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Comparative analysis of throughfall observations in six different forest stands: Influence of seasons, rainfall- and stand characteristics

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Abstract

Throughfall, that is, the fraction of rainfall that passes through the forest canopy, is strongly influenced by rainfall and forest stand characteristics which are in turn both subject to seasonal dynamics. Disentangling the complex interplay of these controls is challenging, and only possible with long-term monitoring and a large number of throughfall events measured in parallel at different forest stands. We therefore based our analysis on 346 rainfall events across six different forest stands at the long-term terrestrial environmental observatory TERENO Northeast Germany. These forest stands included pure stands of beech, pine and young pine, and mixed stands of oak-beech, pine-beech and pine-oak-beech. Throughfall was overall relatively low, with 54–68% of incident rainfall in summer. Based on the large number of events it was possible to not only investigate mean or cumulative throughfall but also its statistical distribution. The distributions of throughfall fractions show distinct differences between the three types of forest stands (deciduous, mixed and pine). The distributions of the deciduous stands have a pronounced peak at low throughfall fractions and a secondary peak at high fractions in summer, as well as a pronounced peak at higher throughfall fractions in winter. Interestingly, the mixed stands behave like deciduous stands in summer and like pine stands in winter: their summer distributions are similar to the deciduous stands but the winter peak at high throughfall fractions is much less pronounced. The seasonal comparison further revealed that the wooden components and the leaves behaved differently in their throughfall response to incident rainfall, especially at higher rainfall intensities. These results are of interest for estimating forest water budgets and in the context of hydrological and land surface modelling where poor simulation of throughfall would adversely impact estimates of evaporative recycling and water availability for vegetation and runoff.

KEYWORDS
forest hydrology, forest stand characteristics, interception, leaf area index, rainfall characteristics, seasonal effects, stratified event analysis, throughfall, tree species effects

1 | INTRODUCTION

The vegetation canopy acts like a filter and changes the patterns and dynamics of rainfall as it enters the biosphere. These patterns and dynamics of throughfall are of interest in terms of both water and matter fluxes (Crockford & Richardson, 2000; Heartsill-Scalley et al., 2007; Levia Jr & Frost, 2003; Siegert et al., 2017; Staelens et al., 2008). In forested regions where water is sometimes scarce it is especially important to understand how different forest stands impact and diminish the much-needed rainfall input (Carlyle-Moses, 2004), because this input is important for both tree water supply and groundwater recharge. The loss of rainfall input to interception is therefore relevant across all seasons: in many regions trees largely rely on water from the unsaturated zone and are thus dependent on rainfall during the growing season, while groundwater recharge often occurs only in the dormant season (due to increased interception, evaporation and root water uptake in summer).

Groundwater levels in northeastern Germany have been decreasing over the last decades, likely as a result of a mixture of land management and climate change (Germer et al., 2011; Heinrich et al., 2018). In addition, a series of droughts in recent years strongly impacted both agriculture and forests. Climate projections suggest that annual rainfall distribution and intensity distributions are likely to change: drier summers, longer periods without rain, slightly wetter winters, more high-intensity rainfall (Kunz et al., 2017). As similar changes are expected in many regions of the world, it is therefore imperative to better understand which forest stands are most resilient to these changing conditions but also how forest management, which includes the choice of tree species, influences the forest water budget.

Throughfall is influenced by a number of different factors: (a) forest stand characteristics, such as stand density, canopy and tree species (André et al., 2011; Crockford & Richardson, 2000; Levia Jr & Frost, 2003; Llorens & Gallart, 2000; Pypker et al., 2005; Siegert et al., 2016; Siegert & Alexander, 2019), and (b) rainfall characteristics (plus meteorological conditions) (Carlyle-Moses et al., 2004; Crockford & Richardson, 2000; Keim et al., 2006; Llorens et al., 1997; Staelens et al., 2008). Furthermore, there are seasonal dynamics to consider, which can mean a change in rainfall characteristics but also a change in tree canopy characteristics (Herbst et al., 2008; Staelens et al., 2008). The latter has the interesting side effect that it allows us to investigate the different interception behaviour of the fully leafed canopy of deciduous trees in summer to the bare tree crown in winter (similar to the 'wood area index' studied by Llorens and Gallart (2000)), which has often been neglected in previous studies and requires more research (Klingaman et al., 2007; Staelens et al., 2011).

Carrying out comparative studies of throughfall comes with several challenges: for robust analyses it is necessary to collect data for a large number of rainfall events if possible with a distribution of the event characteristics that is representative for the site (Llorens et al., 1997; Staelens et al., 2008). A robust comparison of different forest stands requires them to be in the same vicinity and thus subject to the same driving forces (meteorological conditions and rainfall events). Only events measured at all forest stands should be included in the analysis. However, even if we accomplish all this, we might still be faced with the challenge that the different interception behaviour of summer and winter canopy can be obscured by seasonally different rainfall characteristics (Forgeard et al., 1980; Herbst et al., 2008; Sadeghi et al., 2020; Staelens et al., 2008) or that the relationship of throughfall to forest stand characteristics also depends on rainfall characteristics (Park & Cameron, 2008).

Basal area, stand density and leaf area index (LAI) are often used to describe forest stands (e.g., Crockford & Richardson, 2000; Marin et al., 2000; Oyarzún et al., 2011; Park & Cameron, 2008). While basal area and stand density remain approximately constant over the seasons, LAI at the deciduous and mixed forest stands undergoes a change (Staelens et al., 2008). As the woody and the leafy components of the LAI are likely to have different effects on throughfall, we are specifically comparing two sites where LAI remains more or less constant over the seasons (two pine stands of different ages) with two purely deciduous and two mixed sites. Looking at this ensemble of six neighbouring forest stands as well as the large number of monitored events allows us to investigate the effect of different rainfall characteristics, such as intensity and amount, but also to account for the seasonal changes in rainfall characteristics and throughfall fractions. We therefore focus specifically on the following research objectives: (a) Analysing the dependence of throughfall on rainfall characteristics across six different forest stands based only on events measured in parallel at all sites. (b) Identifying the impact of forest stand on seasonal changes in throughfall and (c) Identifying and separating the possibly superimposed seasonal effects of rainfall and canopy characteristics.

The main features of this investigation are:

- The comparative analysis of six different forest stands (several mixed species forest stands as well pure deciduous and conifer stands) based on representative throughfall data due to the large catch area of the trough systems.
- The robustness of the comparison between sites and seasons as a result of the large number of events while at the same time using only rainfall events that were measured in parallel at all six forest stands.

Based on the large number of events it was possible to not only investigate mean or cumulative throughfall but also its statistical distribution. These results are also of interest in the context of hydrological modelling (where throughfall is often calculated based on a simple interception storage linked to the leaf area index LAI) as was recently stated by Gutmann (2020): 'Measurements in a wide variety of vegetation canopies and climates are critical to advancing what are often global modelling endeavours (e.g., for climate and weather applications)…'.

2 | DATA AND METHODS

2.1 | Research area

The study area, the catchment of Lake Hinnensee, is located in the Müritz National Park (subsection Serrahn) in north-eastern Germany (53°18′N, 13°9′E). It is part of the Northeast German Lowland Observatory (TERENO-NE) that was established for interdisciplinary geo-ecological research on the regional impacts of climate and land use change (Heinrich et al., 2018) as part of the TERENO network. The study area is located on a relic of the last glaciation, an outwash plain that developed in the direct forefront of the Weichselian ice sheet (Kaiser et al., 2020). Elevations range between 63 and 115 m.a.s.l. It is characterized by glaciofluvial, sporadically aeolian sediments of homogeneous sandy texture. Cambisols with different levels of podzolization and with low water holding capacity prevail (Kaiser et al., 2020). The landscape is dominated by lakes (there is no stream network) and mixed deciduous and coniferous forests. Mean annual precipitation is 629 mm (1950–2019; climate station 'Serrahn', run by the German Weather Service DWD) and mean annual temperature is 8.7°C (2005–2019; climate station 'Feldberg/Mecklenburg', also run by the DWD).

The forest in the study area is composed of homogeneous as well as mixed stands of the predominant species European beech (*Fagus sylvatica* L.), Scots pine (*Pinus sylvestris* L.) and sessile oak (*Quercus petraea* L.).

2.2 | Experimental design and methods

Our experimental design for measuring throughfall covers six forest plots with a maximum distance of less than 2 km between them (Figure 1). The plots are within three single-species stands of young pine (age about 35 years), old pine (70 years) and beech (135 years), and three mixed stands all with a mix of ages between 100 and 170 years. Only the old pine has any significant understory (*Vaccinium myrtillus* – blueberry bushes). Stand characteristics were determined by surveys of each 40x50m plot (Table 1). LAI measurements were carried out on overcast days with a LICOR LAI-2200 at 29–39 locations per forest stand. The LAI values include the LICOR standard correction for clumping (LICOR LAI-2200 Instruction Manual, 2010) as clumping can lead to an underestimation of LAI values especially in conifer stands. As this correction has some inherent uncertainty we also redid our LAI correlation analysis based on uncorrected ('effective') LAI, as well as with a second clumping-corrected LAI based on a clumping factor of 0.7 determined by Goude et al. (2019) for Scots Pine. For the mixed stands this clumping correction was weighted by the fraction of pine trees.

Throughfall was measured at each plot with trough systems. One trough system is composed of three troughs which were installed with a 120°-angle relative to each other (Figure 2). The three troughs funnel the water into a single tipping bucket gauge with a bucket volume of 100 mL. The troughs, tubes and tipping buckets were carefully cleaned on a regular basis to avoid malfunctioning due to litter or dust. To account for spatial variability within in each plot, five trough systems were randomly distributed within the forest stand. The catch area of each trough system is 1.32 m^2, that is, 6.6 m^2 for each stand in total. This large catch area ensures a reliable and representative average despite the known large spatial variability of throughfall. Gross rainfall was measured with one identical trough system plus an additional standard tipping bucket on a nearby grass-covered clearing of about 40 m in diameter (eastern rain gauge in Figure 1), with two nearby weather stations used for occasional gap-filling of the rainfall time series (one is the northern rain gauge on Figure 1, the other one is located just south of the lake, outside of the map). Data from a weather station 1.5 km north of Lake Hinnensee was used for the statistical models (see section 2.4). This data set included air temperature, wind velocity and vapour pressure deficit VPD calculated from relative humidity and air temperature. Beginning and end of the leafed and leafless periods were determined by visual inspection of time-lapse imagery. The beginning of the leafed period (i.e. summer) was identified as the point in time when canopy looked similarly dense as

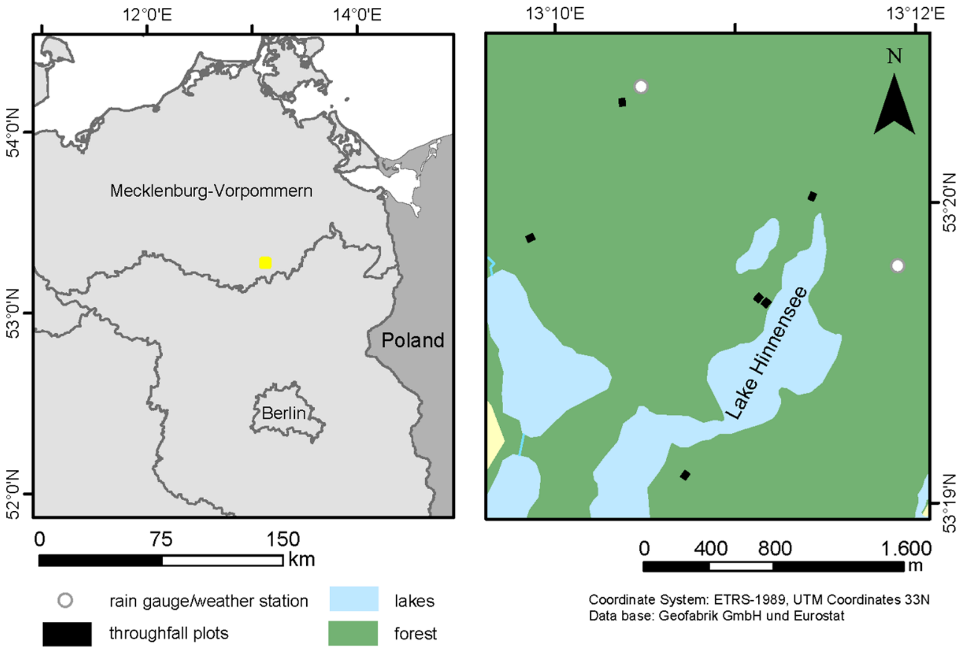


FIGURE 1 Location of the research area (left), location of the throughfall measurement plots (right)

TABLE 1 Forest stand characteristics

Forest stand	Acronym	Species	Age	DBH	Basal area	Stand density	LAIsummer	LAIwinter
Young pine	YP	Pine	35	14	47.9	3040	4.27	4.48
Pine	P	Pine	70	29	32.5	470	2.26	2.64
Beech	B	Beech	135	45	35.4	170	4.64	1.18
Oak/beech	OB	Oak	100–170	24	34.4	865	4.55	1.43
		Beech		13				
Pine/beech/oak	PBO	Pine	100–170	9	43.7	695	5.71	1.97
		Beech		18				
		Oak		12				
Pine/beech	PB	Pine	100–170	52	53.7	330	7.20	2.23
		Beech		35				

Note: Age [years], DBH = average diameter at breast height [cm] as average per species, BA = Basal area [m^2/ha], stand density [trees/ha].

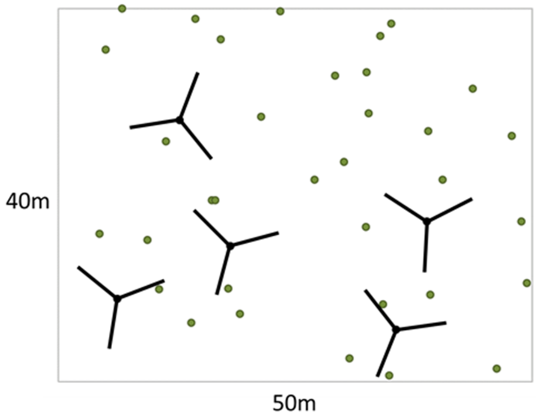


FIGURE 2 Experimental design of the throughfall plots which consists of 5 trough systems with a total catch area 6.6 m^2 (here exemplarily site B, the beech plot)

in summer and the beginning of the leafless period was taken at the point in time when most of the leaves had fallen (see resulting time periods in the Appendix Table A1).

2.3 | Event selection

The rainfall events for our analyses were extracted from the rainfall time series. The end of an event was identified by a break in rainfall of at least 12 h, a time period which is likely to allow for previously intercepted water to evaporate so that the new event starts with an empty interception storage (André et al., 2011; Spencer & van Meerveld, 2016). For the throughfall analyses we only used events when at least four of the five trough systems per site were producing reliable data at each of the forest stands (i.e., events that were monitored in parallel at all sites). Events during periods with snow (identified from visual inspection of time-lapse imagery) were excluded from the analysis. Furthermore, events where measured throughfall was higher than gross rainfall by 1 mm or more due to heterogeneous rainfall input as well as technical failures were excluded from the analysis. For the analysis of throughfall fractions the remaining fractions >1 were set as equal to 1. However, this last step had little influence on the results.

For detailed analyses of the effect of seasonal canopy differences the data set was further reduced to a so-called optimal data set. This subset only included events with similar rainfall amounts and maximum intensities, that is, only those summer events where one or several corresponding events of the same characteristics could be found in winter and vice versa. Only events with differences in maximum intensity <0.5 mm/h and differences in rainfall amount <0.5 mm qualified for this optimal data set.

2.4 | Statistical analyses

2.4.1 | Differences in average throughfall between sites and seasons

To test for significant differences of throughfall between the forest stands the Tukey's honestly significant difference (HSD) test was used. The significance level was set to $p < 0.05$. The Tukey test compares all possible pairs of mean values and determines which mean values differ from the rest. Differences between the observations are considered significant if the difference in the mean values is higher than the expected standard error. To test for differences between the seasons both, the t-test and the more robust Wilcoxon rank sum test were used and their results compared.

2.4.2 | Relationship between site LAI and median throughfall

While our six data points are the bare minimum for a regression, we nevertheless related LAI for each site and season to the corresponding median rainfall fractions and determined the R^2 and p-value to estimate the strength of the relationship.

2.4.3 | Relationships between meteorological variables and throughfall on event basis

Linear statistical models were used to analyse the interrelationships between meteorological forcing (mainly rainfall characteristics) and the generated throughfall amount. These statistical models were always determined separately for each forest stand and season, that is, the leafed season (from now on simply called 'summer') and the leafless season (from now on called 'winter'). Three sets of statistical models with throughfall amount as the target variable were generated: (a) with either rainfall amount or maximum rainfall intensity as the single predictor, (b) with rainfall and maximum intensity as predictors and (c) a stepwise linear regression (based on Akaike Information Criterion AIC and a combined forward and backward stepwise search) starting with a full set of meteorological variables: rainfall amount, maximum intensity, mean intensity, mean air temperature, mean wind velocity and mean vapour pressure deficit VPD (the latter four all averaged over the event duration). In case (a) we then compared the slopes of the regression lines to investigate the seasonal differences in our throughfall relationships. The purpose of model generation in cases (b) and (c) was to determine which additional variables (apart from rainfall amount) might improve the models and if and in which way this differs between forest stands and seasons. All data analyses were carried out using R: A Language and Environment for Statistical Computing (R Core Team, 2020) and here especially the tidyverse package (Wickham et al., 2019), dplyr package (Wickham et al., 2021) and ggpubr package (Kassambra, 2020).

3 | RESULTS

3.1 | Event identification and rainfall properties

Five hundred and thirty-four rainfall events were extracted for the entire measurement period from October 2014 to April 2019. We identified 249 events in the leafed period (here from now on called 'summer') and 285 events in the leafless period (from now on called 'winter') with a total rainfall amount of 1341 mm and 1335 mm, respectively. Small rainfall events dominate throughout the year with about 85% of the events amounting to less than 10 mm.

Restriction to events measured at all sites in parallel resulted in a significantly reduced set of 346 rainfall events with throughfall data (summer: 186, winter: 160) (Figure 3). The events selected for the throughfall analysis have similar distributions in total rainfall amounts and maximum rainfall intensities as all rainfall events during the monitoring period and are thus a representative sample (Figure 3). However, the distributions differ between the seasons, with more high intensity events occurring in summer and more small and low intensity events occurring in winter (Figure 3).

We also find that the relationship between rainfall amount and maximum intensity differs between seasons (Figure 4). For similar maximum intensities summer events have lower rainfall amounts than winter events, thus the slope of the summer regression line is steeper than for the winter.

3.2 | Throughfall response patterns at the six forest stands

Throughfall fractions, that is, the fraction of gross rainfall captured below the canopy (excluding stemflow), were determined for all 346 events. In a first step we compared the cumulative and mean throughfall fractions across all sites by separating winter and summer events (Figure 5). The cumulative throughfall fraction is the ratio of total throughfall to total gross rainfall summed over all events, whereas the mean throughfall fraction is the mean of all individual event-based throughfall fractions. Cumulative throughfall fractions are dominated by event types producing the largest amount of rainfall (see Figure A1 in the Appendix for the distribution). They range between 51 and 76%. The young pine stand (YP) has low numbers with about 50% in both seasons.

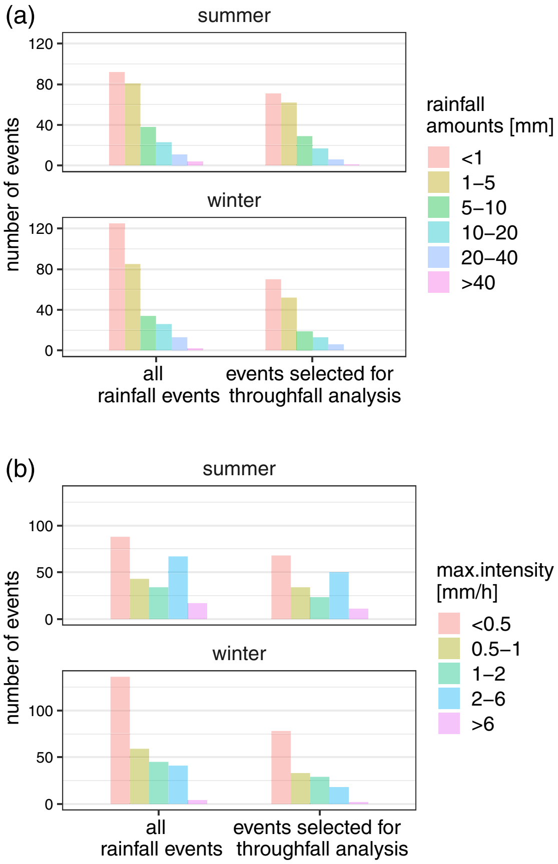


FIGURE 3 The distribution of rainfall event characteristics for all identified rainfall events in comparison to the distribution of rainfall event characteristics for the events selected for the throughfall analysis. Only events measured at all sites with at least 4 trough systems were included in the analysis (346 of the 534 rainfall events)

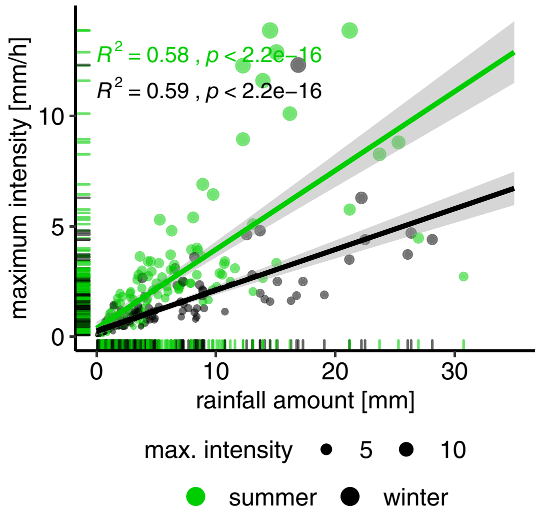


FIGURE 4 Maximum rainfall intensity vs. event rainfall amount, colour-coded by season. Circle size corresponds to maximum intensity. 1d marginal distributions are provided along the axes. Only the events used for the throughfall analysis are shown

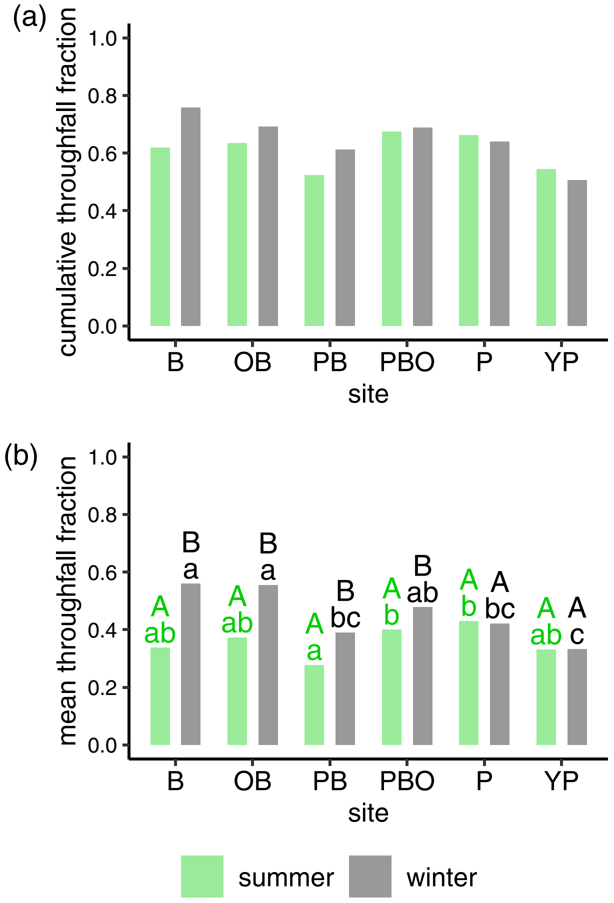


FIGURE 5 Site intercomparison of (a) cumulated throughfall as fraction of cumulated rainfall for both seasons, (b) mean event throughfall as a fraction of event rainfall. The lower-case letters above the bars show the results of the Tukey HSD test, testing for differences among the mean values across all sites for both seasons separately. The upper-case letters show the results of the Wilcoxon rank sum test, testing for differences between seasons for each site separately. In both cases significant differences are indicated by different letters. Deciduous forest stands on the left (B: beech; OB: Oak & Beech), mixed stands in the middle (PB: Pine & Beech; PBO: Pine, Beech & Oak) and pine stands on the right (P: Pine; YP: young Pine)

Median throughfall fractions are more strongly dominated by the complete distribution and event types occurring in large numbers (see Figure A1 in the Appendix), irrespective of the throughfall amount they produce, while mean throughfall fractions are more sensitive to outliers/extreme events (which in this case will be the large and high intensity events). We find that seasonal differences are lowest for cumulative, larger for mean and largest for median throughfall fractions. Winter throughfall fractions are markedly higher than summer throughfall fractions for the deciduous and mixed stands, while there is no significant seasonal difference in throughfall fraction for the two pine sites (P and YP) (Figure 5). While the differences in season for the PBO site were significant with respect to the robust Wilcoxon rank sum test, the *t*-test resulted in a *p*-value just above the confidence level of 0.05. Statistical testing for significant differences of the mean throughfall fractions among the forest stands (Figure 5b), showed that in winter the values for the pure deciduous stands (B, OB) were significantly different from the pure pine stands (P, YP) and from the mixed pine-beech stand (PB). The mixed stand PBO was only significantly different from YP. In summer PB was significantly different from PBO and P with *p*-values <0.05. At *p*-values<0.1 we also see differences between P and B, YP and between PB and OB.

The distribution of throughfall fractions is similar in summer and winter when the tree canopy stays similar, as in the two pine stands (Figure 6, compare also Figure 5 for means).

In the deciduous and mixed stands, we see strong seasonal differences in the distributions. The summer distributions are skewed towards the low throughfall fractions, but with a secondary peak at higher fractions. For the mixed stands PB and PBO the winter distribution is less skewed towards the higher fractions than for the purely deciduous stands where winter throughfall fractions clearly peak above 60%. For scatterplots of throughfall fractions vs. rainfall see Figure A2 in the Appendix.

In summer we see a trend of increasing throughfall fraction with increasing maximum rainfall intensity, while in winter we observe lower throughfall fractions <50% for the lowest intensity class but then similarly high throughfall fractions for all other intensity classes (with slightly lower values for the young pines) (Figure 7). A similar pattern can be seen when stratifying the data set by rainfall amounts (see Appendix, Figure A3). In summer the higher intensities produce similar throughfall fractions for pine and beech, but the lower maximum intensities generate much less throughfall in the deciduous and mixed than in the pine stands. Especially at the lowest intensity, hardly any throughfall is generated in the deciduous and mixed stands (Figure 7).

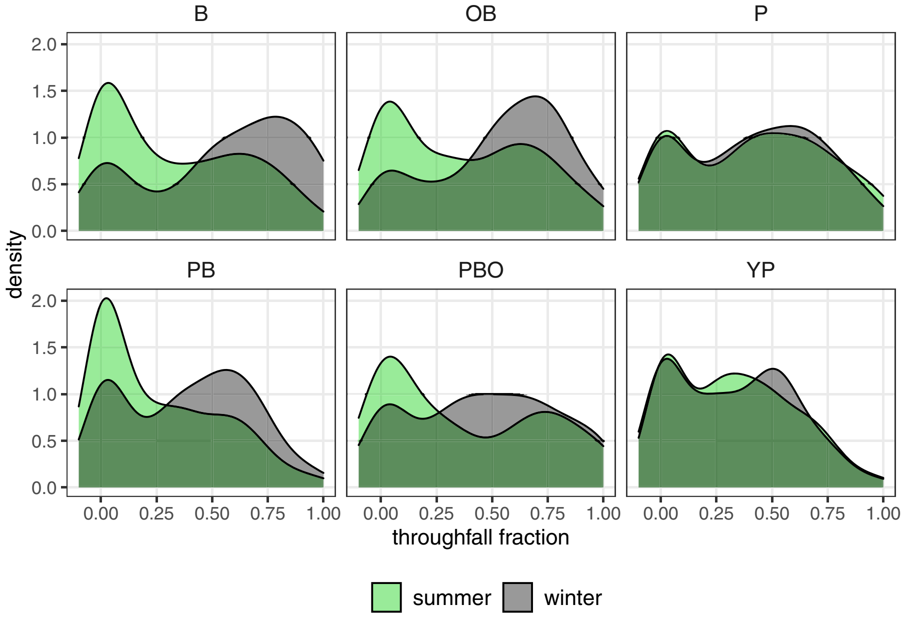


FIGURE 6 Density plots of throughfall fractions comparing summer and winter distributions for all six forest stands (transparent colouring to allow for full visibility despite overlapping distributions). B: Beech; OB: Oak & Beech; PB: Pine & Beech; PBO: Pine, Beech & Oak; P: Pine; YP: young Pine

3.3 | Role of forest stand characteristics

The six forest stands are different in their structural characteristics: the young pines have a dense stand and the highest LAI in winter, the pine-beech stand PB has the highest LAI in summer and most pronounced seasonal change in LAI and the beech stand has the lowest stand density and the lowest LAI in winter (Table 1 and Figure 8).

In a comparative analysis of forest stand characteristics across all sites, correlations between the three variables leaf area index (LAI), basal area (BA) and stand density (SD) (Table 1) where determined. Due to the dynamics of LAI for the mixed and deciduous stands there are pronounced seasonal differences in correlations (Table 2): LAI and BA are highly correlated in summer ($R = 0.77$) and less so in winter ($R = 0.45$). LAI and stand density, on the other hand, are highly correlated in winter ($R = 0.88$) and are not correlated in summer ($R = -0.16$). There is also little correlation between basal area and stand density ($R = 0.33$).

While six data points are the bare minimum to even recognize correlations, we were nevertheless interested to see how median event throughfall fractions related to site LAI for each maximum rainfall intensity class and also over all events (Figure 8). We find that in summer the relationship is strongest for maximum intensities between 0.5 and 2 mm/h (at the lowest intensities basically no throughfall is generated) (Figure 8a). On the other hand, in winter the relationship is relatively strong for all but highest maximum intensities (where uncertainties are large due to the fact that this class only contains 2 events) (Figure 8b). Correlations across all events are strong with $R^2 > 0.8$ in both seasons (Figure 8). To avoid spurious correlations due to the inherent uncertainty of the clumping correction provided by the LICOR 2200 we redid the analysis with both the effective (uncorrected) LAI and a second clumping correction (see Figure A4 in the Appendix). However, all three approaches yielded similar relationships between LAI and throughfall.

3.4 | Linear statistical models as a tool for forest stand intercomparison

The simplest model of throughfall vs. rainfall amounts shows high and statistically significant correlations for all sites and seasons (Figure 9) with *p*-values <0.0001. Seasonal differences in regression slope are strongest for the young pine and the pine stand for the complete data set (Figure 9a). The young pine and the pine-beech stands have the lowest slopes, irrespective of season (see Appendix Figure A5 for a direct comparison of slopes). Slopes generally decrease if the data set is reduced to lower ranges of rainfall amounts and intensities, thus excluding the large and high intensity events (Figure 9b). This decrease is more pronounced for the summer slopes, which drop below the winter slopes (where actually the winter slopes for the two deciduous stands hardly change at all). As a result, we find increased seasonal differences in slopes, especially for the mixed and deciduous sites, while the seasonal differences for the pine sites vanish. The *p*-values for the intercept were only significant at the 0.001 or 0.0001 level in summer.

Statistical models with maximum intensity as the only predictor had lower values of R^2 compared to the models based on rainfall amount, and summer slopes were always lower than winter slopes (Figure A6 in the Appendix).

Statistical models using both rainfall amount and maximum intensity as predictors of throughfall amount did not show any improvement in R^2 over using rainfall amount as the single predictor. Nevertheless, maximum intensity was significant as a predictor at the 0.05 level for beech and oak-beech in winter, for pine-beech and pine-beech-oak in summer and for young pine in both seasons. Coefficients ranged between 0.21 and 0.27, only pine-beech-oak had a lower value of 0.12.

Stepwise linear regression based on a full set of meteorological variables only rarely identified additional predictors: at the 0.05 level mean rainfall intensity was significant for pine (in combination with maximum intensity) and young pine in summer and only for young

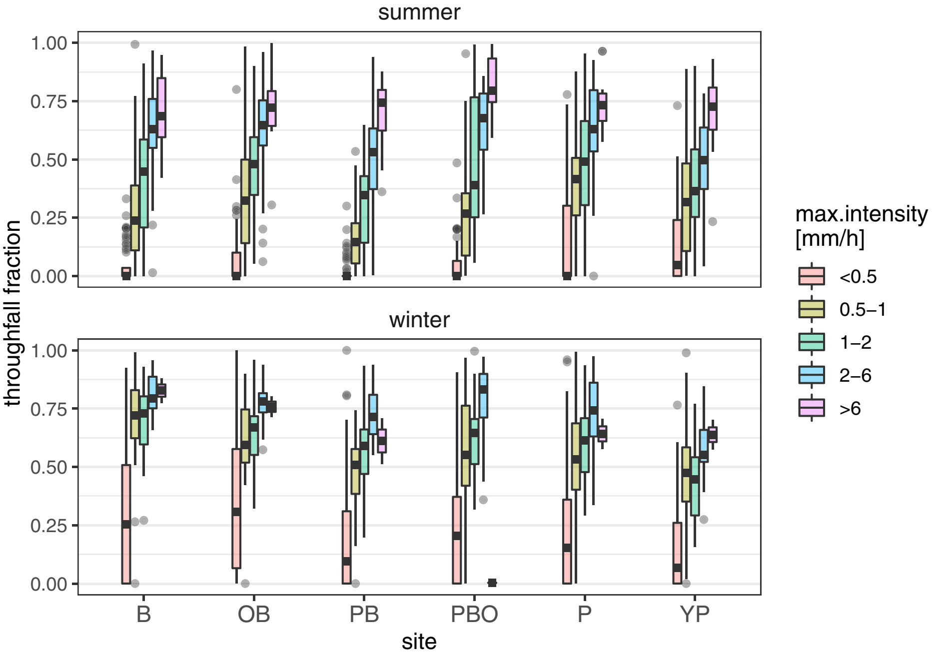


FIGURE 7 Throughfall as fraction of total rainfall on event basis: comparison of all sites for the leafed (summer) versus leafless (winter) period and for different maximum rainfall intensities. B: Beech; OB: Oak & Beech; PB: Pine & Beech; PBO: Pine, Beech & Oak; P: Pine; YP: young Pine

pine in winter. Mean wind velocity was significant for pine-beech-oak and young pine in summer. If selected, rainfall intensities generally had positive coefficients (apart from the mean rainfall intensity for pine and young pine in summer), while wind velocity had negative coefficients. Due to cross-correlation between VPD and air temperature they were included in separate runs and due to cross correlation of rainfall amount and duration we excluded event duration from the model.

3.5 | Seasonal differences in throughfall: separating rainfall and canopy effects

As both LAI and rainfall characteristics change with the seasons it is difficult to separate these effects. We attempted to reduce the effect of seasonal changes in rainfall characteristics by subsampling our event data sets for only those rainfall events that had similar corresponding events in the respective other season (see chapter 2.3). This optimized data set included 135 summer events and 125 winter events with similar distributions of amounts and maximum intensities in both seasons (Figures 10 and A7 in the Appendix). We also compared this optimized data set with simple subsampling based on a reduction in range only (to exclude large and high intensity events) (Figure A7).

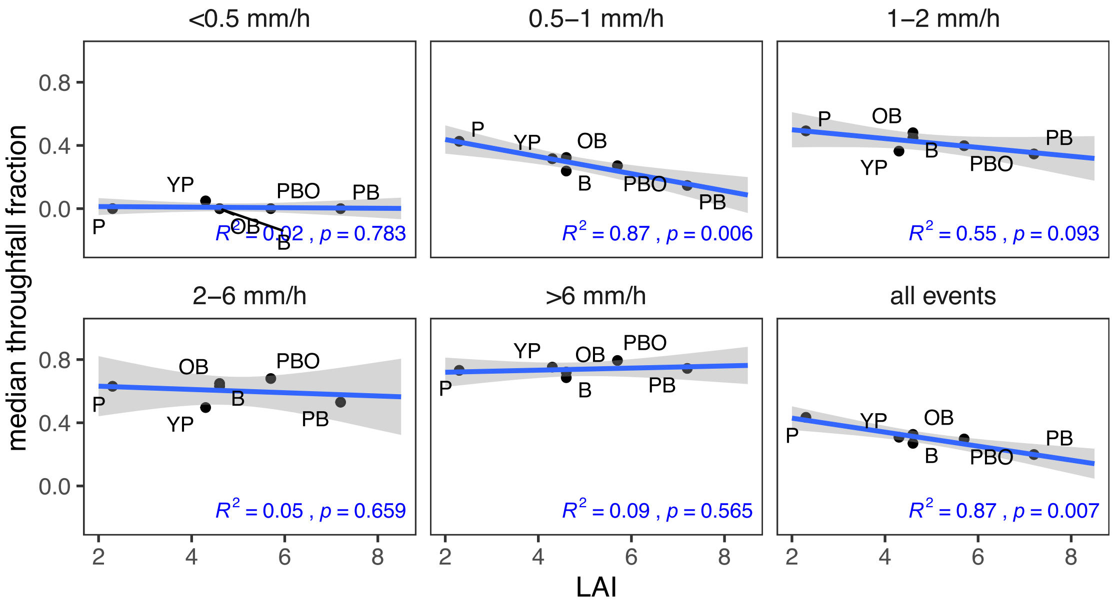
The distribution of the throughfall fractions for the optimized subset of rainfall events differs both from the distribution of the original (complete) data set as well as from the range-based reduction (Figure 11). In summer, the peak at low throughfall fractions increases (red arrows in Figure 11), while the secondary peak at higher throughfall fractions diminishes or disappears (blue arrows). This shift is observed at all forest stands but is most pronounced in the mixed and deciduous stands.

4 | DISCUSSION

4.1 | Sources of error and uncertainties

As it is difficult to estimate the uncertainties of the analyses quantitatively, the following is more of a qualitative assessment. For our comparative analyses we assume that throughfall at all sites is driven by the same rainfall input, due to the close proximity of the forest stands and based on our comparison of the two rain gauges (for locations see Figure 1). However, some of the stands are at about 2 km distance from the main rain gauge (trough system in a clearing), so small deviances in rainfall input are possible. Our five trough systems per forest stand provide a large enough catch area to be fairly representative (Ringgaard et al., 2014; Zimmermann et al., 2010). Ringgaard et al. (2014) used only one trough per stand (in contrast to the 15 in our study) and estimated their error to be around 11%. However, due to their positioning under the canopy, the troughs are vulnerable to clogging by leaves and other organic material shed by the trees (Ringgaard et al., 2014). Despite all our efforts in regular cleaning of the throughfall collection systems, some events may be affected by clogging of troughs and tubing. Identifying these events during data pre-processing is at times difficult. Nevertheless, as we are looking at the total event throughfall rather than at the intra-event temporal dynamics we are confident that partial clogging only marginally distorts our results. Another potential source of error for the seasonal comparison is the separation of leafed/leafless periods (i.e., summer/winter). As this separation was done by visual inspection of time-lapse imagery it is prone to uncertainty. Furthermore, the leafless period in our study also contains the period of the first leaf development in spring and the leafed period contains the period of leaf senescence in autumn which leads to a few events impacted by these transition periods. However, due to the large number of events sampled the effect of these events on the outcome of the analyses is likely to be

(a) summer



(b) winter

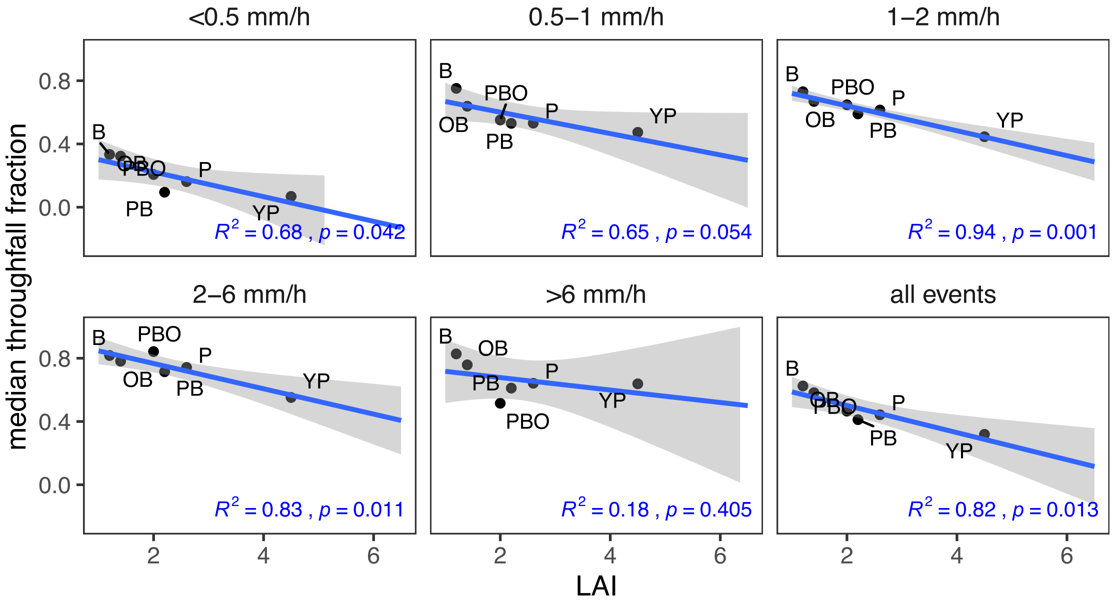


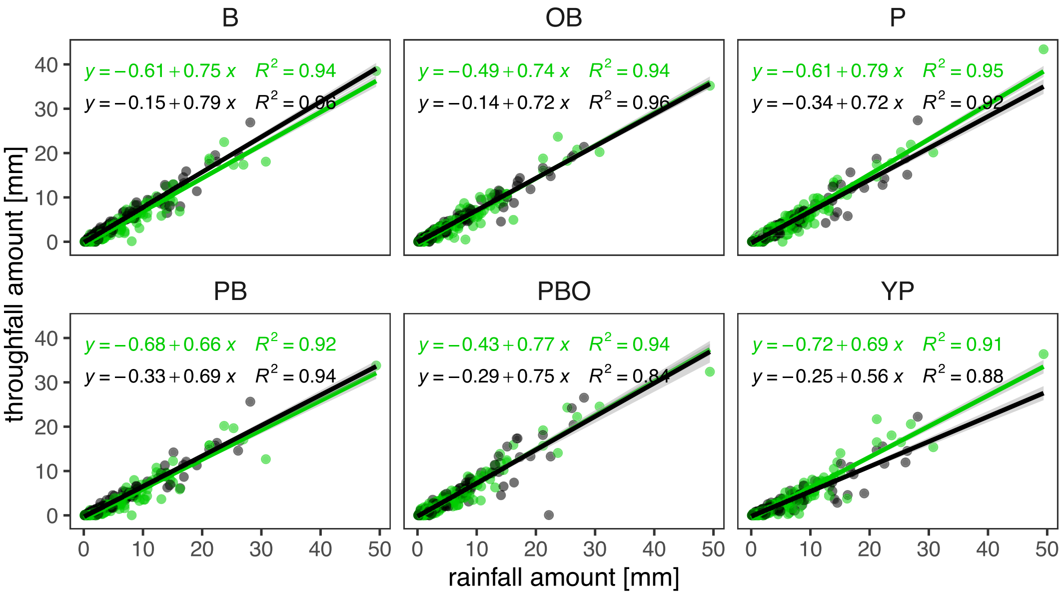
FIGURE 8 Relationship of LAI and median event throughfall fraction split by maximum rainfall intensity classes (mm/h). Grey-shaded area is the 95% confidence interval of the regression. B: Beech; OB: Oak & Beech; PB: Pine & Beech; PBO: Pine, Beech & Oak; P: Pine; YP: young Pine. Careful: Some classes have low numbers of events. For example only two events >6 mm/h in winter, see section 3.1 and Appendix A1 for event distribution

TABLE 2 Pearson correlation coefficients of throughfall fractions (medians and cumulative) and variables describing forest stand characteristics

	MedianTF-LAI	MedianTF-BA	MedianTF-SD	CumTF-LAI	CumTF-BA	CumTF-SD	LAI-BA	LAI-SD	SD-BA
Summer	−0.93	−0.73	0.09	−0.50	−0.77	−0.40	0.77	−0.16	0.33
Winter	−0.90	−0.67	−0.66	−0.95	−0.59	−0.81	0.45	0.88	0.33

Note: TF: Throughfall, LAI: Leaf area index (determined with the standard clumping correction of the LICOR 2200 using the apparent clumping factor), BA: Basal area. SD: Stand density.

(a) complete dataset



(b) amount < 4mm, max. intensity < 2.5mm/h

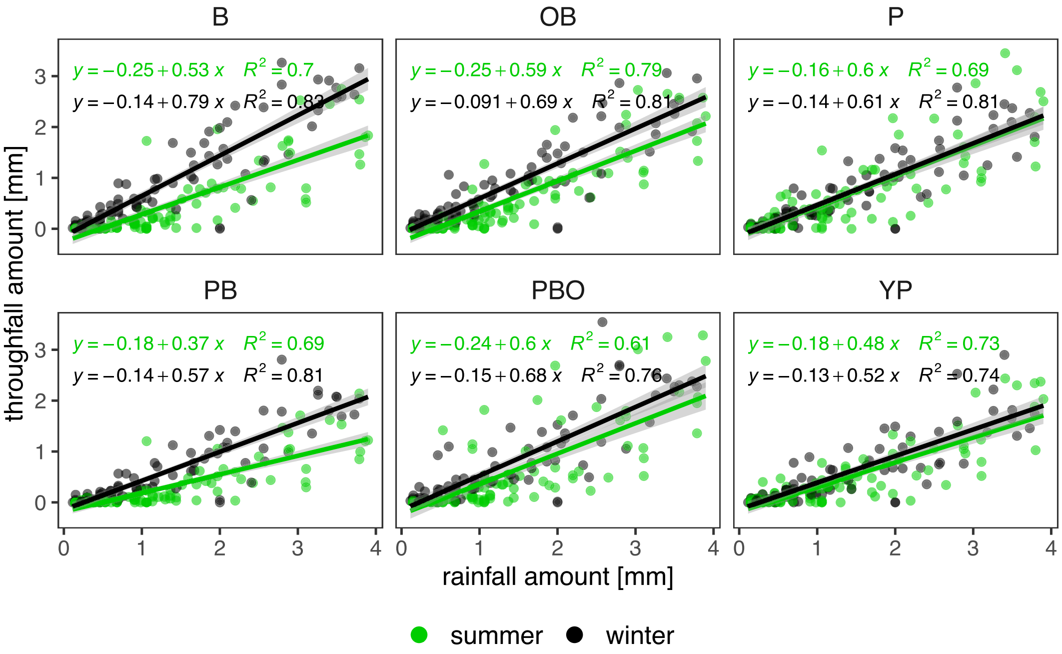


FIGURE 9 Throughfall versus event rainfall (both in mm). (a) Full range, (b) Subset of the low values (rainfall amount <4 mm). All correlations are statistically significant. Grey-shaded area is the 95% confidence interval of the regression. B: Beech; OB: Oak & Beech; PB: Pine & Beech; PBO: Pine, Beech & Oak; P: Pine; YP: young Pine

small (see also Staelens et al. (2008) where leaf-burst and senescence were included in the leafed period). We are also aware of the uncertainty in the correlations obtained across the six forest stands. Nevertheless, we still find these correlations worth reporting, as parallel measurements at six different forest stands are relatively rare and as it is furthermore extremely difficult to carry out a monitoring program for a sufficiently long period at the statistically desired number of forest stands.

4.2 | Impact of rainfall characteristics on throughfall across forest stands

To avoid mixing seasonal effects into the discussion of throughfall dependence on rainfall characteristics and forest stands we focus first solely on the summer events. In summer, the young pine and the mixed pine-beech stand have the lowest cumulative throughfall fractions (52% and 54%) and pine-beech-oak and pine the highest (67.5%

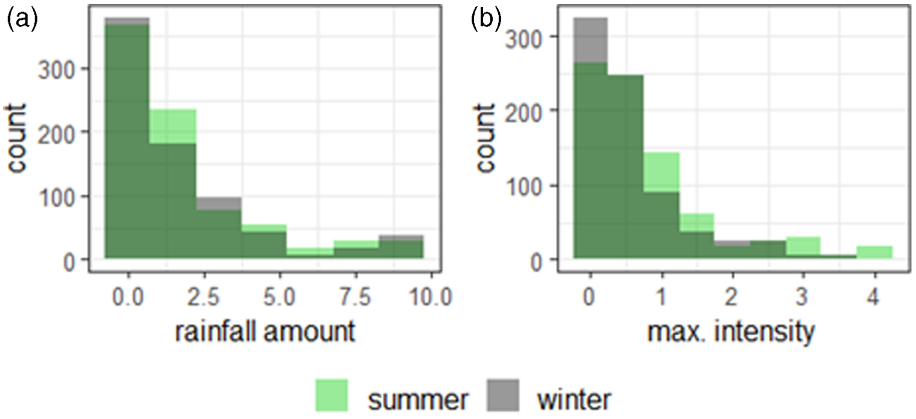


FIGURE 10 Direct comparison of summer and winter distributions of (a) rainfall amount and (b) maximum intensity of the optimized data set. Colour bars are semi-transparent and overlaps between summer and winter show up in dark green

and 66.3%), though not much higher than the other stands. On the other hand, beech and pine-beech have the lowest mean throughfall fractions and pine the highest with throughfall at the pine-beech stand being significantly lower than at the pine stand (Figure 5). As mentioned in the results, cumulative fractions will be dominated by events producing large amounts of rainfall (i.e. events with maximum intensity >2 mm/h, see Appendix Figure A1), while median fractions will be controlled by the complete event distribution, thus also smaller events which occur in large numbers (i.e. events with maximum intensity <2 mm/h, see Appendix Figure A1). Focusing on event throughfall distributions and medians is therefore more robust and also more informative with respect to the interception processes (Llorens et al., 1997; Staelens et al., 2008). The correlation analysis of LAI and median throughfall fractions for different maximum intensity classes showed that only the events in the 0.5–2 mm/h classes had a high and significant correlation (Figure 8). No correlation in the lowest intensity class was due to the fact that this class quite consistently produced no or little throughfall at the mixed and deciduous sites (Figures 7 and 8). Likewise, the highest intensity resulted in similarly high throughfall fractions across all forest stands (Figures 7 and 8). Similar changes in the relationships of throughfall and forest characteristics depending on rainfall event classes were found by Park and Cameron (2008) and Staelens et al. (2006). A possible explanation for this lack of correlation is that at high intensities the flexible leaves will give way to the force of the rainfall and their interception storage is reduced. Under these conditions LAI measured during dry conditions is no longer a good proxy for interception storage. A decrease of maximum canopy storage with increasing drop size (which is often related to intensity) was also found by Calder et al. (1996), but not by Link et al. (2004). They assume that this lack of dependence on rainfall intensity might be related to the particularly dense canopy at their site with an LAI of 8.6.

As for the distributions of throughfall fractions (Figure 6) we see that the summer distributions for the deciduous and mixed stands are more skewed towards the low throughfall fractions compared to the pine stands, but with a secondary peak at higher fractions. This secondary peak is likely again the result of the large and high-intensity rainfall events (similar to the distributions found in Keim et al. (2004).

4.3 | Dependence of seasonal differences in throughfall on forest stands

There are clear seasonal differences in correlations between the three quantitative descriptors of forest stand characteristics LAI, BA (see also Park et al., 2000), SD and median and cumulative throughfall fractions (Table 2). These differences are due to the different aspects of forest stand characteristics and their seasonal dynamics. The fact that LAI is strongly correlated with BA in summer but not in winter, but that for correlation with SD it is vice versa can be explained by old deciduous trees having a dense canopy in summer despite low stand density (Table 1). Thus, stand density is not linked to the leaf component of LAI. On the other hand, winter LAI is more closely related to stand density as the number of trees is linked to the woody component of LAI. LAI here is not only referring to leaves but is more of a Plant Area Index (PAI) which also includes the woody area (Levia Jr & Frost, 2006). Basal area combines aspects of stand density and diameter which can be a proxy for tree age and thus potentially also crown extent and density. It is therefore more strongly linked to the leaf aspect of LAI (Table 2) resulting in higher correlations with median throughfall fraction in summer. Along those same lines Llorens and Gallart (2000) differentiated between wood area index, leaf area index and total area index (= the sum of wood and leaf area index). They also determined specific storage for pine needles versus branches and stems, and found that branches and stems had much higher storage capacities than the needles. A study in a eucalypt plantation and a study in China yielded similar results (Crockford & Richardson, 1990; Li et al., 2016).

We found statistically significant differences between the seasons for mean throughfall fractions of the deciduous and mixed stands.

Distributions of throughfall fractions also differ strongly between the seasons, with a much higher peak at the lowest fractions in summer and a pronounced peak at higher fractions in winter (Figure 6). However, these seasonal differences were not observed for the two pine sites (P and YP) where not only the means but also the distributions remain similar, irrespective of season (Figures 5 and 6). The fact that pine throughfall fractions for lower intensity events increase slightly in winter (Figure 7) is most likely the result of the

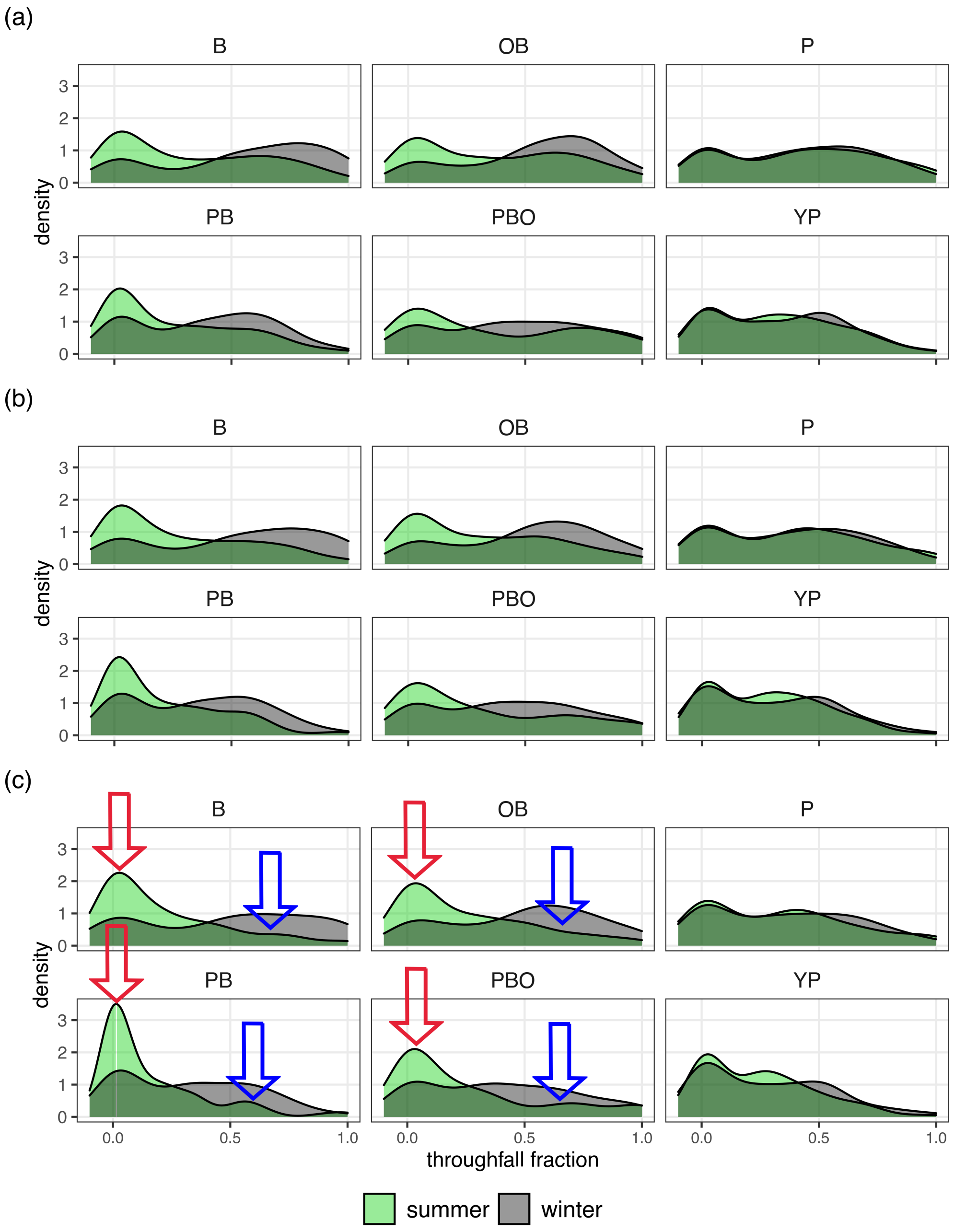


FIGURE 11 Density plots of throughfall fractions of (a) the complete data set, the same as Figure 6, (b) the reduced data set using simple limits (rainfall amount <11 mm and max. Intensity <5 mm/h), (c) the optimized data set, where winter and summer events are comparable in their characteristics (see Figure 10). The arrows indicate the most pronounced shifts in the summer distribution in the optimized compared to the complete data set with red arrows pointing at increases and blue arrows at decreases. B: Beech; OB: Oak & Beech; PB: Pine & Beech; PBO: Pine, Beech & Oak; P: Pine; YP: young Pine

seasonal decrease in evaporation and/or potentially needle shedding, which usually occurs in autumn. However, in our case needle shedding had no measurable effect on LAI. Overall, these observations indicate that the change in seasonal throughfall fraction distribution is related to the change in LAI. The fact that the distribution of winter throughfall fractions is less skewed towards the higher fractions for sites PB and PBO compared to the purely deciduous stands B and OB is likely the result of the intermixed pine trees. While the similarity of the pine stands distributions in summer and winter suggests that the change in rainfall characteristics might actually have only little impact, one needs to keep in mind that deciduous and coniferous trees are likely to be affected in different ways by high intensity events and that changes in rainfall characteristics might in part be compensated by changes in evaporation (see e.g., Ringgaard et al., 2014). The latter was also found in a study where beech throughfall did not show significant differences in summer and winter, likely due to the effect of high intensity events in summer (Forgeard et al., 1980), similar to a study in England (Herbst et al., 2008), a study in north-east Spain (Mużyło et al., 2012) and a study in Chile (Iroumé & Huber, 2002). That the different stands respond differently to high-intensity events is also confirmed by the fact that maximum intensity was a significant predictor in the multiple regression for the mixed and pine stands in summer, but only in winter for the two deciduous stands.

In our study median fractions even for higher intensity events (up to 6 mm/h) are strongly correlated to LAI (see also Park et al., 2000) in winter (Figure 8), in contrast to the findings of Sadeghi et al. (2020). As in winter the LAI is predominantly made up of woody components this correlation supports the hypothesis stated above, that the more rigid parts of the canopy can still serve as interception storage, also at high intensities (when leaves become less efficient but not needles of a pine canopy). Also, the fact that the decrease in regression slope between rainfall and throughfall amount, observed when the data set is reduced to exclude the large and high intensity events (Figure 9b and Appendix Figure A5), is pronounced in summer, less pronounced in winter and not observed at all for the two deciduous stands in winter further supports this hypothesis. Interestingly, the *p*-values for the intercept were significant at the 0.001 or 0.0001 level in summer but not in winter. This seasonal difference is likely related to a more pronounced threshold for throughfall generation in summer as a result of the higher interception storage as well as stronger evaporative effects. In contrast, Staelens et al. (2006) could not find a relationship between branch cover and throughfall in the dormant season, possibly because they were studying a much smaller scale with 48 funnel-type throughfall collectors under a single dominant beech tree.

The stepwise linear regression based on a full set of meteorological variables led to inconclusive results and will require additional research. We found that overall only few additional meteorological predictors proved significant. In contrast to the results of Staelens et al. (2008) neither air temperature nor VPD as measures of evaporation were selected as predictors by the stepwise linear regression, and wind was a significant predictor only at the young pine and the pine-beech-oak site in summer.

4.4 | Separation of the superimposed seasonal effects of rainfall and canopy characteristics

To reduce the effect of seasonal changes in rainfall characteristics on the comparison of forest stands with respect to their seasonally varying canopy characteristics (as also described by Mużyło et al., 2012) we subsampled our event data sets for only those rainfall events that had similar corresponding events in the respective other season (Figures 10 and A7). We found that the resulting throughfall fraction distributions of the mixed and deciduous stands are even more strongly dominated by the low fractions in summer than in the complete data set, while at the same time the secondary peak at the higher fractions disappears (Figure 11). Changes in distributions of the pine stands were much less pronounced. These observations indicate that the secondary peak at the higher fractions was caused by the combination of leaf canopy and high intensity rainfall. The small differences in the distributions of the pine stands are likely due to differences in meteorological conditions and increased evaporation which was obscured in the complete data set by the presence of the large and high-intensity summer events. The comparison with the data sets where large and high-intensity rainfall events were excluded by simple thresholds shows that this way of subsetting is insufficient to reduce the seasonal rainfall effect. The seasonal differences in rainfall characteristics remain, causing only a reduction in magnitude of the secondary peak, but not its disappearance (Figure 11).

4.5 | Broader impacts

As to the broader context of these throughfall observations with respect to tree water demand and groundwater recharge we find that deciduous forest stands are advantageous with respect to groundwater recharge, due to the pronounced peak in high throughfall fraction in winter. In the study region, groundwater recharge in summer is low to non-existent due to tree water uptake and the overall not very high rainfall amounts. On the other hand, the pine stand seems to have an advantage in summer as the higher throughfall fractions provide more water for root uptake even at lower rainfall intensities. However, as the projected changes in rainfall include an increase in event intensities, this change might actually favour the deciduous stands with their leaf canopy that becomes inefficient as interception storage at high intensities. This high-intensity input is especially advantageous in combination with the sandy soils in this region, as high infiltration capacities make surface runoff unlikely and instead favour root zone recharge. In these soils the large and high-intensity events are likely to infiltrate to greater depth compared to the small and low intensity events, making the water less available to evaporation while at the same time providing water access to a larger volume of roots.

In the modelling context, and especially in the case of large-scale models working at a daily time step, throughfall is often roughly estimated by defining a maximum interception storage based on LAI and a factor (most often 0.2 or 0.3 mm/day) (Bohn et al., 2014; Müller Schmied et al., 2014). We find that this approach leads to an overestimation of throughfall by 37% on average across sites and even by >50% at two of the sites. This estimate is based on a back of the envelope comparison to throughfall amounts calculated from the winter regressions shown in Figure 9. As we are only using the winter data we assume that evaporation is negligible. These findings indicate the importance and potential future use of the throughfall monitoring data and results presented here. Only adequate data and better process understanding can lead to better process representation in models (Gutmann, 2020) which are then used to estimate impacts of climate change and management adaptations.

5 | CONCLUSIONS

The experimental design covering six different forest stands and a large number of parallel-measured rainfall events allowed us to identify differences in throughfall behaviour between mixed, deciduous and pine stands. Based on the large number of events it was possible to not only investigate mean or cumulative throughfall but also statistical distributions. The distributions of throughfall fractions, that is, the ratio between throughfall and gross rainfall volumes at the event scale, show distinct differences between the three types of forest stands, that is, the deciduous, mixed and pine stands. The deciduous stands have a pronounced peak at low throughfall fractions and a secondary lower peak at high fractions in summer, as well as a pronounced peak at higher throughfall fractions in winter. The mixed stands interestingly behave like deciduous stands in summer and like pine stands in winter: their summer distributions are similar to the deciduous stands but the winter peak at high throughfall fractions is much less pronounced. Instead, due to the intermixed pines the winter distributions become much more similar to the pine stand distributions (which do not show distinct differences between summer and winter). In contrast, the distributions of the optimized set of rainfall events (containing only events which have corresponding magnitudes in the other season with respect to amount and intensity) lose the secondary summer peak at high rainfall fractions in the mixed and deciduous stands. This observation indicates that this secondary peak is caused by the larger number of high-intensity events in summer. Yet, these results also show that the seasonal changes in rainfall characteristics can indeed obscure the effect of the seasonal change in canopy characteristics.

Disentangling the complex interplay of seasonal effects of tree canopies, rainfall event characteristics and forest stand characteristics on throughfall is only possible based on long-term monitoring and a large number of throughfall events measured in parallel at different forest stands. We found that the different features of the canopy, that is, the woody features (branches and twigs) and pine needles on the one hand, and the leaves on the other hand, responded differently to incident rainfall. We hypothesize that the leaves become less efficient as interception storage at high rainfall intensities, giving way to the force of the rain, while this does not happen with the less flexible pine needles and woody parts of the canopy.

While our study focused on simple forest stand characteristics such as LAI and only differentiated between summer (leafed) and winter (leafless) it would be worthwhile to also investigate other leaf structure characteristics which can vary between species and over the course of the growing season, such as hydrophobicity and leaf angles (Campellone et al., 2020; Holder, 2012, 2013). Our results are of interest for estimating forest water budgets and in the context of hydrological and land surface modelling where the poor simulation of throughfall would adversely impact estimates of evaporative recycling and water availability for vegetation and runoff.

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DATA AVAILABILITY STATEMENT

Some of the data described here is already available on the TERENO data portal (https://www.tereno.net/ddp/). However, while the throughfall data will be made available at this platform in the future, it is currently only available on request from the authors. The data from the weather stations Serrahn and Feldberg/Mecklenburg are available from the German Weather Service DWD (https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/).

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REFERENCES

André, F., Jonard, M., Jonard, F., & Ponette, Q. (2011). Spatial and temporal patterns of throughfall volume in a deciduous mixed-species stand. *Journal of Hydrology*, *400*(1–2), 244–254. https://doi.org/10.1016/j.jhydrol.2011.01.037

Bohn, F. J., Frank, K., & Huth, A. (2014). Of climate and its resulting tree growth: Simulating the productivity of temperate forests. *Ecological Modelling*, *278*, 9–17.

Calder, I. R., Hall, R. L., Rosier, P. T. W., Bastable, H. G., & Prasanna, K. T. (1996). Dependence of rainfall interception on drop size: 2. Experimental determination of the wetting functions and two-layer stochastic model parameters for five tropical tree species. *Journal of Hydrology*, *185*(1), 379–388. https://doi.org/10.1016/0022-1694(95)02999-0

Campellone, S. V., Levia, D. F., & Montalto, F. A. (2020). Differences in submillimetre surface morphology and canopy interception storage capacities of Gleditsia triacanthos L.(honeylocust) in relation to canopy phenophase and position. *Ecohydrology*, *13*(3), e2192.

Carlyle-Moses, D. E. (2004). Throughfall, stemflow, and canopy interception loss fluxes in a semi-arid Sierra Madre oriental matorral community. *Journal of Arid Environments*, *58*(2), 181–202. https://doi.org/10.1016/S0140-1963(03)00125-3

Carlyle-Moses, D. E., Laureano, J. S. F., & Price, A. G. (2004). Throughfall and throughfall spatial variability in Madrean oak forest communities of northeastern Mexico. *Journal of Hydrology*, *297*(1), 124–135. https://doi.org/10.1016/j.jhydrol.2004.04.007

Crockford, R. H., & Richardson, D. P. (1990). Partitioning of rainfall in a eucalypt forest and pine plantation in southeastern Australia: III determination of the canopy storage capacity of a dry sclerophyll eucalypt forest. *Hydrological Processes*, *4*(2), 157–167. https://doi.org/10.1002/hyp.3360040206

Crockford, R. H., & Richardson, D. P. (2000). Partitioning of rainfall into throughfall, stemflow and interception: Effect of forest type, ground cover and climate. *Hydrological Processes*, *14*(16–17), 2903–2920.

Forgeard, F., Gloaguen, J. C., & Touffet, J. (1980). Interception des précipitations et apport au sol d'éléments minéraux par les eaux de pluie et les pluviolessivats dans une hêtraie atlantique et dans quelques peuplements résineux en Bretagne. *Annales des Sciences Forestières*, *37*(1), 53–71. https://doi.org/10.1051/forest:19800104

Germer, S., Kaiser, K., Bens, O., & Hüttl, R. F. (2011). Water balance changes and responses of ecosystems and Society in the Berlin-Brandenburg Region – A review. *DIE ERDE – Journal of the Geographical Society of Berlin*, *142*(1–2), 65–95.

Goude, M., Nilsson, U., & Holmström, E. (2019). Comparing direct and indirect leaf area measurements for scots pine and Norway spruce plantations in Sweden. *European Journal of Forest Research*, *138*(6), 1033–1047.

Gutmann, E. D. (2020). Global Modeling of Precipitation Partitioning by Vegetation and Their Applications. In: Van Stan, II J., E. Gutmann, & J. Friesen (Eds.), *Precipitation Partitioning by Vegetation*. Springer. https://doi.org/10.1007/978-3-030-29702-2_7

Heartsill-Scalley, T., Scatena, F. N., Estrada, C., McDowell, W. H., & Lugo, A. E. (2007). Disturbance and long-term patterns of rainfall and throughfall nutrient fluxes in a subtropical wet forest in Puerto Rico. *Journal of Hydrology*, *333*(2–4), 472–485. https://doi.org/10.1016/j.jhydrol.2006.09.019

Heinrich, I., Balanzategui, D., Bens, O., Blasch, G., Blume, T., Böttcher, F., Borg, E., Brademann, B., Brauer, A., Conrad, C., Dietze, E., Dräger, N., Fiener, P., Gerke, H. H., Güntner, A., Heine, I., Helle, G., Herbrich, M., Harfenmeister, K., … Wilken, F. (2018). Interdisciplinary geo-ecological research across time scales in the northeast German lowland observatory (TERENO-NE). *Vadose Zone Journal*, *17*(1), 180116. https://doi.org/10.2136/vzj2018.06.0116

Herbst, M., Rosier, P. T. W., McNeil, D. D., Harding, R. J., & Gowing, D. J. (2008). Seasonal variability of interception evaporation from the canopy of a mixed deciduous forest. *Agricultural and Forest Meteorology*, *148*(11), 1655–1667. https://doi.org/10.1016/j.agrformet.2008.05.011

Holder, C. D. (2012). The relationship between leaf hydrophobicity, water droplet retention, and leaf angle of common species in a semi-arid region of the western United States. *Agricultural and Forest Meteorology*, *152*, 11–16.

Holder, C. D. (2013). Effects of leaf hydrophobicity and water droplet retention on canopy storage capacity. *Ecohydrology*, *6*(3), 483–490.

Iroumé, A., & Huber, A. (2002). Comparison of interception losses in a broadleaved native forest and a Pseudotsuga menziesii (Douglas fir) plantation in the Andes Mountains of southern Chile. *Hydrological Processes*, *16*(12), 2347–2361. https://doi.org/10.1002/hyp.1007

Kaiser, K., Schneider, T., Küster, M., Dietze, E., Fülling, A., Heinrich, S., Kappler, C., Nelle, O., Schult, M., Theuerkauf, M., Vogel, S., de Boer, A. M., Börner, A., Preusser, F., Schwabe, M., Ulrich, J., Wirner, M., & Bens, O. (2020). Palaeosols and their cover sediments of a glacial landscape in northern Central Europe: Spatial distribution, pedostratigraphy and evidence on landscape evolution. *Catena*, *193*, 104647.

Kassambara, A. (2020). Ggpubr: 'ggplot2' based publication ready plots. R package version0.4.0. https://CRAN.R-project.org/package=ggpubr

Keim, R. F., Skaugset, A. E., Link, T. E., & Iroumé, A. (2004). A stochastic model of throughfall for extreme events. *Hydrology and Earth System Sciences*, *8*(1), 23–34. https://doi.org/10.5194/hess-8-23-2004

Keim, R. F., Skaugset, A. E., & Weiler, M. (2006). Storage of water on vegetation under simulated rainfall of varying intensity. *Advances in Water Resources*, *13*, 974–986.

Klingaman, N. P., Levia, D. F., & Frost, E. E. (2007). A comparison of three canopy interception models for a leafless mixed deciduous forest stand in the eastern United States. *Journal of Hydrometeorology*, *8*(4), 825–836.

Kunz, M., Mohr, S., & Werner, P. C. (2017). Niederschlag. In G. Brasseur, D. Jacob, & S. Schuck-Zöller (Eds.), *Klimawandel in Deutschland*. Springer Spektrum. https://doi.org/10.1007/978-3-662-50397-3_7

Levia, D. F., Jr., & Frost, E. E. (2003). A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. *Journal of Hydrology*, *274*(1–4), 1–29.

Levia, D. F., Jr., & Frost, E. E. (2006). Variability of throughfall volume and solute inputs in wooded ecosystems. *Progress in Physical Geography*, *30*(5), 605–632.

Li, X., Xiao, Q., Niu, J., Dymond, S., van Doorn, N. S., Yu, X., Xie, B., Lv, X., Zhang, K., & Li, J. (2016). Process-based rainfall interception by small trees in northern China: The effect of rainfall traits and crown structure characteristics. *Agricultural and Forest Meteorology*, *218–219*, 65–73. https://doi.org/10.1016/j.agrformet.2015.11.017

LICOR. (2010). LAI-2200 Plant Canopy Analyzer: Instruction Manual. https://www.licor.com/documents/6n3conpja6uj9aq1ruyn

Link, T. E., Unsworth, M., & Marks, D. (2004). The dynamics of rainfall interception by a seasonal temperate rainforest. *Agricultural and Forest Meteorology*, *21*, 171–191.

Llorens, P., & Gallart, F. (2000). A simpli®ed method for forest water storage capacity measurement. *Journal of Hydrology*, *14*, 131–144.

Llorens, P., Poch, R., Latron, J., & Gallart, F. (1997). Rainfall interception by a Pinus sylvestris forest patch overgrown in a Mediterranean mountainous abandoned area I. Monitoring design and results down to the event scale. *Journal of Hydrology*, *199*(3), 331–345. https://doi.org/10.1016/S0022-1694(96)03334-3

Marin, C. T., Bouten, W., & Sevink, J. (2000). Gross rainfall and its partitioning into throughfall, stemflow and evaporation of intercepted water in four forest ecosystems in western Amazonia. *Journal of Hydrology*, *237*(1–2), 40–57. https://doi.org/10.1016/S0022-1694(00)00301-2

Müller Schmied, H., Eisner, S., Franz, D., Wattenbach, M., Portmann, F. T., Flörke, M., & Döll, P. (2014). Sensitivity of simulated global-scale freshwater fluxes and storages to input data, hydrological model structure, human water use and calibration. *Hydrology and Earth System Sciences*, *18*(9), 3511–3538.

Mużyło, A., Llorens, P., & Domingo, F. (2012). Rainfall partitioning in a deciduous forest plot in leafed and leafless periods. *Ecohydrology*, *5*(6), 759–767. https://doi.org/10.1002/eco.266

Oyarzún, C. E., Godoy, R., Staelens, J., Donoso, P. J., & Verhoest, N. E. C. (2011). Seasonal and annual throughfall and stemflow in Andean temperate rainforests. *Hydrological Processes*, *25*(4), 623–633. https://doi.org/10.1002/hyp.7850

Park, A., & Cameron, J. L. (2008). The influence of canopy traits on throughfall and stemflow in five tropical trees growing in a Panamanian plantation. *Forest Ecology and Management*, *255*(5–6), 1915–1925. https://doi.org/10.1016/j.foreco.2007.12.025

Park, H.-T., Hattori, S., & Kang, H.-M. (2000). Seasonal and inter-plot variations of stemflow, throughfall and interception loss in two deciduous broad-leaved forests. *Journal of Japan Society of Hydrology and Water Resources*, *13*(1), 17–30. https://doi.org/10.3178/jjshwr.13.17

Pypker, T. G., Bond, B. J., Link, T. E., Marks, D., & Unsworth, M. H. (2005). The importance of canopy structure in controlling the interception loss of rainfall: Examples from a young and an old-growth Douglas-fir forest. *Agricultural and Forest Meteorology*, *130*(1–2), 113–129. https://doi.org/10.1016/j.agrformet.2005.03.003

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Ringgaard, R., Herbst, M., & Friborg, T. (2014). Partitioning forest evapotranspiration: Interception evaporation and the impact of canopy structure, local and regional advection. *Journal of Hydrology*, *517*, 677–690. https://doi.org/10.1016/j.jhydrol.2014.06.007

Sadeghi, S. M. M., Gordon, D. A., & Van Stan, I. I. (2020). A global synthesis of Throughfall and Stemflow hydrometeorology. In I. Van Stan John, E. Gutmann, & J. Friesen (Eds.), *Precipitation partitioning by vegetation: A global synthesis* (pp. 49–70). Springer International Publishing. https://doi.org/10.1007/978-3-030-29702-2_4

Siegert, C. M., Levia, D. F., Hudson, S. A., Dowtin, A. L., Zhang, F., & Mitchell, M. J. (2016). Small-scale topographic variability influences tree species distribution and canopy throughfall partitioning in a temperate deciduous forest. *Forest Ecology and Management*, *359*, 109–117. https://doi.org/10.1016/j.foreco.2015.09.028

Siegert, C. M., Levia, D. F., Leathers, D. J., Van Stan, J. T., & Mitchell, M. J. (2017). Do storm synoptic patterns affect biogeochemical fluxes from temperate deciduous forest canopies? *Biogeochemistry*, *132*(3), 273–292. https://doi.org/10.1007/s10533-017-0300-6

Siegert, C. M., Drotar. N. A., & Alexander, H. D. (2019). Spatial and temporal variability of throughfall among oak and co-occurring non-oak tree species in an upland hardwood Forest. *Geosciences*, *9*(10), 405. https://doi.org/10.3390/geosciences9100405

Spencer, S. A., & van Meerveld, H. J. (2016). Double funnelling in a mature coastal British Columbia forest: Spatial patterns of stemflow after infiltration: Double Funnelling in a mature coastal British Columbia Forest. *Hydrological Processes*, *30*(22), 4185–4201. https://doi.org/10.1002/hyp.10936

Staelens, J., De Schrijver, A., Verheyen, K., & Verhoest, N. E. C. (2006). Spatial variability and temporal stability of throughfall water under a dominant beech (*Fagus sylvatica* L.) tree in relationship to canopy cover. *Journal of Hydrology*, *330*(3–4), 651–662. https://doi.org/10.1016/j.jhydrol.2006.04.032

Staelens, J., Herbst, M., Hölscher, D., & De Schrijver, A. (2011). Seasonality of hydrological and biogeochemical fluxes. In *Forest hydrology and biogeochemistry* (pp. 521–539). Springer.

Staelens, J., Schrijver, A. D., Verheyen, K., & Verhoest, N. E. C. (2008). Rainfall partitioning into throughfall, stemflow, and interception within a single beech (*Fagus sylvatica* L.) canopy: Influence of foliation, rain event characteristics, and meteorology. *Hydrological Processes*, *22*(1), 33–45. https://doi.org/10.1002/hyp.6610

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D. A., François, R., & Yutani, H. (2019). Welcome to the Tidyverse. *Journal of Open Source Software*, *4*(43), 1686.

Wickham, H., François, R., Henry, L., & Müller, K. (2021). dplyr: A grammar of data manipulation. R package version 1.0.3. https://CRAN.R-project.org/package=dplyr

Zimmermann, B., Zimmermann, A., Lark, R. M., & Elsenbeer, H. (2010). Sampling procedures for throughfall monitoring: A simulation study: Sampling procedures for throughfall monitoring. *Water Resources Research*, *46*(1), W01503. https://doi.org/10.1029/2009WR007776

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APPENDIX A

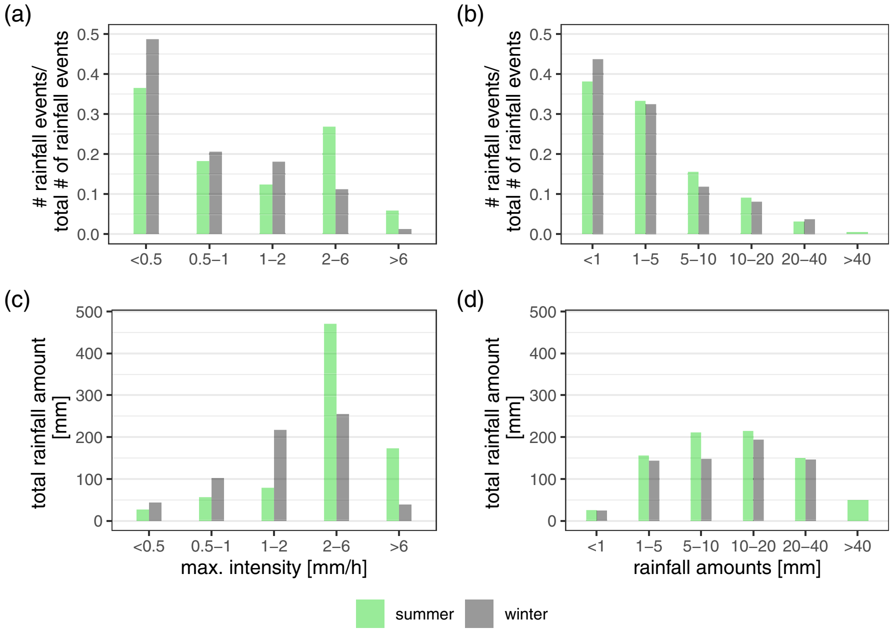


FIGURE A1 Relative event number and cumulated rainfall amount distributions for different classes of maximum rainfall intensities (a, c) and of event rainfall amounts (b, d)

FIGURE A2 Event throughfall fractions as a function of total event rainfall amount for all forest stands colour coded by season. Circle size corresponds to the maximum event rainfall intensity. (B: Beech; OB: Oak & Beech; PB: Pine & Beech; PBO: Pine, Beech & Oak; P: Pine; YP: young Pine). The event throughfall fraction initially increases steeply with rainfall amount and stabilizes at a certain rainfall level in both periods. This asymptotic behaviour is less pronounced at the young pine site

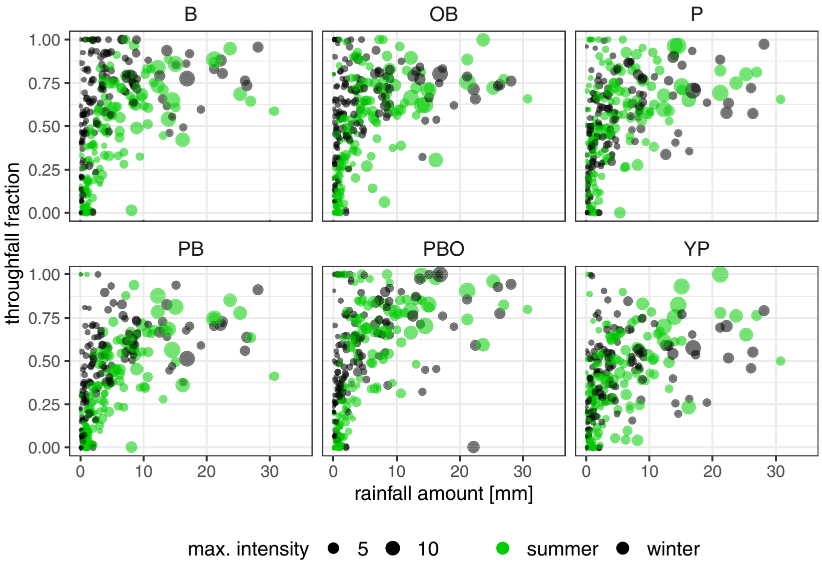
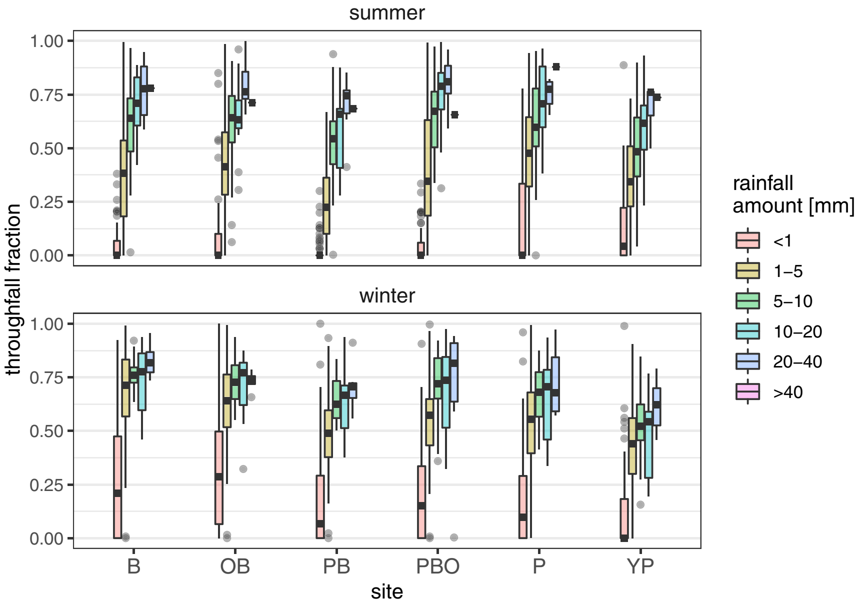


FIGURE A3 Throughfall as fraction of total rainfall on event basis: Comparison of all sites for the leafed (summer) vs. leafless (winter) period and for different event rainfall amounts. B: Beech; OB: Oak & Beech; PB: Pine & Beech; PBO: Pine, Beech & Oak; P: Pine; YP: young Pine



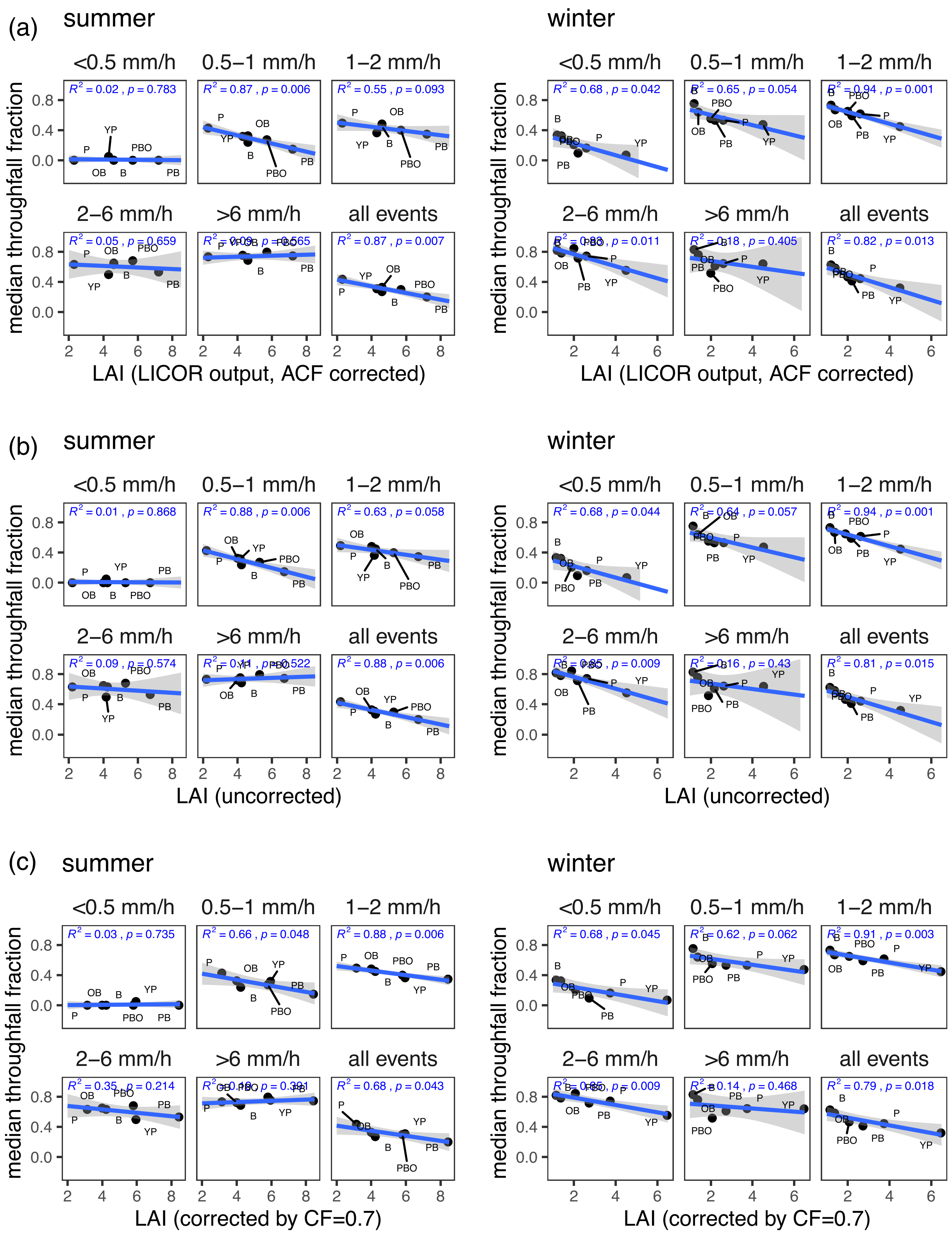


FIGURE A4 Different approaches for LAI determination for summer (left) and winter (right): (a) LICOR output (corrected by apparent clumping factor ACF), (b) effective (uncorrected) LAI, (c) LAI corrected with clumping factor of scots pine determined by Goude et al., 2019. B: Beech; OB: Oak & Beech; PB: Pine & Beech; PBO: Pine, Beech & Oak; P: Pine; YP: young Pine

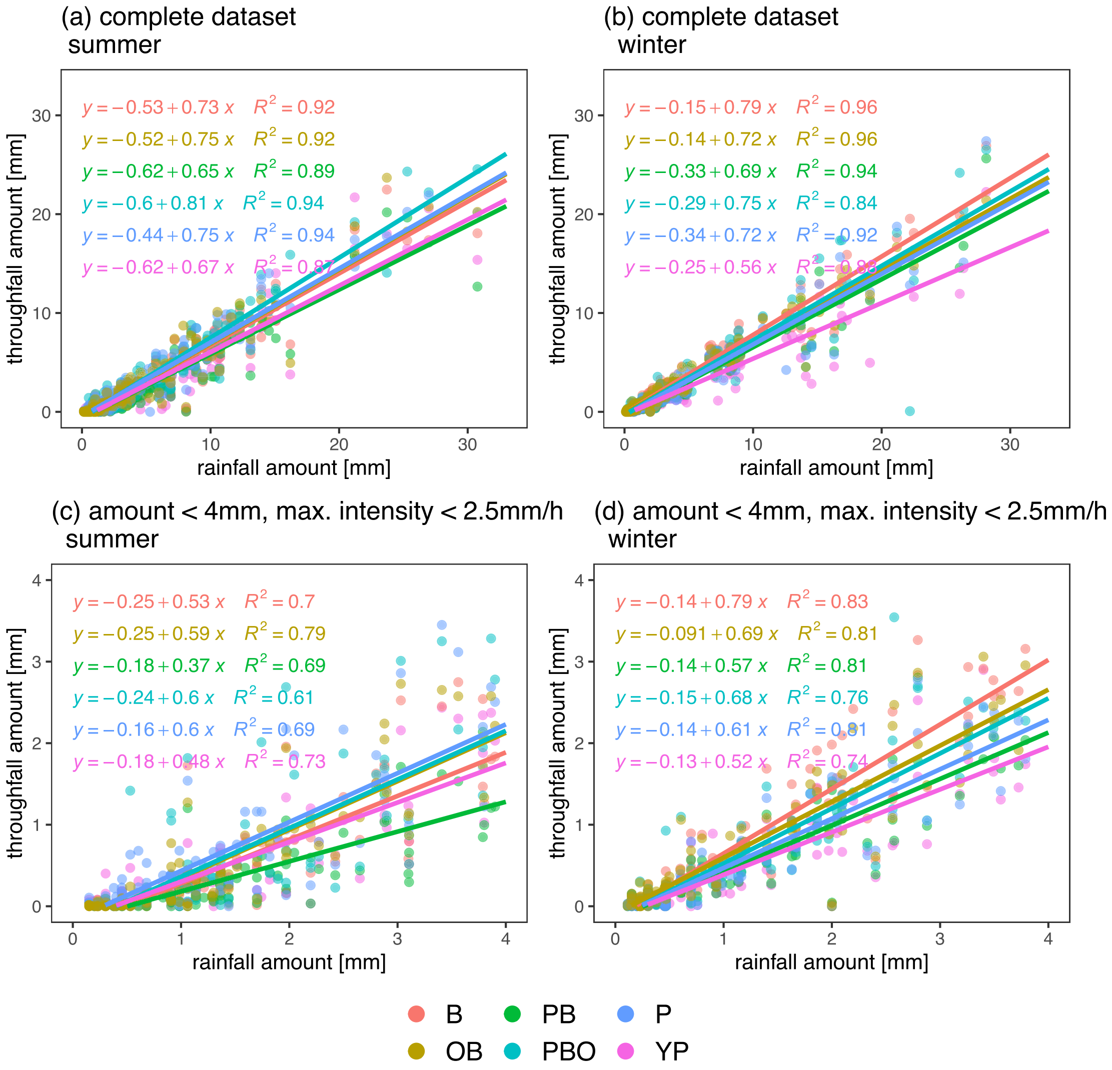


FIGURE A5 Direct comparison of linear regressions for the two seasons and two subsets of the data (complete dataset here without the maximum rainfall event of almost 50 mm). B: Beech; OB: Oak & Beech; PB: Pine & Beech; PBO: Pine, Beech & Oak; P: Pine; YP: young Pine

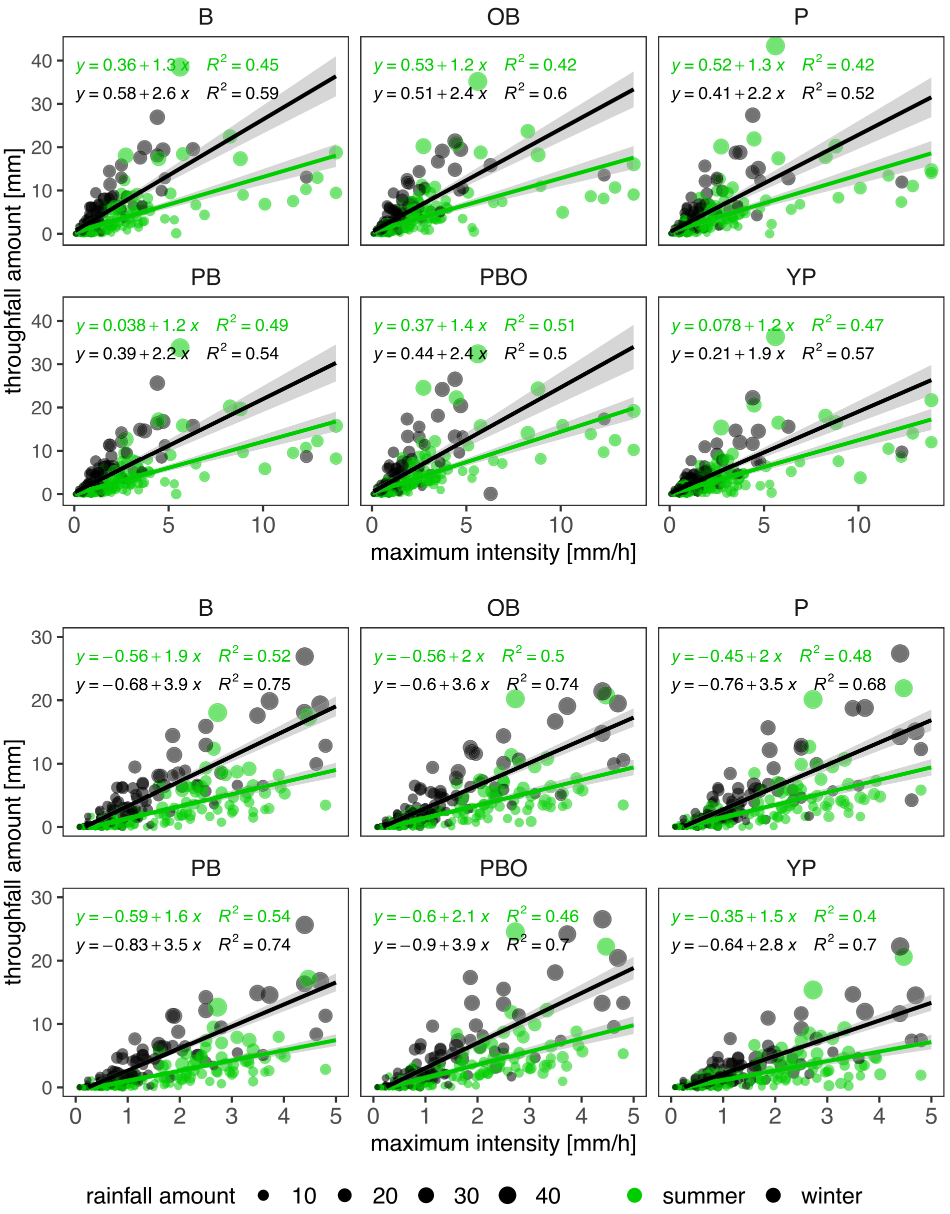


FIGURE A6 Throughfall amount vs. maximum intensity. Upper plot full data set, lower plot reduced data set with maximum intensity <5 mm/h. B: Beech; OB: Oak & Beech; PB: Pine & Beech; PBO: Pine, Beech & Oak; P: Pine; YP: young Pine

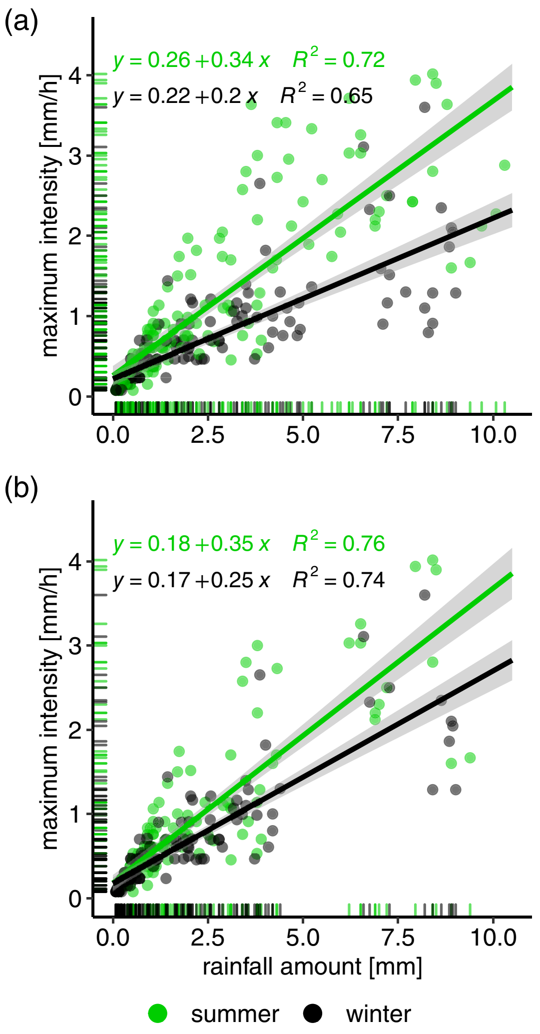


FIGURE A7 Comparison of the differences between summer and winter rainfall event characteristics for (a) the reduced data set using simple range limits (rainfall amount <11 mm and max. Intensity <5 mm/h) and (b) the optimized data set, where winter and summer events are more similar in their characteristics. 1D marginal distributions are provided along the axes. We find that for the optimized data set of rainfall events both slope and intercept of the two regression lines between rainfall amount and maximum intensity for winter and summer become more similar, both compared to the complete data set as well as compared to the range-based reduction

TABLE A1 Leafed periods during the study period ('summer') with the corresponding remainders being the leafless periods ('winter')

Year	Start	End
2015	01.05.2015	01.11.2015
2016	04.05.2016	26.11.2016
2017	12.05.2017	16.11.2017
2018	02.05.2018	15.11.2018