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Comparison of Rainfall Partitioning and Estimation of the Utilisation of Available Water in a Monoculture Beech Forest and a Mixed Beech-Oak-Linden Forest

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Abstract: Monoculture forests formed by *Fagus sylvatica* L. belong to one of the most sensitive forest ecosystems, mainly at low altitudes. Cultivation of this species in mixed stands should reduce its sensitivity to drought in the vegetation period, which is why we researched the water balance in one pure-beech (i.e., monoculture) and one beech–oak–linden (i.e., mixed) forest. This research was carried out in Drahanská vrchovina in the Czech Republic in the period 2019–2021. The total precipitation was measured, together with its partitions (i.e., throughfall and stemflow), and the crown interception was also calculated. The total forest transpiration was calculated from the values measured on the sample trees. The values of each rainfall partition and transpiration (and their percentages) were compared. The rainfall partitions in the monoculture forest differed from those in the mixed forest. While, on average, the annual percentages of the throughfall, stemflow and crown interception in the monoculture forest were 63%, 6% and 31%, respectively, these partitions in the mixed forest were 76%, 2% and 22%, respectively. The crown interception was greater in the monoculture (31% of precipitation) and the effective precipitation (i.e., the sum of throughfall and stemflow) was greater in the mixed forest (78% of precipitation). The greatest differences (in each rainfall partition) between the monoculture and mixed forest were in the summer and winter. The throughfall was greater in the mixed forest (ca. 22% in the summer and ca. 12% in the winter), and the stemflow was greater in the monoculture forest (ca. 66% in the summer and ca. 51% in the winter). The mean annual transpiration was 318 (±52) mm in the monoculture and 451 (±58) mm in the mixed forest, i.e., about 99 (±65) mm more in the mixed forest than in the monoculture forest. The transpiration, in comparison with the effective precipitation, made up, on average, 70% of the effective precipitation in the monoculture forest. On the other hand, the transpiration reached 71% (in 2019), 74% (in 2020) and even 100% (in 2021) of the effective precipitation in the mixed forest. Our results show that an oak–beech–linden mixed forest can manage water better than a beech monoculture because more precipitation leaked through the mixed forest onto the soil than through the monoculture, especially via the throughfall in the summer. On the other hand, the amount of water that transpired was greater in the mixed forest than in the monoculture. However, the utilisation of the effective precipitation by trees was very similar in the monoculture in all three years, while, in the mixed forest, the utilisation of the effective water by trees increased, which may have been caused by the saturation of the deeper soil layers with water in the first two years of measurement. We can, Therefore, say that, at lower altitudes, it will be more suitable in the future to cultivate beech in mixed forests because of the assumed lack of water (mainly in early spring and summer).

Keywords: rainfall partition; throughfall; stemflow; crown interception; transpiration

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1. Introduction

The ongoing climate change is bringing about an increase in the air temperature and a change in the annual precipitation distribution, including longer periods of drought in the vegetation period and an increase in intensity in the form of torrential rains [1,2]. The changes that are forecasted to come will reach such a magnitude during one forest generation [3] that the forest will not be able to adapt. This could lead to a reduction in the forest's functionality and to local or large-area disintegration of forest ecosystems [4,5]. European beech (*Fagus sylvatica* L.) suffers from drought [6,7], especially when the lack of water comes at the beginning of spring [8]. On the other hand, oak (*Quercus* spp. L.) is less sensitive to drought [9]. According to Theurillat and Guisan [10], beech forests could be replaced naturally by more drought-resistant oak–hornbeam forests (*Quercus robur* L., *Q. petraea* (Matt.) Liebl. and *Carpinus betulus* L.) in the driest places. Proper forest management enhances forests' resilience to climate change by improving whole-tree water use [11].

The tree species composition of the forest has a great effect on water retention and water balance in the landscape [12]. The rainfall partitioning in the stand varies among species [13]. Precipitation can fall to the ground in one of two ways. The first is throughfall, when the rain drips through the crown onto the soil [14]. According to Nordén [15], beech has the lowest throughfall (out of five researched broad-leaved trees), with the increasing throughfall for maple (*Acer platanoides* L.), linden (*Tilia cordata* Mill.) and hornbeam (*Carpinus betulus*) trees and, finally, oak (*Quercus petraea*, *Quercus robur*), which has the greatest throughfall. The second is stemflow, where the water flows down the moist branches and the trunk to the soil around it [14]. The differences in the amount of the water flowing down the trunks are considerable, depending on the species. Spruce, with its dense crown, spread-out branches and coarse bark, has a stemflow of only 1–2% and, on the other hand, beech, with its scourge crown and smooth trunk, reaches a stemflow of 15–18% [13]. In 69% of the cases observed worldwide, the stemflow (with various combinations of species and climate) is less than 2% [16]. The throughfall and stemflow are called "effective precipitation" [17], and this constitues the amount of water that the tree species can actually utilise.

Different tree species affect also the output part of the hydrological cycle in various ways [18–21]. Crown interception and transpiration are the greatest partitions of evapotranspiration, and it is not possible to specify which one returns more water to the atmosphere [22–24]. Crown interception is a hydrological process of considerable significance [25], especially inside stands, where the amount of the precipitation entrapped by the crown makes up more than 25% [26]. The percentage of the crown interception varies in the range of 10–50% of the total annual precipitation [27]. It can even reach almost 100%, when there is less than 1 mm of precipitation [28]. The percentage distribution of rain among throughfall, stemflow and crown interception varies, depending on the species composition of the forest [13,14,16]. While the crown interception reaches 10–50% of the precipitation, the transpiration reaches as much as 60% of the evapotranspiration in specific cases [27,29]. In terrestrial conditions, transpiration returns around 39% of the precipitation to the atmosphere, if we consider water drain [30]. Stands of European beech and sessile oak exhibit different patterns of transpiration due to their root system type, stomatal regulation in response to environmental variables, leaf area index or forest management [30,31]. A recent study indicated that oak in the mixed forest transpired more water than beech, especially in the dry periods [32]. It was most likely due to different rooting patterns. On the other hand, the availability of soil water should be higher in the oak or mixed forest compared to that in a monoculture stand of beech [15]. What we lack, however, is a comprehensive

study that compares the hydrological balance of a European beech forest with a mixture of sessile oak and beech at the drought-prone sites.

To address the hydrology of monoculture stands of beech and its mixtures, we focused on the differences between the two forests at the lower altitudes in the Czech Republic (CR). We chose one pure-beech and one oak–beech–linden forest. They were located at an altitude of the lower the part of the ecological limit of the pure-beech forest. The beech here can be potentially displaced by oak. We assumed that there would be a difference in the distribution of the rainfall partitions (i.e., the throughfall, stemflow and crown interception) between pure and mixed forests. We hypothesised that the throughfall would be higher and interception lower in the mixed forest than in the monoculture beech forest, due to a low LAI of oak. The second goal was to compare sap flow in both forests. We hypothesised that the transpiration from the mixed stand would be greater, due to the presence of oak, than from the monoculture stand of European beech.

2. Materials and Methods

2.1. Site Description

The measurement was carried out from 2019 to 2021 on two researched forest plots (250 m apart) that were located near Brno (49°16′49.3″ N; 16°39′01.4″ E) in the CR at an altitude of around 400 m a.s.l. For comparison, the following two different broad-leaved forests were chosen:

- Monoculture—no undergrowth, 48–61 years old, 0.255 ha in size;
- Mixed—no undergrowth, 72 years old, 0.83 ha in size.

Characteristic parameters of the forests are entered in Table 1.

Table 1. Characteristics of forests.

Stand	Species	Species Composition [%]	Mean DBH ± SD [cm]	Mean Height ± SD [m]	PAI ± SD	LAI ± SD	WAI ± SD
Monoculture forest	*Fagus sylvatica*	100	19.1 ± 6.4	18.6 ± 3.0	6.9 ± 0.1	5.1 ± 0.1	1.7 ± 0.1
Mixed forest	*Fagus sylvatica*	50	17.8 ± 9.0	18.5 ± 9.4	4.0 ± 0.2	2.9 ± 0.2	1.1 ± 0.1
	Quercus petraea	40	21.8 ± 5.5	22.6 ± 10.4			
	Tilia cordata	10	15.9 ± 8.8	15.9 ± 6.4			

Note(s): SD—standard deviation; DBH—diameter at breast height; PAI—plant area index; LAI—leaf area index; WAI—woody area index.

The soils of the forests were classified as Cambisol, according to IUSS Working Group WRB [33]. The climate is humid continental [34], with a mean annual air temperature of 9.4 °C and a precipitation of 613 mm, according to the long-term normal 1981–2010 taken from the weather station in Brno-Tuřany [35].

Microclimate parameters were measured from 2019 with the aid of a meteorological station, located in a carefully selected open area (uninfluenced by the structure of a canopy forest) at similar distances from both forests. The following instruments were mounted on the meteorological station:

- A Pronamic Pro professional rain gauge (PRONAMIC®, Skjern, Denmark) in conjunction with a Minikin ERi event recorder (EMS Brno Ltd., Brno, Czech Republic) with a resolution of 0.2 mm for measuring the precipitation;
- A Minikin RTHi sensor (EMS Brno Ltd., Brno, Czech Republic) for measuring the intensity of falling global radiation (GR), air temperature (T) and relative air humidity (RH);

- An Atmos 22 ultrasonic anemometer (METER Group, Pullman, WA, USA) with a MicroLog SDI-MP datalogger (EMS Brno Ltd., Brno, Czech Republic) for windspeed measurement.

Data from the RTHi sensor and the Atmos 22 anemometer were used for calculating the potential evapotranspiration (PET) using the Penman–Monteith equation [36]. The vapour pressure deficit (VPD) was calculated from T and RH data [36]. Comparing the available water and evaporation, the cumulative water deficit (CWD), as the difference between cumulative PET and cumulative T, was calculated using the method described by Čermák and Prax [37]. Based on articles by Yan et al. and Zapater et al. [38,39], it was decided not to measure the soil moisture. Yan et al. [38] observed no obvious relationship between transpiration and soil moisture, based on the results of the hysteretic effect of the precipitation on the transpiration and the changes in magnitude of LAI during the vegetation period. Zapater et al. [39] show that frequent measurement of soil water potential [40,41] and volumetric humidity [42,43] provides inaccurate results.

The areas of the plots were measured, and the height (H), crown projected area (CPA) and diameter at breast height (DBH) were measured on all trees therein. A measurement grid with 20 × 10 m line spacing was laid out on both plots, the total number of points being 141 in the beech forest and 306 in the mixed forest. Above these points, the plant area index (PAI) and the woody area index (WAI) were measured using LaiPen (PSI, CR) in July and January, respectively (where LAI was calculated as PAI minus WAI).

2.2. Measurement of Throughfall

The throughfall was collected as follows:

- From 1st March until 30th November, using a rectangular plastic trough with a retaining area of 0.4 m^2, and sent through a small pipe to a small plastic barrel. Each barrel was marked with a number and weighed empty, and this weight was recorded.
- From 31st October until 1st April, using a round plastic bucket with a retaining area of 0.07 m^2. Each bucket was marked with a number and weighed empty, and this weight was recorded.

In each plot, five troughs and ten buckets were evenly laid out. Above them, PAI and WAI were measured in July and January, respectively. The water volume in the barrels and buckets was measured ca. each 14 days (more often after ample rainfall). The weight of the filled barrel/bucket was measured repeatedly using OCS-F 50 kg scales (Getscales Int'l Trading Co., Shanghai, China), accurate to 10 g, and the weight of the empty barrel/bucket was subtracted (from this weight), in order to obtain the net weight of the water. Since 1 litre of water weighs 1 kg, we converted the net weight (in kilograms) to volume (in litres). The throughfall was calculated for each month separately and re-calculated to volume per square metre. The mean amount of throughfall per m^2 was calculated for each forest, according to the mean value of PAI (or WAI in winter) in the plots and above the troughs or buckets.

2.3. Measurement of Stemflow

The healthy and undamaged trees, in which the stemflow was measured, were chosen according to their species composition and social position (based on a histogram of the DBHs) in the forests. The stemflow was carried out on 10 trees—4 dominant trees (D), 3 co-dominant trees (C) and 3 suppressed trees (S)—in one beech forest and on 10 beech trees (3D, 4C, 3S), 10 oak trees (3D, 4C, 3S) and 6 linden trees (2D, 2C, 2S) in the mixed forest. A piece of garden hose was wound around the trunk of each tree, under an angle of ca. 30°, and held from underneath using polyurethane foam (Figure 1A). After stiffening up of the foam (which permanently fixed the hose to the trunk), the upper part

of the hose was cut off along its entire length. Subsequently, the cropped edge of the hose, which was closer to the trunk, was glued to the trunk with Universal silicone (Figure 1B), and the outlet part of the hose was inserted into a barrel.

The water volume inside the barrels was measured in the same way as in Section 2.2 above. With DBH and CPA, the amount of the stemflow from each tree was calculated using regression curves for each forest and species and re-calculated per square metre.

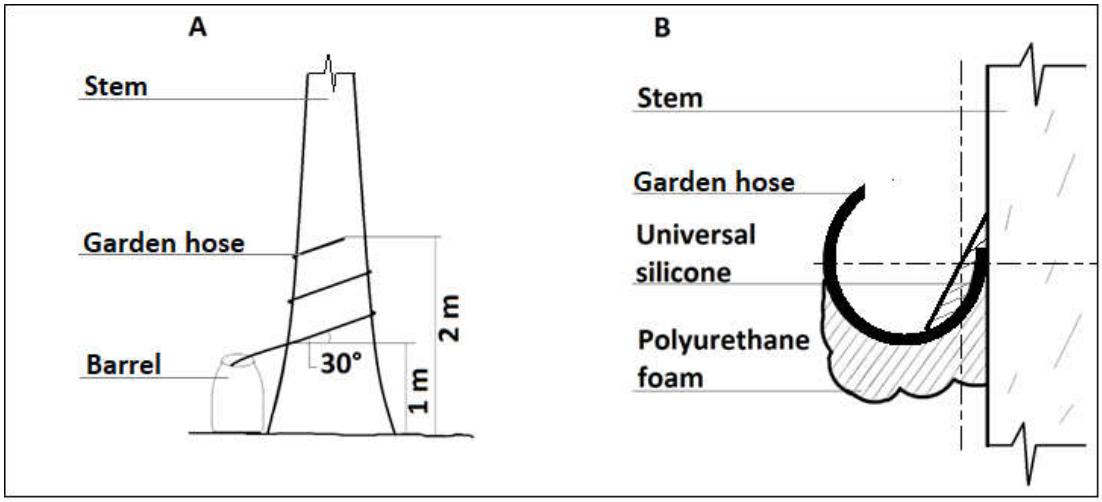

Figure 1. The measuring of the stemflow. (**A**) Stemflow and (**B**) anchoring of the hose to the trunk.

2.4. Measurement of Sap Flow

Sap flow was measured on six healthy and undamaged trees in the monoculture forest and on nine healthy and undamaged trees in the mixed forest. The trunk heat balance (THB) method, with internal heating and sensing, was used for measuring sap flow [44]. EMS81 sap flow sensors (EMS Brno Ltd., Brno, Czech Republic) were installed on the trunk 1.3 m above the ground. The THB system is almost independent of sap flow and the radial profile, and the measurement sensor is integrated above the heated area [45,46]. The calculated values of specific sap flow (Q) per unit of trunk circumference ($kg \cdot day^{-1} \cdot cm^{-1}$) were measured at 1 min intervals with average values being stored every 15 min. The sap flow for the entire tree (Q_{tree}) was calculated by multiplying Q by the tree circumference (excluding the bark and phloem layer, whose thicknesses were measured during installation) and summed up daily. The upscaling of Q_{tree} from individual- to stand-level transpiration (TR) was conducted according to the methodology formulated by Čermák et al. [44]. Q_{tree} of the DBH classes was calculated based on scaling curves of tree DBH. According to Nalevanková et al. [30], stand-level sap flow (Q_{stand}) was then obtained as the Q_{tree} values of mean trees of individual DBH classes multiplied by the numbers of trees in the classes, n_i, and summarised for the stand area unit of 1 ha:

$$Q_{stand} = \sum_{i=1}^{i=m} (Q_{tree}) \times n_i$$

The non-dimensional coefficient, S, was subsequently computed by dividing Q_{stand} by Q_{tree}, for which it was measured directly according to Nalevanková et al. [30]:

$$S = \frac{\sum Q_{stand}}{\sum Q_{tree}}$$

The values of the sap flow at the tree level were multiplied by coefficient S, in order to obtain these values for stand level. On the daily timescale, the sap flow was considered equal to the daily TR (as the time lag between the breast height measurement), and the crown TR was eliminated.

2.5. Statistical Analysis

Data were processed in Mini32 software (EMS Brno Ltd., Brno, Czech Republic), which is compatible with that used in all other equipment. Statistical analysis of the data was performed using TIBCO Statistica™ (Statsoft, Tulsa, OK, USA) for all analyses, with a reliability interval of 95%. Normality of the data distribution was examined before the main analysis. The main effects (i.e., temperature, precipitation and their partitions and transpiration) were analysed using ANOVA, after which Fisher's LSD test was applied, in order to identify differences among the main effects and their interactions.

3. Results

3.1. Microclimate

The mean annual precipitation and the mean precipitation in the vegetation period of the long-term 1981–2010 normal (hereinafter referred to as Normal) did not differ from those from the period 2019–2021 (hereinafter referred to as Researched Period). However, there were differences in certain months, between Normal and Researched Period. More precipitation always fell in June than in Normal ($p = 0.0047$; Table 2); on the other hand, there was considerably less precipitation in March and April, and slightly less in July than in Normal.

The average summer temperature of Researched Period was warmer, compared to that in Normal. The annual temperatures and precipitation in the dispersion graph showed that the year 2019 achieved the values of Normal, but the years 2020 and 2021 were different. These years were colder than those in Normal and, furthermore, the year 2020 experienced more precipitation. A more detailed analysis of the individual months showed that

- The year 2020 was colder from April to October (with less precipitation from March to May and more precipitation from June to October) than Normal;
- The year 2021 was colder (with less precipitation from March to June and September to October) than Normal.

Table 2. Mean monthly, annual and seasonal (VP–vegetation period; i.e., from the second half of March until the first half of October) precipitation during 2019–2021, their mean and comparison with long-term normal 1981–2021 (Normal). Mean monthly, seasonal and annual air temperatures and their comparison with Normal. The monthly precipitation recorded during 2019–2021 was as follows: more than 70% less than Normal (red); 50–70% less than Normal (bold red); more than 30% more than Normal (blue) and double that of Normal (bold blue). The monthly temperatures recorded during 2019–2021 were: ca. 1–2 °C lower than Normal (blue); more than 2 °C lower than Normal (bold blue); ca. 1–2 °C higher than Normal (red) and 2 °C and higher than Normal (bold red). The values are supplemented with standard deviations (±SD). Months are represented by Roman numerals.

Precipitation [mm]														
Month/Year	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**	**Σ Year**	**Σ VP**
2019	24	34	35	**19**	95	97	70	56	66	46	52	41	635	449
2020	**16**	41	31	**7**	68	**182**	66	73	77	**108**	29	49	747	581
2021	42	23	**14**	**20**	53	118	75	134	**11**	**13**	51	41	595	424
Mean	27 ± 13	32 ± 9	27 ± 11	15 ± 7	72 ± 21	132 ± 44	70 ± 5	88 ± 41	51 ± 35	56 ± 48	41 ± 16	45 ± 6	659 ± 122	485 ± 85
1981–2010	33 ± 16	33 ± 18	39 ± 22	39 ± 23	69 ± 30	77 ± 29	80 ± 41	68 ± 42	57 ± 35	38 ± 25	44 ± 18	44 ± 17	613 ± 95	427 ± 36
Temperature [°C]														
Month/Year	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**	**ϕ Year**	**ϕ VP**
2019	−1.9	**2.1**	**6.3**	10.7	**11.3**	**21.1**	19.3	20.1	14.2	9.8	**6.1**	**1.9**	10.1	15.2
2020	−1.2	**3.1**	5.0	8.5	**10.3**	**15.7**	**16.7**	18.0	13.5	8.3	3.1	0.9	8.5	13.0
2021	−1.4	−1.5	1.9	**5.1**	**10.4**	18.0	18.6	**15.5**	13.4	**7.7**	3.4	1.0	**7.7**	12.7
Mean	−1.5 ± 0.4	1.2 ± 2.4	4.4 ± 2.3	8.1 ± 2.8	10.7 ± 0.6	18.3 ± 2.7	18.2 ± 1.3	17.9 ± 2.3	13.7 ± 0.4	8.6 ± 1.1	4.2 ± 1.7	1.3 ± 0.6	8.8 ± 1.2	13.6 ± 1.4
1981–2010	−1.5 ± 2.9	0.1 ± 2.9	4.3 ± 2.0	9.9 ± 1.6	14.9 ± 1.4	17.7 ± 1.4	19.9 ± 1.6	19.5 ± 1.6	14.7 ± 1.6	9.4 ± 1.4	3.9 ± 2.0	−0.4 ± 1.8	9.4 ± 0.8	15.1 ± 4.2

The differences between the cumulative potential evapotranspiration (CPET) and cumulative precipitation (CP) were significant each year during the monitored period (Figure 2). From February 2019, the values of CPET were higher than those of CP, and at the end of the year, the values of CPET were about 38% higher than those of CP. In 2020 (a year with above-average precipitation), the values of CPET and CP were equal up to April. From this month on, the values of CPET were higher than those of CP, and at the end of the year, the difference was 22%. In 2021, the values of CPET and CP were equal in March, and at the end of measurement (in October), the values of CPET were about 41% higher than those of CP.

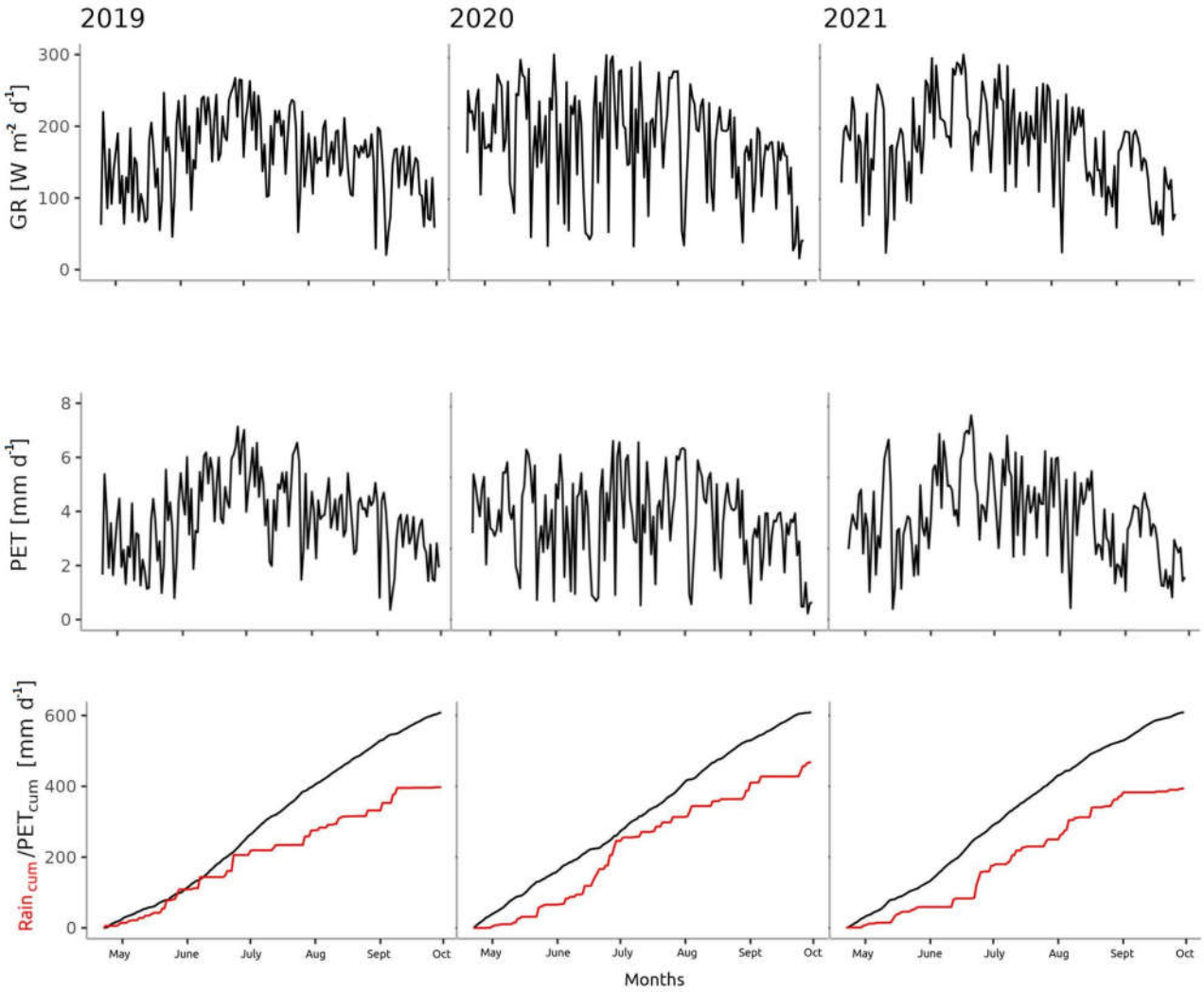

Figure 2. Global radiation (GR), potential evapotranspiration (PET), cumulative potential evapotranspiration (PET_{cum}) and cumulative precipitation ($Rain_{cum}$) during 2019–2021.

3.2. Distribution of Precipitation

We found out that the percentages of the precipitation that reached the forest floor (i.e., throughfall and stemflow) and the crown interception differed between the monoculture and mixed forests (throughfall: p = 0.0001; stemflow: p = 0.0474; crown interception: p = 0.0004; Figure 3). The annual precipitation, on average, comprised 63% throughfall, 6% stemflow and 31% crown interception in the monoculture forest and, on average, 76%, 2% and 22%, respectively, in the mixed forest. During the vegetation period (from April to October), the percentages of throughfall, stemflow and crown interception were similar to the annual percentages, and they were 61.1%, 7.5% and 31.8%, respectively, in the monoculture, and 76.3%, 2.6% and 21.2%, respectively, in the mixed forest. The statistically significant differences were p = 0.0001 (throughfall), p = 0.0314 (stemflow) and p = 0.0002 (crown interception). On the other hand, the percentage distribution of precipitation in the winter (from November to March) was different to that in the vegetation period. In the monoculture forest, there was more throughfall (67.9%; p = 0.0020), less stemflow (3.6%; p = 0.0413) and similar crown interception, relative to the throughfall, stemflow and crown interception throughout the year. In the mixed forest, there was similar throughfall and crown interception (75.6 and 22.6%) and less stemflow (1.8%; p = 0.0426), relative to the throughfall, stemflow and crown

interception throughout the year. The greatest differences in individual partitions of distribution of precipitation between monoculture and mixed forest arose from June to September and from November to January. In this time, there was more throughfall in the mixed forest (ca. 22% in the summer; ca. 12% in the winter) and more stemflow in the monoculture forest (ca. 66% in the summer; ca. 51% in the winter).

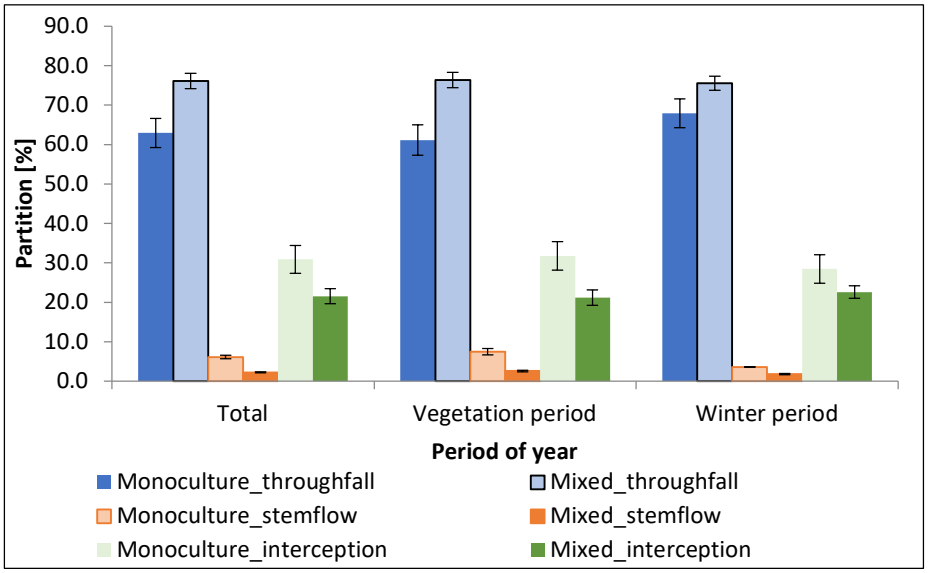

Figure 3. Mean values of the rainfall partitions within the monoculture and mixed forests during the year, vegetation period and winter period.

3.3. Transpiration

During 2019–2021, the mean total amount of annual transpiration of the monoculture forest was 318 (±52) mm and that of the mixed forest was 451 (±58) mm, i.e., about 99 (±65) mm greater ($p = 0.0192$; Figure 4). However, from the viewpoint of the percentage of the effective precipitation that fell through the crowns, the transpiration was almost constant in the monoculture forest throughout these three years (70 ± 3% on average). On the other hand, the percentage of the transpiration of the effective precipitation was 71% (in 2019), 74% (in 2020) and almost 100% (in 2021). The transpiration, in comparison with the effective precipitation, shows that the monoculture forest reacted to the increase in the precipitation (in 2020) by increasing transpiration flow (by about 29% in 2020, compared to 2019); however, percentage wise, relative to the effective precipitation, only about 2% more was utilised in 2020 than in 2019. During 2021 (the precipitation was similar to that in 2019), the transpiration was comparable to that in 2019, but the effective precipitation was less utilised (by about 6% than in 2019). The mixed forest reacted to the increased precipitation in 2020 (as did the monoculture forest) by increasing transpiration flow (by about 27%), but the utilisation of the effective precipitation was only about 4% greater. In 2021 (i.e., the year, in which the precipitation was similar to that in 2019), the transpiration of the mixed forest reached a similar value, as in 2020 (which was a very rainy year), and the utilisation of the effective precipitation was about 41% greater than that in 2019.

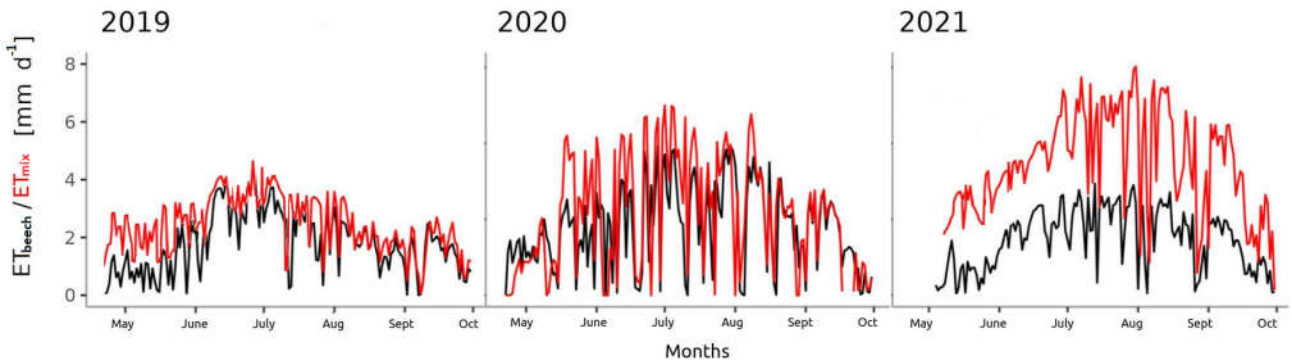

Figure 4. Transpiration (ET) within the monoculture (ET_{beech}) and mixed (ET_{mix}) forests.

4. Discussion

Throughfall in the mixed forest was higher than that in the pure-beech forest. Even though the stemflow was higher in the pure-beech forest than in the oak–beech mixture, the total amount of water reaching the soil was still larger in the mixed forest. According to Levia and Frost [47], more than 70% of precipitation reaches the ground via throughfall. In our research, this was the case only in the mixed forest. On the other hand, the throughfall in beech forests varies within the range 60–95%, in the review written by Peck [13]. The difference between the mixed oak–beech forest and the monoculture forest of beech is in line with Nordén [15], where beech has the least throughfall and oak the most.

In the monoculture forest, the annual percentage of the amount of the stemflow was 6% (8% during the vegetation period and just under 4% in the winter). This amount is larger than that presented by Mattaji et al. [48], who show the stemflow in the beech forest as being only 1.2%, or van Stan and Gordon [16], who describe that the stemflow is under 2% in more than two-thirds of the cases worldwide. Levia and Frost [47] estimate that less than 5% of the precipitation is distributed through stemflow. On the other hand, Mitscherlich [49] and Peck [13] agree that stemflow in beech forests can reach a mean value of 12%. The result described by van Stan and Gordon [16] is similar to that of our mixed forest, where the annual stemflow was 2.3% (2.6% during the vegetation period and 1.8% in the winter). The difference in the percentage of the stemflow between the monoculture and mixed forest can occur not only due to differences in the LAI, WAI and PAI but also due to differences in the types of bark [47,50]. While the smooth bark of beech has a smaller soaking area and faster flow of water down the trunk, the furrowed barks of oak and linden have larger soaking areas and their roughness reduces the speed of the water running down the trunk, which, in turn, increases the probability of evaporation [51].

The annual crown interception was almost 31% in the monoculture and 22% in the mixed forest, with negligible differences between summer and winter. It varies within the wide range for European beech from 5 % to 48% [13]. The crown interception in the mixed forest was lower than that in the monoculture forest. The higher LAI (or WAI and PAI too) of beech than the other broad-leaved species matches its higher rainfall interception well, as interception is largely a function of LAI [52]. Interception may vary between summer and winter. For example, Klamerus-Iwan and Błońska [53] estimated 6% in a forest with bare trees and 22% in a fully leaved forest. Surprisingly, we found no statistical differences in the interception between summer and winter in either forest. Many authors [13,53–56] estimated a lower percentage of interception in a beech forest than we did. The differentness in the crown interception values among the forests studied could be caused by the different distribution and intensities of precipitation. Since our site is more on the drier side of the beech ecological distribution and because

the studied beech forest had a fully closed canopy, the share of interception in the hydrological balance may be greater than that stated by the above-mentioned authors.

These authors do not specify whether the crown interception was determined from all precipitation or whether their calculations did not include some precipitation events. Safeeq and Fares [28] present that, when there is less than 1 mm of precipitation, the water reaches the soil only on windless days and if the crowns are still moist from previous precipitation. Rahmani et al. [57] even show that, when there is less than 5 mm of precipitation, it is accumulated in the beech crowns and, subsequently, evaporates. Our study includes all precipitation events, where those providing less than 1 mm and 5 mm were 3% and 22%, respectively, throughout the entire period. If we had not included the precipitation events providing less than 5 mm, the crown interception in the monoculture forest would have been only one-third of what was measured, and there would have been no crown interception in the mixed forest. This means that the precipitation events providing less than 5 mm also had a considerable share in the throughfall and stemflow in the mixed forest with 50% beech, which disproves the assumption about evaporation of precipitation put forward by Rahmani et al. [57].

The mixed forest transpired more water than the beech forest, which was in line with what Leuzinger et al. state [58]. On average, 70% of the effective precipitation was used in the transpiration process in the beech forest and even more in the mixed forest. However, 100% utilisation of the effective precipitation by the root systems is not realistic [59,60]. It can, therefore, be concluded that mainly oaks can receive water from other, less accessible, sources due to the different distribution of the root system in the soil and the different hydrological properties of their conductive system. Fan et al. [61] describe an average rooting depth of 5.23 m for oak and 0.8 m for beech. With such a distributed root system, beech mainly utilised the near-surface soil water, i.e., the effective precipitation, as is described by Fabiani et al. [32]. On the other hand, oak could use the effective precipitation and, also, the groundwater, which its deep roots were able to reach [62]. As a result of this, oak could receive enough water in the dry period. Moreover, oak roots could transfer (accessible) groundwater to the surrounding beeches, whose root systems were in the drier soil layer, through hydraulic lift [39,63,64].

5. Conclusions

Our results show that an oak–beech–linden mixed forest can manage water better than a beech monoculture, because more precipitation leaked through the mixed forest onto the soil than through the monoculture, especially via the throughfall in the summer. On the other hand, the amount of water that transpired was greater in the mixed forest than in the monoculture. The utilisation of the effective precipitation by trees was very similar in the monoculture in all three years. However, in the mixed forest, the utilisation of the effective water by trees increased in the last year of the study, which may have been caused by the saturation of the deeper soil layers with water in the first two years of measurement. We can, therefore, say that, at lower altitudes, it will be more suitable in the future to cultivate beech in mixed forests because of the assumed lack of water (mainly in early spring and summer).

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Abbreviations

C	co-dominant trees
CP	cumulative precipitation
CPA	crown projected area
CPET	cumulative potential evapotranspiration
CR	Czech Republic
CWD	cumulative water deficit
D	dominant trees
DBH	diameter at breast height
ET	transpiration
ET_{beech}	transpiration within monoculture forest
ET_{mix}	transpiration within mixed forest
GR	global radiation
H	height
LAI	leaf area index
Normal	long-term 1981–2010 normal
P	precipitation
PAI	plant area index
PET	potential evapotranspiration
PET_{cum}	cumulative potential evapotranspiration
Q	specific sap flow
Q_{stand}	stand-level sap flow
Q_{tree}	sap flow of entire tree
$Rain_{cum}$	cumulative precipitation
Researched Period	period 2019–2021
RH	relative humidity
S	suppressed trees
SD	standard deviation
T	air temperature
THB	trunk heat balance
TR	transpiration
VP	vegetation period
VPD	vapour pressure deficit
WAI	woody area index

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