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Contribution to understanding precipitation regime in the mountain spruce forests of Babia hora – Oravské Beskydy using throughfall index

J. Vorčák, J. Merganič, J. Škvarenina, K. Merganičová

J. Vorčák, Stredná odborná škola lesnícka, Medvedzie 135, 027 47 Tvrdošín, Slovensko, E-mail: vorcak@soultv.sk, J. Merganič, FORIM, Výskum, inventarizácia a monitoring lesných ekosystémov, Huta 14, 962 34 Železná Breznica, Slovensko, Česká zemědělská univerzita v Praze, Fakulta lesnická a dřevařská, Kamýcká 1176, 165 21 Praha 6 – Suchdol, www.forim.sk, E-mail: j.merganic@forim.sk, J. Škvarenina, Technická Univerzita vo Zvolene, Masarykova 24, 960 53 Zvolen, E-mail: jarosk@vsld.tuzvo.sk, K. Merganičová, FORIM, Výskum, inventarizácia a monitoring lesných ekosystémov, Huta 14, 962 34 Železná Breznica, Slovensko, E-mail: k.merganicova@forim.sk.

Abstract: Vorčák, J., Merganič, J., Škvarenina, J., Merganičová, K. 2009: Contribution to understanding precipitation regime in the mountain spruce forests of Babia hora – Oravské Beskydy using throughfall index. – *Beskydy*, 2 (1): 85–94

The presented paper analyses how fog precipitation affects interception and throughfall in spruce mountain forests in the temperate zone of Europe. The plots selected for the collection of rainfall and throughfall were located within the area of nature reserve Babia hora, from which the data were collected from the year 2001 to 2005. The gauges were situated in four different locations (open space, crown's periphery, young stand and forest opening) at an elevation ranging from 1330 to 1350 m above sea level. The results indicate that in the examined region, the deposition of horizontal precipitation on vegetation surfaces occurs, which reduces the interception losses, and even causes the net gain of water. The positive effect of horizontal precipitation on water regime grows with the decreasing gross precipitation at open space, while this effect is evident for the precipitation in the form of rain, but not snow. The correlation coefficients between throughfall and rainfall fluctuated from 0.69 to 0.99 in the case of rainfall, and from 0.424 to 0.955 in the case of snowfall, which indicates strong correlation between throughfall and gross precipitation. High values of throughfall indices underneath crown´s periphery suggest that under drip points we can expect the net gain of water, which has a positive effect on natural regeneration and understorey vegetation. The regeneration underneath crown´s periphery is promoted not only by higher net precipitation, but also by higher amount of nutrients dissolved in precipitation.

Keywords: throughfall, fog precipitation, Jackknife procedure, crown´s periphery, drip point

Introduction

Forests are becoming more and more important for humans not only as a producer of wood, but also as a key element of environment. They effect climate and enhance soil and water conditions. Forests are known to act as water catchments thanks to their ability to accumulate and retard water outflow, which has a positive effect on hydrological cycle (Hríbik et al. 2007). It is generally accepted that trees provide shelter from rainfall (Fahey 1964), i.e. that only a portion of the actual rainfall reaches soil (Petrík et al. 1986), which is called throughfall. The rest of the rainfall is intercepted on the vegetation surface of a forest stand (forest canopy, shrubs, herbs), and evaporated back to the atmosphere. This portion represents the loss component in the equation of water balance. Most commonly, the interception is obtained as a difference between the rainfall at open space and the rainfall that reaches the ground beneath the forest canopy (throughfall&stemflow). This parameter is usually assessed for a longer time period (vegetation season, year), and then it is referred to as aggregate interception, as an amount of rainfall intercepted on forest canopy in a particular time period (Minďáš et al. 2001).

Water intercepted on forest canopy is subject to non-productive (interception) evaporation of a similar nature as evaporation from free water line. Interception evaporation is mainly driven by climatic factors (temperature, moisture, air flow). In addition, the total value of interception depends also on the character of forest canopy, particularly on the following factors: tree species composition, crown closure, stocking, stand age (Hríbik, Škvarenina 2007, Lančarič et al. 2001, Petrík et al. 1986; Valtýni, 1986). Weaver (1972) reported that coniferous species were due to the structure of their leaves better adapted for the extraction of fog moisture than broadleaved species. According to Ovington (1954 in Fahey 1964), coniferous species can intercept up to 5 times more water than what can be retained on broadleaves.

Numerous measurements worldwide detected the differences in the interception process at different elevations. In the conditions of Slovakia and the Czech republic, the interception represents the loss component in water balance up to elevations of 600–850 m above sea level. At higher elevations, „occult – horizontal" precipitation from fog and montane cloud belt causes the reduction of interception losses. In these forests, clouds and fogs often impinge upon vegetation and deposit moisture in the form of condensed droplets (Weaver 1972), and thus, saturate the interception capacity of the forests. Hence, vertical precipitation (rain and snow) reaches the ground with no losses, or the losses are eliminated by additional water coming from fog or clouds (Krečmer 1973, Kantor 1981, Škvarenina 1998, Minďáš 1999, Minďáš, Škvarenina 1998). Studies from mountain forests revealed that net precipitation (i.e. the amount of rainfall that reaches the ground beneath the forest) can even sometimes exceed the actual rainfall amount (Eugster et al. 2002, Stadtmüller, Agudello 1990, Willis et al. 1975, Weaver 1972). This happens when the fog droplets, which are filtered by forest canopy, coalesce on the vegetative surfaces to form larger water droplets that drip to the forest floor (Holder 2003).

Although fog precipitation is probably of greater importance in tropical areas, where the water content of atmosphere is high, it was also observed in some other parts of the world, e.g. in Northern America (Willis et al. 1975). Weaver (1972) stated that the occurrence of negative interception (i.e. gain of water) depends on latitude and elevation, which determines the presence of critical temperatures that result in the condensation of water vapour (Holder 2003).

Since the research in this area is oriented mainly at tropical regions, and partly at coastal temperate forests with a lack of exact information about mountain forests in the temperate Europe, the aim of our study was to examine if fog precipitation occurs also in spruce mountain forests in the temperate zone of Europe, and how it affects the interception and the throughfall. Since the location of examined forests theoretically meets the conditions for fog precipitation to occur, i.e. high elevations and cool temperatures (see the section Material), we expected to reveal the net gain of water in throughfall.

Material and methods

Babia hora (1725 m) is an isolated mountain massif belonging to the outer Western Carpathian mountain range. The massif of Babia hora extends approximately 10 km from the west to the east at the Slovak-Polish border. From the south, it towers over the Oravská-Nowotargská kotlina (valley), which is situated 1100 m below. In Slovakia, such a difference in elevation occurs only in the High and in the Low Tatras. The massif is influenced by western and northwestern airflow due to which the precipitation rates are high, and the climate is severe. The mean annual precipitation of the area is 1600 mm, and the mean annual temperature is 2 °C.

The massif of Babia hora is built of tertiary flysch rocks, mainly sandstones, marl, claystones, slate and conglomerates. The soil types that occur in the area are leptosol, andosol, and podzol, which is most frequent there due to high precipitation rates.

The plots selected for the collection of rainfall and throughfall were located within the area of nature reserve, which was established in 1926 and enlarged in 1974 to its contemporary size of 503.94 ha (Korpeľ 1995). The forests in the reserve are pure Norway spruce (*Picea abies* [L.] Karst.) stands with a small admixture of rowan (*Sorbus aucuparia* L.) and in the eastern part also of silver fir (*Abies alba* Mill.). Average proportion of Norway spruce in tree species composition is 99% (calculated from the inventory data by Merganič et al. 2003).

The selection of the plots for the collection of vertical and horizontal precipitation both as rainfall and snowfall, and the collection of throughfall beneath the forest canopy was performed in accordance with the principles of international monitoring of pollution (ICP – Forest, Level II). For the collection, open polyethyl gauges made from the material that was chemically inert against rainwater adjusted according to the international forest monitoring. Two types of gauges with the area of 201 cm^2 and 433.7 cm^2 were used for the collection of rainfall, and snowfall, respectively. The gauges were situated in four different locations at an elevation ranging from 1330 to 1350 m above sea level as described below:

- one gauge located at open space (Šťaviny – meadow)
- one gauge located underneath the mature Norway spruce tree (205 years old) at the periphery of its crown
- one gauge located underneath the young stand (30 years old)
- one gauge located in the forest opening of a size of 180 m^2

The gauges were established on June 14th 2001 and the data from the gauges were collected until January 2nd 2005 at approximately monthly intervals. For the purpose of this work, we used only the data from the three complete hydrologic years.

The data were analysed by a throughfall index (*IT*) defined as follows:

$$IT_{ijk} = \frac{\sum_{l=1}^{n} T\_mm_{ijk}}{\sum_{l=1}^{n} GP\_mm_{ik}} \qquad (1)$$

where:

i .... 1, 2 form of precipitation (rainfall, snowfall)
j .... 1, 2, 3 collection places in the forest stand (crown´s periphery, young forest, forest opening)
k .... 1, 2, 3 hydrologic year
l .... 1, 2 … *n* collection of precipitation
T_mm ..... throughfall in mm
GP_mm .. gross precipitation in mm

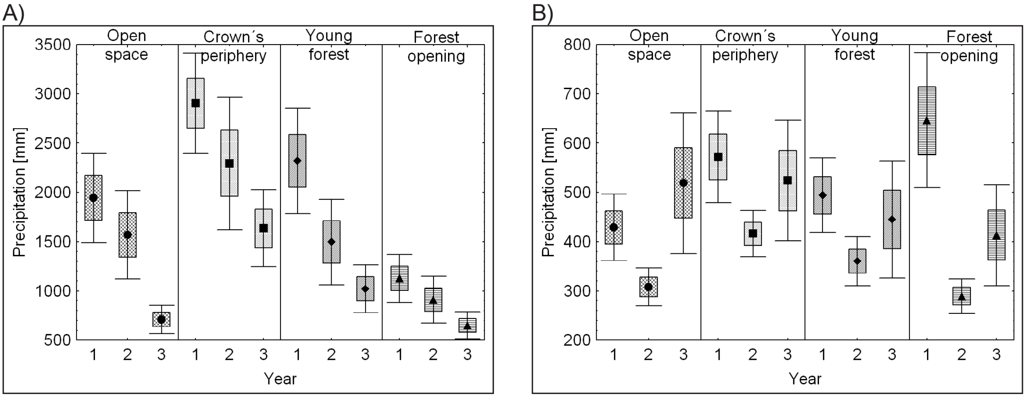
The index represents the proportion of throughfall from the apparent gross precipitation measured at open space. The variation of throughfall indices and the variation of the precipitation sum was calculated using Jackknife procedure in order to determine 68% and 95% confidence intervals of throughfall indices and sums. All together, we quantified and examined 18 throughfall indices (2 forms of precipitation x 3 collection places x 3 hydrologic years).

Results

During the examined time period from the year 2001 to 2004, the amount of gross precipitation at open space, and also throughfall at all three collection places underneath the forest stand significantly decreased (Fig. 1). While in the hydrologic year 2001–2002 the annual gross precipitation was 2373 mm; in the year 2002–2003 it was 1877 mm; and in the year 2003–2004 the annual precipitation was only 1228 mm. This means that the precipitation decreased in its amount by approximately 500 mm per year, while this reduction refers mainly to the precipitation from rain (Fig 1), although in the second year we also observed significantly lower snowfall than in the other two years. The highest amount of snow fell in the third year (Fig. 1). The year 2003 represents a turning point in the climate, as since this year the precipitation amount has been significantly decreasing and the temperature has been growing in the examined region (Borsányi personal communication).

The values of throughfall differ between the three collection points in the stand. The highest values were obtained underneath crown´s periphery, followed by young forests, and the lowest throughfall except one case (snowfall in the first year) was observed in the forest opening (Fig. 1). In 10 out of 18 examined cases, throughfall was greater than gross precipitation at open space. Excess water in throughfall underneath crown´s periphery in the form of rain is more-less constant when compared with rainfall at open space, and makes approximately 900 mm per year regardless of the hydrologic year (Fig. 1a).

When we examine the temporal performance of precipitation in Fig. 2, we can see that the highest amount of precipitation falls in summer and autumn months. Snowfall is the greatest in February and March. Throughfall copies the performance of gross precipitation at open space. In the months with high rainfall, high throughfall occurs, too. In such cases, throughfall beneath the periphery of the crown exceeded rainfall, except when rainfall was extremely high, as in June 2006. In the months with low precipitation, the differences between the open space and the collection points situated in the stand diminished (Fig. 2).



Legend: ●, ■, ◆, ▲ sum of precipitation, 68% confidence interval (sum ± standard error of sum), 95% confidence interval (sum ± 2 × standard error of sum)

Fig. 1: Absolute values of aggregate precipitation in the form of rain (A) and snow (B) collected in the four collection places in three examined hydrologic years

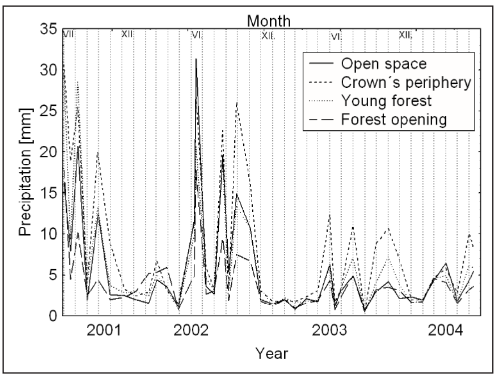
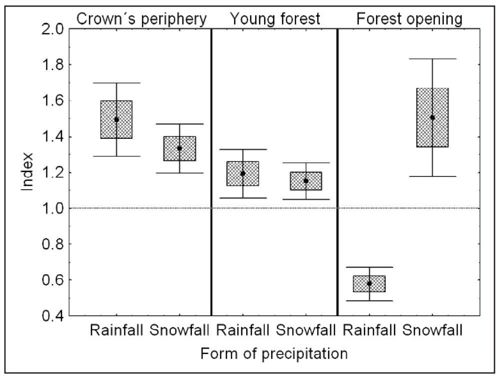


Fig. 2: Temporal performance of daily average precipitation collected in individual collection places



Legend: ● throughfall index, 68% confidence interval (index ± standard error of index), 95% confidence interval (index ± 2 × standard error of index)

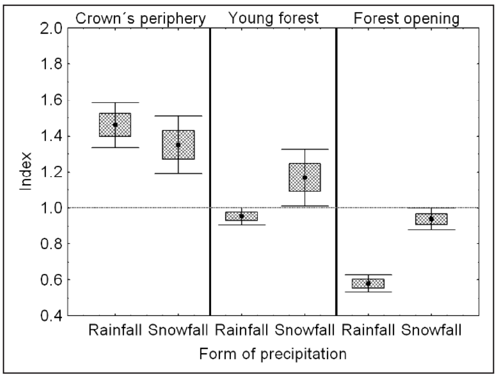
Fig. 3: Throughfall indices calculated for the first hydrologic year 2001-2002

The analysis of the values of the throughfall index in individual years can provide us with some additional information about the magnitude of the difference between open space and collection points in the stand. In the first hydrologic year (2001–2002), all but one value are significantly greater than 1, which means that throughfall in the stand conditions exceeded rainfall at open space (Fig. 3). The only exception is throughfall in the form of rain in the forest opening, where the index has a value of 0.58, which means the loss of water at the magnitude of 42%. The highest value of the index (1.5) was calculated for the throughfall of rain underneath crown´s periphery and the throughfall of snow in the forest opening. The indices of the young stand for rain and snow were very similar. The significant difference between the forms of precipitation was found only in the forest opening (Fig. 3).

The situation in the second hydrologic year (2002–2003) is slightly different from the first year. The index values greater than 1 were obtained only for the collection place underneath crown´s periphery and for snow throughfall in the young stand (Fig. 4). In the forest opening, the values of the throughfall index are significantly lower than 1 indicating positive interception. In the young stand, throughfall in the form of rain is not significantly different from rainfall at open space at 95% significance level, since the value 1 falls within the 95% confidence interval of the value of the index calculated for the young stand. Significant differences between rain and snow throughfalls were detected for the forest opening and the young stand (Fig. 4).

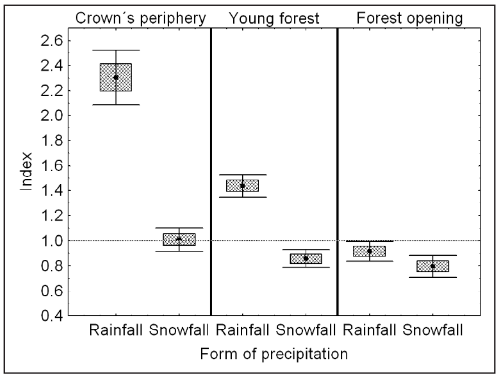
In the third hydrologic year (2003–2004), the situation changes again. Underneath crown´s periphery we observed a very high value of the index for throughfall in the form of rain equal to 2.3 (Fig. 5), which suggests that at this collection point, the gain of water was equal to 130% when compared with rainfall at open space in this year. On the other hand, the troughfall of snow underneath crown´s periphery was not significantly different from snowfall at open space. In the case of the young forest, the index value was significantly different from 1 for the throughfall in the form of rain, while the throughfall of snow was lower than at open space. The index values of throughfall both for rain and snow were significantly lower than 1 (Fig. 5).

As mentioned in the introduction, the interception, and hence, the throughfall depends on a number of factors. The primary factor is the apparent gross precipitation that falls in the region. In Fig. 6a and 6b, we analysed the relationship between the index values of throughfall at the three collection points in the stand and the gross annual rainfall (Fig. 6a) or snowfall (Fig. 6b) at open space. As shown in Fig. 6, the differences between the collection points become less evident as the annual gross precipitation increases. In the case of rainfall (Fig. 6a), the values of the throughfall index decrease with increasing aggregate annual rainfall at open space. This



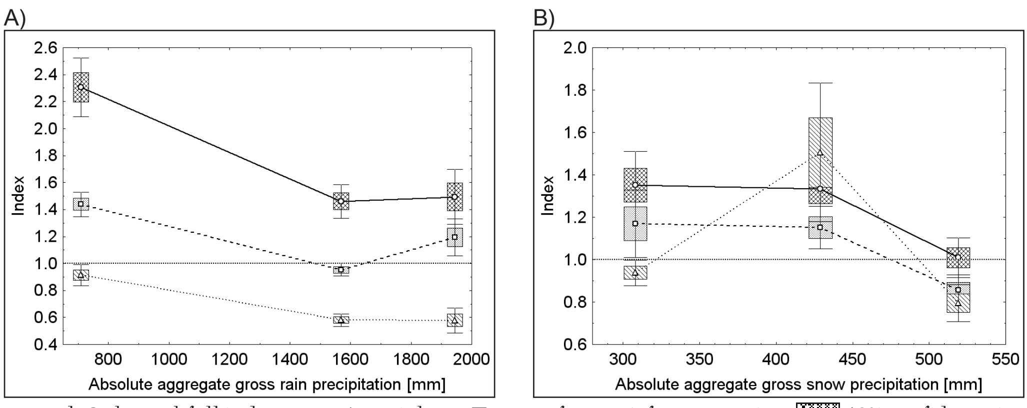
Legend: ● throughfall index, ▩ 68% confidence interval (index ± standard error of index), ⊥ 95% confidence interval (index ± 2 × standard error of index)

Fig. 4: Throughfall indices calculated for the second hydrologic year 2002–2003



Legend: ● throughfall index, ▩ 68% confidence interval (index ± standard error of index), ⊥ 95% confidence interval (index ± 2 × standard error of index)

Fig. 5: Throughfall indices calculated for the third hydrologic year 2003–2004



Legend: ⊖ throughfall index crown´s periphery, ⊡ young forest, △ forest opening, ▩ 68% confidence interval (index ± standard error of index), ⊥ 95% confidence interval (index ± 2 × standard error of index)

Fig. 6: Relationship between throughfall index values and absolute aggregate gross precipitation in the form of rain (A) and snow (B) at open space

trend is the most obvious underneath crown´s periphery.

In the case of snow throughfall, such a trend is not so obvious. Both underneath crown´s periphery and young forest, the values first decrease very slightly and only when the annual snowfall exceeds 430 mm, the decrease of the throughfall index values becomes more significant. The throughfall index values of the forest opening do not show to be related to annual snowfall (Fig. 6b).

Discusion

The results from our analysis show that in the mountainous spruce forests of Babia hora located at an elevation of approximately 1300 m above sea level the throughfall underneath the forest stand often exceeds precipitation collected at open space. These results indicate that in the examined region, the deposition of horizontal precipitation on vegetation surfaces occurs, which reduces the interception losses, and even causes the net gain of water. The positive effect of horizontal precipitation on water regime grows with the decreasing gross precipitation at open space (Fig. 6a). This was observed also in so called cloud forests in other regions of the world, where fog and cloud precipitation plays the most important role in the months with low rainfall, i.e. during the so called dry season (Juvik, Perreira 1973, Stadtmüller, Agudello 1990, Holder 2003, Bruijnzeel 2005).

Similarly as reported in other studies (e.g. Holder 2003), our results revealed high variability of throughfall depending on the canopy above the collection places. On average, the highest throughfall index values (1.5 to 2.3) were revealed at the periphery of the crown (Fig. 1–4), which means that the net gain of water at this drip point fluctuated from 50% to 130% of annual rainfall. These values are quite high when compared with other studies, since our experiment is based on the measurements of only one location. For example, Holder (2003) recorded approximately 39% of the precipitation coming from fog underneath drip points. The highest throughfall at crown´s periphery was observed also in the study of Willis et al. (1975) who were examining the spatial distribution of throughfall beneath the forest canopy. The authors stated that the distribution pattern of throughfall was subject to a great variation depending on a number of climatic and biological factors (Voight 1960 in Willis et al. 1975). Biotic factors include the tree species, tree density, age, height, and branching patterns (Rutter 1963 in Willis et al. 1975).

Usually, the throughfall is greater in younger forests, where the canopy is not as extensive as in mature stands (Fahey 1964). In our case, the throughfall underneath the thicket is smaller than underneath crown´s periphery (Fig. 1–6) due to negative interception resulting from fog deposition on vegetation that increases with larger canopy surface. In addition, Germer et al. (2006) reported that smaller trees tend to produce more stemflow than larger trees, which can also have an effect on the redistribution of throughfall in young stands.

Climatic factors affecting throughfall are wind, rainfall intensity and duration, time intervals between rainfall, and water droplet size (Rutter 1963 in Willis et al. 1975). Several authors reported strong correlations between throughfall and rainfall with correlation coefficients usually exceeding the value of 0.7, and often reaching the values very close to 1 (e.g. Juvik, Perreira 1972, Weaver 1972, Willis et al. 1975), while simple linear (Fahey 1964, Juvik, Perreira 1972, Weaver 1972) or log-linear regression models (Willis et al. 1975) are usually applied to describe this relationship. In our study, we used simple linear regression to analyse this relationship separately for each place of gauges, each year and each for of precipitation (rain vs. snow). Thus, all together we obtained 18 regressions, from which only 3 were insignificant. The correlation coefficients fluctuated from 0.69 to 0.99 in case of rainfall, and from 0.424 to 0.955 in case of snowfall, which indicates strong correlation between the throughfall and gross precipitation.

The rainfalls of the same intensity but differing in duration result in varying amounts of throughfall. In general, the more intense the rainfall and the higher its gross precipitation, the higher the proportion of throughfall, although the length of the rainfall has a positive effect on the time available for water evaporation, thus reducing the throughfall (Willis et al. 1975). Hence, in June 2002, when we did not observe the net gain of water from fog in any of the collection places (Fig. 2), there were most probably long-lasting rainfalls, during which adsorbed water had more time to evaporate from the leaves causing the reduction of throughfall.

The amount of throughfall is also influenced by the occurrence of wind. Several studies revealed that on windward sites there is higher throughfall than on leeward sites (Weaver 1972). Vegetation directly exposed to wind receives the largest quantity of fog precipitation (Holder 2003), which can explain the high values observed in our study, since the collection places were located on western, windward slopes of the massif of Babia hora.

Stadtmüller, Agudello (1990) found that throughfall is also affected by topography with the highest values obtained on ridges and lowest on concave slopes. These authors reported an average net gain of precipitation in throughfall of approx. 30% of rainfall regardless of topography, while on ridge the gain was almost 80%. Also Weaver (1972) detected higher throughfall on ridge and the windward site than on the leeward.

Although the net gain of water underneath drip points is high, it cannot be taken as a representative value of the situation in the forest stand as a whole, where the gain can be much lower if any. For example, Bruijnzeel (2001) who made a thorough literature review on cloud forests, reported the average net precipitation to be equal to 112% in the upper montane cloud forests (range 81–179%), i.e. the net gain of water from cloud deposition on vegetation was "only" 12%. Holder (2003), who detected high water inputs from fog precipitation under crown´s periphery mentioned above, found that the net gain of water from fog was only 7% for the whole stand. Similarly, our results also showed that the throughfall underneath the young forest was lower than underneath crown´s periphery, though except two cases (one case for rainfall and one case for snowfall) all values of the throughfall index exceeded 1, which means that the canopy of the young forest can also intercept fog.

When analysing the annual pattern, negative interception occurs in summer and lasts until late autumn or early winter resulting in the net gain of water both underneath crown´s periphery and the young forest (Fig. 2). Interestingly, in the first and the second year, index values exceeded 1 also in the case of snowfall (Fig. 3 and 4) indicating the presence of fog precipitation during the time with snow.

The forest opening showed a completely inverse pattern with all but one value of the index being lower than one, which suggests that the forest opening is in the rainfall shadow, i.e. its microclimate, and hence, also its water input, is highly affected by the surrounding stand. Significantly higher amount of throughfall in the forest opening was observed in the first year in the form of snow (throughfall index is equal to 1.5, Fig. 3), which could be explained by unloading of snow from the surrounding trees.

Based on the published information as well as on our results, which showed large variability of throughfall values highly depending on the collection place (with net loss or gain of water from –42% up to +130%), it is questionable if the examined forests of Babia hora have overall a positive bilance from fog deposition. According to Germer et al. (2006) negative average interception, i.e. higher amount of throughfall than the incident rainfall, can only be expected in some special forest types, e.g. montane cloud forests, while in other cases such values can be caused by either underestimation of rainfall or overestimation of throughfall. To obtain a reliable answer whether mountain forests of Babia hora behave like cloud forests, further more detailed studies aimed at examining the distribution of throughfall underneath the canopy are needed, since several studies showed great spatial variability of throughfall underneath the forest canopy (Willis et al. 1975, Germer et al. 2006).

However, there is no doubt that underneath crown´s periphery we can expect the net gain of water, since the indices were highly significantly different from 1. This excess amount of water at drip points has a positive effect on natural regeneration and understorey vegetation (Willis et al. 1975), which was also observed during our study, since at drip points; we found abundant and vital natural regeneration of Norway spruce. The regeneration underneath crown´s periphery is promoted by higher net precipitation as well as by higher amount of nutrients dissolved in precipitation (Tuček et al. 2004). The canopy shelter has a positive effect on microclimate at the particular place (Fleischer 1999). In addition, at such drip points the regeneration does not have to compete with understorey vegetation (*Athyrium distentifolium* Tausch, *Dryopteris austriaca ssp. spinulosa* Moll., and *Sorbus aucuparia* L.), which is most abundant in forest openings. In spring, the places underneath drip points are often free of snow, while forest openings still have high snow cover. All these positive effects on microclimate, competition with vegetation, water and nutrient cycle are further enhanced, when the natural regeneration grows on lying deadwood (Mai 1999).

Conclusion

In the presented paper, we analysed throughfall pattern in temperate mountain spruce forests of Central Europe. The results indicate that in the region of Babia hora the deposition of horizontal precipitation on vegetation surfaces occurs, while the values of throughfall index exceeded 1. The highest throughfall index values (from 1.5 to 2.3) were found at the periphery of the crown, which mean that underneath these drip points the excess amount of water can be expected, which promotes natural regeneration and understorey vegetation. However, the net gain of water was also detected underneath the young forest suggesting that the canopy of young forest can also intercept fog. The positive effect of horizontal (fog) precipitation on water regime was found to increase as the gross precipitation at open space decreases.

Acknowledgments

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