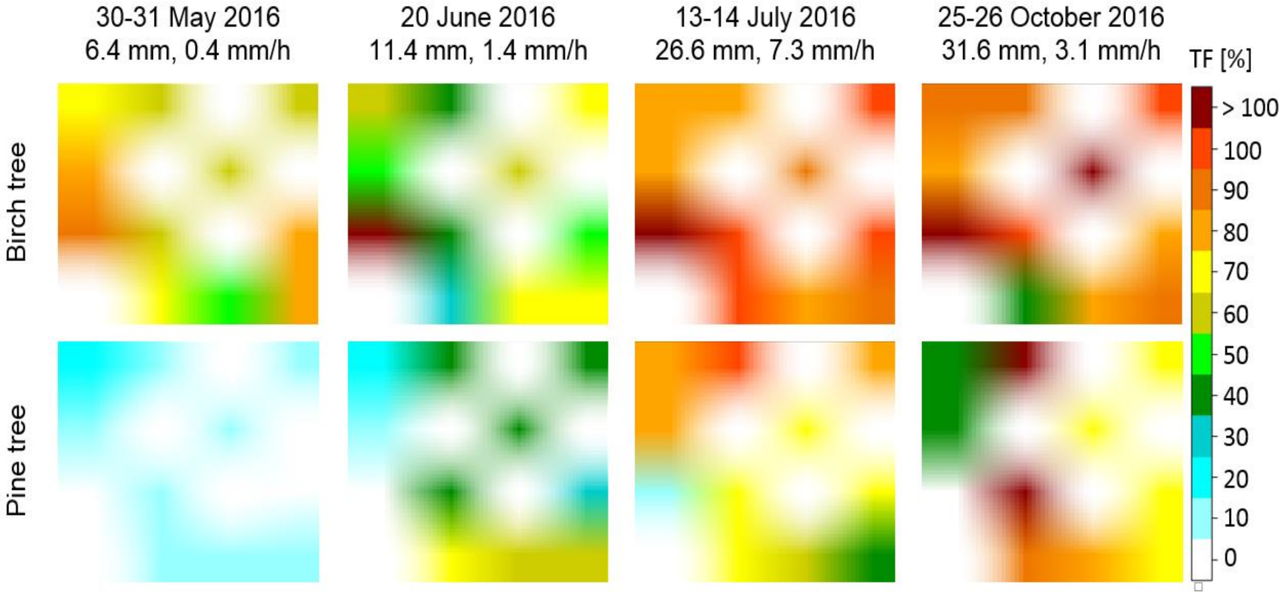

***Figure 8:** Examples of visualized throughfall spatial distribution for 4 events with various rainfall amounts and intensities. Throughfall is expressed as percent of rainfall in the open.*

***Slika 8:** Primeri vizualizacije prostorske porazdelitve prepuščenih padavin za 4 dogodke z različnimi količinami in intenzitetami padavin. Prepuščene padavine so izražene kot delež padavin na prostem.*

***Table 3:*** *Properties of throughfall events, grouped using hierarchical clustering according to throughfall spatial distribution under the birch tree (average value ± standard deviation).*

***Preglednica 3:*** *Lastnosti dogodkov prepuščanja padavin, združenih v razrede po metodi hierarhičnega razvrščanja glede na prostorsko porazdelitev prepuščenih padavin pod brezo (povprečna vrednost ± standardna deviacija).*

| Cluster | No of events | Vegetation period | Rainfall [mm] | Duration [h] | Intensity [mm/h] | MVD [mm] | Throughfall [%]* |
|---|---|---|---|---|---|---|---|
| 1 | 1 | Leafed | 12.6 | 3.7 | 3.4 | 1.78 | 24 |
| 2 | 4 | Leafed | 13.7<br>(± 4.0) | 20.7<br>(± 9.9 ) | 0.8<br>(± 0.4) | 1.33<br>(± 0.42) | 81<br>(± 4) |
| 3 | 6 | Leafed | 8.2<br>(± 1.4) | 8.5<br>(± 7.6) | 1.5<br>(± 0.7) | 1.81<br>(± 0.17) | 58<br>(± 6) |
| 4 | 6 | Leafed | 26.5<br>(± 6.9) | 11.4<br>(± 3.8) | 2.5<br>(± 0.5) | 1.80<br>(± 0.49) | 72<br>(± 10) |
| 5 | 8 | Leafless | 32.5<br>(± 24.0) | 27.3<br>(± 21.1) | 1.5<br>(± 0.9) | 1.55<br>(± 0.37) | 79<br>(± 8) |
| 6 | 5 | Leafed and leafless | 40.6<br>(± 26.8) | 12.0<br>(± 5.6) | 3.8<br>(± 2.0) | 2.24<br>(± 0.69) | 74<br>(± 10) |

* % of rainfall in the open

***Table 4:*** *Properties of throughfall events, grouped using hierarchical clustering according to throughfall spatial distribution under the pine tree (average value ± standard deviation).*

***Preglednica 4:*** *Lastnosti dogodkov prepuščanja padavin, združenih v razrede po metodi hierarhičnega razvrščanja glede na prostorsko porazdelitev prepuščenih padavin pod borom (povprečna vrednost ± standardna deviacija).*

| Cluster | No of events | Vegetation period | Rainfall [mm] | Duration [h] | Intensity [mm/h] | MVD [mm] | Throughfall [%]* |
|---|---|---|---|---|---|---|---|
| 1 | 7 | Leafed | 7.9<br>(± 2.2) | 10.5<br>(± 8.4) | 1.5<br>(± 1.1) | 1.76<br>(± 0.17) | 19<br>(± 8) |
| 2 | 4 | Leafed and leafless | 27.7<br>(± 8.3) | 9.3<br>(± 5.6) | 3.9<br>(± 2.0) | 2.48<br>(± 0.89) | 81<br>(± 11) |
| 3 | 7 | Leafed and leafless | 34.0<br>(± 24.7) | 18.1<br>(± 10.9) | 2.3<br>(± 1.3) | 1.72<br>(± 0.38) | 61<br>(± 9) |
| 4 | 9 | Leafed and leafless | 33.8<br>(± 22.0) | 26.1<br>(± 20.7) | 1.6<br>(± 0.8) | 1.34<br>(± 0.22) | 50<br>(± 10) |
| 5 | 3 | Leafed and leafless | 24.2<br>(± 15.9) | 10.6<br>(± 2.6) | 2.2<br>(± 1.3) | 1.94<br>(± 0.15) | 39<br>(± 9) |

* % of rainfall in the open

## 4. Discussion

In the year 2016 throughfall under the birch accounted for 73% of rainfall in the open and for 56% under the pine. Similar values of throughfall between 73% and 84% were also reported for the deciduous forests with birch trees (Herbst et al., 2008; Siegert et al., 2016), whereas throughfall values observed in pine forests and plantations were on general higher, between 57% and 89% of rainfall in the open (Llorens et al., 1997; Bryant et al., 2005; Buttle and Farnswoth, 2012). In our study we observed significant differences in the amount of throughfall between the leafed and leafless periods, a 20% difference for the birch and a 12% difference for the pine trees with higher throughfall values during the leafless period. The observed differences between the leafed and leafless periods are quite high in comparison to the 3.6% difference observed in the deciduous forest in the Pyrenees (Muzylo et al., 2012), the 2%-6% difference measured for old deciduous forest in central Germany (Krämer and Hölscher, 2009), and the 3.1% difference observed on the south plot in the Mediterranean deciduous forest in Slovenia (Šraj et al., 2008a). However, Šraj et al. (2008a) reported a similar difference of 22.3% in throughfall among vegetation periods for the north plot in Mediterranean deciduous forests, a 17% difference was measured by Staelens et al. (2008) under a beech canopy in deciduous forest in Belgium, and Siegert et al. (2016) observed a reduction in throughfall partitioning during the leafed period by 13.2%, 12.1% and 9.4% respectively on the north, west, and south facing slopes of a deciduous forest in Maryland, USA, respectively. The larger differences of throughfall values between the leafed and leafless periods were on general observed on smaller study plots such as under a single beech (Staelens et al., 2008) or on small scale plots facing in different directions (Siegert et al., 2016). On larger study plots in the forests (Krämer et al., 2009; Muzylo et al., 2012) the differences were lower. This might be similar to the influence of the collection area of the collectors on the variability of point throughfall (Kowalska et al., 2016). However, Šraj et al. (2008a) ascribed the insignificant difference in throughfall values between the vegetation periods at two similarly sized plots to the occurrence of drip points on the northern plot with less dense canopies.

The throughfall amount under both tree canopies differed between the measurement points with an average CV of 30% in the case of birch tree and 40% in the case of pine tree (Figure 2). In other similar studies lower average throughfall CV values were reported for forests: 15.9%-20.1% in a deciduous forest in Maryland (Siegert et al., 2016), 14.6% in a mixed coniferous forest in Poland (Kowalska et al., 2016), and 21% in a Douglas fir forest stand in Netherlands (Raat et al., 2002). However, Keim et al. (2005) reported similar throughfall CV values as he defined them for young (19%) and old (54%) conifer stands and for deciduous stands in the leafed (34%) and leafless (24%) periods. The differences in the observed variability of measured throughfall may be the consequence of collector's area and the observation period length, as larger collectors and longer observation periods decrease the variability in measured throughfall (Kowalska et al., 2016). The collectors used by Siegert et al. (2016), Kowalska et al. (2016), and Raat et al. (2002) were larger (324 cm2, 201 cm2 and 320 cm2, respectively), whereas the collectors used by Keim et al. (2005) were smaller (9.2 cm2) than those used in the present study (78.5 cm2). The study by Keim et al. (2005) was also the shortest, with only 5.5 months of measurements, whereas others lasted between 9 and 13 months. Additionally, the deviation between the throughfall CV values may also be influenced by the measurements performed under a single tree canopy instead of in the forest. For example, Fang et al. (2015) measured throughfall spatial variability under an individual pine canopy and calculated the throughfall CV of 35.5%. In the present study the largest difference among throughfall values at measurement points during one event was 197% for the birch tree and 155% for the pine tree (Figures 3-4), whereas the large scatter of 160% among the measured throughfall values at points under single olive trees was also observed by Gómez et al. (2002).

For some events the amount of throughfall at specific measurement points exceeded the amount of rainfall in the open. The phenomenon was more frequently observed under the birch tree for events with at least 10 mm of rainfall. In the case of the pine tree it was scarcer and triggered by at least 16.8 mm of rainfall (Figure 3). The share of throughfall larger than 100% of rainfall in the open were also measured by other researchers, namely at the edge of the olive tree canopy after 4.9 mm of rainfall (Gómez et al., 2002), at the canopy edge of the individual pine for more than 13.3 mm of rainfall (Fang et al., 2015), in the deciduous forest at measuring points located 2-6 meters from the trees after 3.3 mm of rainfall (Yousefi et al., 2017), in the oak forest after 1.3 mm of rainfall (Carlyle-Moses et al., 2004), and in the spruce forest in collectors at the edge of the canopy with low plant area index values for more than 5.1 mm of rainfall (He et al., 2014). The occurrence of drip points is assumed to be the consequence of channelling intercepted precipitation by leaves, branches, and stem to specific areas in the canopy (e.g. Carlyle-Moses et al., 2004; Šraj et al., 2008a). As location of their appearance is explained differently by the various researchers, it seems to be related to the specific canopy characteristics of each tree (Gómez et al., 2002; Fang et al., 2015).

According to the results of the regression tree analysis (Figure 5) the spatial variability of throughfall under birch tree is influenced by distance from the stem and additionally by canopy coverage. The highest average throughfall was observed near the stem. This might be the influence of the up-facing branches of birch tree (Table 1), which may channel intercepted rainfall towards the stem (Gerrits et al., 2010; He et al., 2014). Additionally, at measuring point 3 throughfall higher than 100% of rainfall in the open was often measured, which is probably also a consequence of the lowest canopy coverage above this point (Table 2). Lower canopy coverage means that there are fewer canopy elements such as leaves and branches above the measuring point, which would otherwise obstruct falling of precipitation to the ground. Therefore less precipitation is retained in the canopy and the throughfall amount is larger. Higher throughfall values were observed under open or less dense areas in the canopy also by other researchers (Gómez et al., 2002; He et al., 2014; Fang et al., 2015; Dohnal et al., 2014). However, the lowest amounts of throughfall were measured at point 1, which is located near the stem but does not have the highest canopy coverage. The detailed analysis of hemispherical photographs of the canopy above the measurement points showed that there are a few thick branches growing above measuring point 1. Llorens and Gallart (2000) showed that the high specific water retention capacity of branches and stems in comparison to needles plays a key role in rainfall interception. Also He et al. (2014) observed that plant area index (PAI), which includes branches and leaves, influences throughfall spatial variability, whereas no relationship was found for LAI, representing only the area of leaves. Additionally, Nanko et al. (2011) emphasised that the rainwater distribution close to the stem would depend on the arrangement of branches.

For a pine tree with down-facing branches Fang et al. (2015) recognised that the edge effect (relocation of water towards the edge of the canopy) influences the spatial variability of throughfall. Also the pine tree in the present study has down-facing branches (Table 1), but no throughfall concentration was observed at the canopy edge. Rather than distance from the stem, the canopy coverage influenced throughfall spatial variability under the pine tree, which was supported by the results of the decision tree method (Figure 6) and the coefficient of correlation between the point throughfall and canopy coverage (-0.49). Similarly, no relationship between throughfall and distance from the stem was observed in pine stands in other studies (Loustau, 1992; Kowalska et al., 2016).

The influence of LAI on the spatial variability of throughfall was often included in the analysis (Carlyle-Moses et al., 2004; Dohnal et al., 2014; Fang et al., 2015; Siegert et al. 2016). For the pine tree in the present study the vegetation period influences only the amount of throughfall, but not its spatial distribution (Figure 7c-d). This may be attributed mainly to seasonal patterns of the canopy storage capacity (Link et al., 2004; Pypker et al., 2005; Gerrits et al., 2010). Similar was reported for coniferous trees by other researchers (Shachnovich et al., 2008; He et al., 2014; Kowalska et al., 2016). However, for birch tree the differences in spatial distribution of throughfall were observed in addition to differences in its amount (Figure 7a-b). The locations of points with minimal and maximal observed throughfall remained the same in both vegetation periods, whereas intermediate values formed miscellaneous patterns between the vegetation periods. In the leafed period lower amounts of throughfall were observed near the stem and on the left side (points 1, 2, 6, and 11) and higher amounts on the right side (points 4, 5, 7, and 10) of the measurement network, whereas in the leafless period the situation was reversed (Figures 7a, 7b). Changes in patterns of throughfall spatial distribution in the presence and absence of leaves was also observed by others (Gerrits et al., 2010; Kowalska et al., 2016; Yousefi et al., 2017) and were assigned to presence of leaves that shelter some locations of throughfall measurement and promote the occurrence of drip points in others (Helvey and Patric, 1965; Kowalska et al., 2016). Due to the more distinct canopy drainage patterns in the leafed period, Yousefi et al. (2017) noticed more drip points during the leaf-on period than during the leaf-off one. Siegert et al. (2016) calculated higher CV at measuring points in presence of foliage, and Gerrits et al. (2010) noticed a more heterogeneous spatial pattern of throughfall during the summer in comparison to other seasons.

The spatial distribution of throughfall under the trees was graphically presented for each considered event and based on these visual patterns were grouped into clusters by hierarchical clustering using Orange (Demsar et al., 2013). This assignment into clusters in the case of the birch tree was based on the vegetation period and on the amount of rainfall (Table 3). To cluster 1 only one event, recorded on 17 August 2016, was assigned. The event stands out among others due to very low throughfall values. Although throughfall is most influenced by the amount of rainfall (Xiao et al., 2000; Staelens et al., 2008; Šraj et al., 2008a; Siegert and Levia, 2014), for this event a moderate amount of rainfall was measured (Table 3). However, the number of raindrops per event was the lowest, which, as Nanko et al. (2006) already showed, reduces the throughfall. Additionally, the observed raindrops had on average higher velocities and larger diameters than raindrops during other analysed events, which reduced the amount of throughfall in the case of the birch tree. This corresponds with the finding of Zabret et al. (2018), who reported that smaller drop diameter and lower median volume diameter decreased rainfall interception loss by the birch tree. This might be the consequence of the flexible response of birch leaves, which absorb the high energy of large and fast raindrops and manage to retain them due to the small number of such raindrops.

The majority of throughfall events under the birch tree from the leafed period were grouped in clusters 1-4, which differ among themselves according to the amount of rainfall (Table 3). The lowest amounts of rainfall were measured during events grouped in cluster 3, for which throughfall never exceeded 100% at any of the measuring points. Additionally, no significant spatial patterns in throughfall distribution were observed for these events, similarly as reported by Gómez et al. (2002) for events with low rainfall amounts. In general the canopy storage capacity is not yet reached during events with small rainfall amounts; therefore throughfall mainly consists of raindrops falling directly through the gaps in the canopy (Gómez et al., 2002; Nanko et al, 2011). Events with higher rainfall amounts were assigned to cluster 4, expressing the same pattern of throughfall spatial distribution with higher values at the edge of the canopy. A similar pattern was also observed for events with average rainfall amounts, grouped in cluster 2. The branches get thinner towards the edge of the canopy and the influence of leaves on the redistribution of water grows, where fore larger amount of throughfall at the edge of the canopy can be observed (Nanko et al., 2011; Fang et al., 2015).

Throughfall spatial distribution under pine was not grouped according to the vegetation period (Table 4, Figure 7) since the rainfall amount and intensity were recognized as more influential parameters. Events in cluster 1 delivered less than 10 mm of rainfall with quite low intensities and resulted in throughfall values lower than 30% at each measurement point. Events in clusters 2 and 5 delivered similar amounts of rainfall, but events in cluster 2 had higher intensities up to 7.3 mm/h (Table 4). The influence of higher rainfall intensities on increasing the amount of throughfall was already reported (e.g. Xiao et al., 2000; Staelens et al., 2008; Kermavnar and Vilhar, 2017) and also observed in the present study as the throughfall of events in cluster 2 was higher (more than 70% per event) than the throughfall of events in cluster 5 (less than 50% per event). Additionally, spatial distribution of the throughfall of events assigned to each cluster had different pattern. Wind properties were not recognized as affecting these patterns since neither hierarchical clustering (Table 4) nor detailed analysis of meteorological influences on the throughfall at the study plot (Zabret et al., 2018) highlighted its influence. The main difference recognized was that events with higher intensities (cluster 3) at some points also induced throughfall larger than the amount of rainfall in the open. The similar spatial patterns of throughfall were observed for events with larger rainfall amounts or with larger intensities, whereas events with lower rainfall amounts and lower intensities created the opposite pattern. Similar differences were also observed in other studies, as Fang et al. (2015) reported that in low rainfall events the key factor influencing the spatial variation of throughfall was canopy structure, whereas non-spatial variables were more influential during high rainfall events. Gómez et al. (2002) observed a consistent throughfall spatial pattern for high rainfall events and non-consistent patterns for low rainfall events, and Carlyle Moses et al. (2004) observed the influence of tree characteristics only for events with lower amounts of rainfall.

## 5. Conclusions

Throughfall amounts differed significantly among measuring points under both the birch and pine tree with CV of 31% and 42%, respectively. However, its distribution was influenced by various parameters according to the tree species. Under the birch tree point throughfall exceeded the amount of rainfall in the open during 63% of all analysed events, while it was observed only for 13% of the events in the case of the pine tree. Vegetation periods and changes in LAI values influenced the amount of throughfall under both tree species; however, for the birch tree vegetation periods also induced the occurrence of a distinct seasonal throughfall pattern. In addition to the vegetation period also the rainfall amount and its microstructure influenced throughfall variability under the birch tree. Although throughfall patterns under the pine tree remained unchanged between the leafed and leafless period, they formed a specific layout according to the amount of rainfall and its intensity.

## Acknowledgments

The research was partially financially supported by the Slovenian Research Agency through the PhD grant of the first author (K. Zabret).

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