Effect of biotic and abiotic factors on inter and intra-event variability in stemflow rates in oak and pine stands in a Mediterranean mountain area

C. Cayuela[a,*], P. Llorens[a], E. Sánchez-Costa[a], D.F. Levia[b], J. Latron[a]

[a] Surface Hydrology and Erosion Group, IDAEA, CSIC, Jordi Girona 18, 08034 Barcelona, Catalonia, Spain.

[b] Departments of Geography and Plant & Soil Sciences, University of Delaware, Newark, DE 19716, USA.

* Corresponding author

carles.cayuela@idaea.csic.es (C. Cayuela)

Abstract

Stemflow, despite being a small proportion of the gross rainfall, is an important and understudied flux of water in forested areas. Recent studies have highlighted its complexity and relative importance for the understanding of soil and groundwater recharge. Stemflow dynamics offer an insight into the rain water that is stored and released from the stems of trees to the soil. Different attempts have been made to understand the variability of stemflow under different types of vegetation, but rather few have focused on the combined influence of both biotic and abiotic factors that affect the inter and intra-storm stemflow variability, and none known in Mediterranean climates. This study presents stemflow data collected at high temporal resolution for two species with contrasting canopy and bark structures: *Quercus pubescens* Willd. (downy oak) and *Pinus sylvestris* L. (Scots pine) in the Vallcebre research catchments (NE of Spain, 42º 12'N, 1º 49'E). The main objective was to understand how the interaction of biotic and abiotic factors affected stemflow dynamics. Mean stemflow production was low for both species (~1% of incident rainfall) and increased with rainfall amount. However, the magnitude of the response depended on the combination of multiple biotic and abiotic factors. Both species produced similar stemflow volumes, but funneling ratios of some trees diverged significantly. The combined analysis of biotic and abiotic factors showed that, for events of the same rainfall amount, funneling ratios and stemflow dynamics in each species were highly controlled by the interaction of rainfall intensity and tree diameter (DBH).

Key words: Stemflow; Funneling ratio; intra-storm; inter-storm; *Pinus sylvestris*; *Quercus pubescens*

1. Introduction

Stemflow, expressed as volume of water per unit area, represents usually a small proportion of the gross incident precipitation, for this reason it has often been neglected in hydrological studies. Nonetheless, stemflow is a concentrated point source of water that reaches the base of trees, playing an important role on spatial soil moisture variability and groundwater recharge (e.g. Durocher, 1990; Liang et al., 2007; Klos et al., 2014; Spencer and van Meerveld, 2016). Moreover, stemflow fluxes, due to their ability to transport nutrients, may enhance soil biogeochemical “hot spots” and “hot moments” (Levia et al., 2012; McClain et al., 2003; Michalzik et al., 2016). Stemflow production is highly variable across climate regions; its variability is attributed to the different climatic conditions and species composition, thereby making the prediction of stemflow volumes difficult (Levia and Germer, 2015). Stemflow can represent from less than 0.5 up to 20% of gross precipitation (Johnson and Lehmann, 2006; Levia and Frost, 2003) and, in the Mediterranean climate, stemflow represents 3.2 ±0.7% for trees and 19.2 ±5.4% for shrubs (Llorens and Domingo, 2007).

Stemflow production is the result of a complex and dynamic interaction of biotic and abiotic factors. The main biotic factors affecting stemflow production are tree structure and morphology (including tree size, branch structure, branch angle, leaf shape or bark texture) and tree water holding capacity (including canopy and stem storage capacity or epiphyte cover) (Levia and Frost, 2003). Large projected areas and bigger exposed canopies with upwardly inclined branches have been documented to promote stemflow (Aboal et al., 1999; Herwitz, 1986); likewise, species with smooth bark tend to hold less water and enhance stemflow (Carlyle-Moses and Price, 2006; Kuraji et al., 2001; Reid and Lewis, 2009). Recently, it has been discussed that the smallest trees would have higher funneling ratios (Levia et al., 2010; Spencer and van Meerveld, 2016) and may contribute more to the overall stand stemflow, but this relationship seems to be species-specific (Carlyle-Moses and Price, 2006). The main abiotic factors are rainfall (amount, intensity, duration) and wind (speed and duration) characteristics (Levia and Germer, 2015). Research showed that stemflow increases with the rainfall amount, in addition, higher rainfall intensities can result in larger quantities of stemflow (e.g. Aboal et al., 1999; Spencer and van Meerveld, 2016). At the event scale, rainfall rates also affect the stemflow production; for example, laboratory experiments by Dunkerley (2014) showed that intense rainfall could saturate the canopy and the stem storage capacity, consequently generating early stemflow paths. In addition, rainfall with various high intensity peaks produced more stemflow than rainfall events of uniform intensity. Carlyle-Moses and Price (2006) and Staelens et al. (2008) found that high intensity rainfall tended to reduce stemflow rates in favour of throughfall; the same effect was suggested by Levia et al. (2010) who found that funnelling ratios decreased as the 5-min precipitation intensity increased, as a consequence of the stemflow dripping when the maximum transport capacity of stemflow was exceeded. Some authors (Llorens et al., 1997; Neal et al., 1993; Staelens et al., 2008; Van Stan et al., 2014) also suggest that high vapour pressure deficits enhance evaporation and diminish the water contributing to stemflow, therefore, decreasing stemflow rates. On the other hand, precipitation events with high wind velocities or a major prevailing wind direction would promote the wetting of the tree crown, thereby generating preferential stemflow paths and inducing enhanced stemflow production even before reaching the interception storage capacity (Kuraji et al., 2001; Van Stan et al., 2011; Xiao et al., 2000).

The importance of stemflow is not only related to the mean volumes produced in a specific space or time, but it is also related to the stemflow rates at the intra-storm scale; different stemflow intensities can produce different infiltration rates into the soil (e.g. Germer, 2013; Liang et al., 2007, 2011; Spencer and van Meerveld, 2016). As pointed out by Levia and Germer (2015), until now there are only a few studies that have measured the intra-storm stemflow production. For instance, Reid and Lewis (2009) observed a positive correlation between rainfall intensity and water stored in the bark. Germer et al. (2010) showed the relevance of small trees and palms, their maximum 5-min stemflow intensities were 15 times greater than rainfall. Levia et al. (2010) showed the synchronicity between rainfall and stemflow once the bark storage capacity was filled. And recently, Spencer and van Meerveld (2016), confirmed that stemflow intensity was highest when high-rainfall intensity occurred later in the event.

In this study we use 5-min data to examine stemflow dynamics of two species with contrasted architecture and largely spread in Mediterranean mountain areas (Roskov Y. et al, 2017), downy oak (*Quercus pubescens* Willd.) and Scots pine (*Pinus sylvestris* L.). Even though there are studies that focuses on stemflow produced by pines or by oaks, a comparison of stemflow dynamics between both species, in the same climatic conditions, has never been done to the knowledge of the authors. The understanding of their stemflow dynamics will give some light on the hydrological processes that take place under both canopies and would help to improve ecohydrological models. Accordingly, the novelty and main objective of this study is to quantify and analyse the inter- and intra-storm stemflow dynamics of these two species taking into account the interaction between biotic and abiotic factors. We specifically aim to answer the following questions: (i) are stemflow responses and funneling capabilities for Scots pine and downy oak different, both inter and intra-specifically and inter and intra-event? (ii) How do Scots pine and downy oak stemflow respond to different abiotic factors? (iii) What biotic characteristics enhance stemflow inter- and intra-specifically? And (iv) how does the interaction of biotic and abiotic factors affect stemflow dynamics? These questions provide the structural sub-headings used in the following data and methods, results, and discussion sections. Answers to these questions are necessary to better understand the cycling of water within storm events, especially in Mediterranean areas due to their strong inter- and intra- event variability in precipitation.

2. Study area

2.1. The Vallcebre research catchments

The study area is located in the Vallcebre research catchments (NE Spain, 42º 12'N, 1º 49'E) in the eastern Pyrenees at 1100 m asl (meters above sea level), it has been monitored with different hydrologic purposes since 1988. Today, the study area consists of a cluster of nested catchments: Cal Rodó (4.17 km^2), Ca l'Isard (1.32 km^2) and Can Vila (0.56 km^2). Moreover, in the catchments there are two long-term monitored forest plots, one covered by Scots pine and the other by downy oaks. The climate is Sub-

Mediterranean, with a mean annual temperature of 9.1 ºC, a mean annual reference evapotranspiration, calculated by the Hargreaves-Samani (1982) method, of 823 ± 26 mm, and a mean annual precipitation of 862 mm ± 206 mm (1989-2015). Precipitation is seasonal, with autumn and spring usually being wetter seasons, while summer and winter are often drier. Summer rainfall is characterized by intense convective events, while winter precipitation is caused by frontal systems, with snowfall accounting for less than 5% of the precipitation (Latron et al., 2010a, 2010b).

Slopes of the study area were originally vegetated by downy oaks; however, the site was deforested and terraced in the past for agricultural production. At present, the abandonment of agricultural activities has led to a spontaneous afforestation by pine forests (Poyatos et al., 2003). As a result, the forest is predominantly Scots pine, although isolated populations of the original deciduous downy oak forests remain.

2.2. The forest plots

Our study utilized a downy oak and a Scots pine stand, separated by 1 km, to monitor stemflow. The Scots pine stand has an area of 900 m^2, a tree density of 1189 trees ha^{-1}, a basal area of 45.1 m^2 ha^{-1}, is oriented towards the northeast and has an altitude of 1200 m, whereas the downy oak stand has an area of 2200 m^2, a tree density of 518 trees ha^{-1}, a basal area of 20.1 m^2 ha^{-1}, is oriented towards the southeast and has an altitude of 1100m. Both species have different biometric characteristics. Scots pine develops a long and straight trunk with a thick bark topped with a roughly rounded crown and downy oak is a rough-barked deciduous tree that usually develops several trunks and a broad and irregular crown. Despite the inter-specific differences of each species, pines trees presented a more regular pattern regarding to their tree architecture, whereas oak trees presented more irregular architectures.

3. Data and methods

3.1. Rainfall and meteorological data

Meteorological data were obtained from two meteorological towers, 15 and 18 m high, above the oak and pine stands, respectively. The high of the measurements was approximately 1 m above the canopy. Each station monitored air temperature, relative humidity, net radiation, wind speed, and wind direction above their respective canopies. Temperature and relative humidity were used to calculate the vapour pressure deficit (VPD). Gross rainfall was measured for both stands in a nearby clearing (located less than 100 m from each stand) by a tipping-bucket rain gauge (Davis Rain Collector II). All data were measured every 30-seconds and recorded at 5-min intervals by a datalogger (DT80 Datataker, Datataker Inc, OH, USA).

3.2. Monitored trees

In each monitored stand, seven trees were selected to measure stemflow, representing the range of diameter at breast height (DBH) distributions. For each tree, the following biometric parameters were measured: DBH, basal area, height, crown area, crown volume, branch angle, branch diameter, bark depth and trunk lean (Table 1). Moreover, stem bark surface and bark storage capacity were estimated. Stem bark surface was calculated using a logarithmic regression of surface area from DBH (Whittaker and Woodwell, 1967), and bark storage capacity was estimated following the methodology described by Llorens and Gallart (2000).

< Table 1 here please >

3.3. Stemflow monitoring

A stemflow collector ring constructed from a longitudinally cut funnel was placed around the trunk at breast height of each selected tree and sealed with silicone. Each stemflow ring drained to tipping-buckets rain gauges (Davis Rain Collector II). Data were collected at 5-min intervals by a datalogger (DT80 Datataker). Recorded data were downloaded and the stemflow rings were cleaned and checked for leakage weekly. Moreover, data were evaluated for potential errors and converted to stemflow volume through a dynamic calibration of the tipping-buckets (Calder and Kidd, 1978; Iida et al., 2012). The dynamic calibration was crucial due to the high frequency of the bucket tips during events when stemflow intensities exceeded 50 tips in 5 minutes and the capacity of the tipping-bucket mechanism was overwhelmed and the regular calibration underestimated the measured volume. Moreover, we compared the volumes obtained with the tipping-buckets with the volumes of 8 additional trees equipped with stemflow rings and collection bins (60 L); the regression analysis showed a good correlation between mean volumes without statistically significant differences in the linear regression parameters.

3.4. Stemflow and funneling ratios calculation

Stemflow data for this study was collected from May to October 2015. To reduce differences between stands due to significant phenological changes in the oak canopy over the year, as well as different rainfall patterns in the leafed and leafless periods (Muzylo et al., 2012a), only the leafed period was considered. Individual rainfall events were defined according to the time without rainfall between two successive events with at least 1 mm of rainfall. Following Llorens et al. (2014), to ensure that the canopy was dry at the beginning of each rainfall event, an interval of six hours was considered for events occurring during the day and an interval of twelve hours for night events. The end of the event was established when stemflow finished.

Stemflow depth (mm) was calculated by dividing the measured stemflow volume (L) by tree basal area (m^2). Following Levia and Germer (2015), relative stemflow ($S_{(\%R)}$) was calculated as the stemflow percentage of gross rainfall weighted by the number of trees per group of DBH in each stand.

$$S_{(\%R)} = \frac{\left(\frac{\sum_{i=1}^{k}(Sy,i \cdot NTrees,i)}{A}\right) \cdot 100}{P} \qquad (1)$$

where S_y is mean stemflow of all sampled trees (L), N_{Trees} is the number of trees per area, A is the area (m^2), P is incident rainfall (mm) and k is the number of groups of trunk diameter ranges. In each stand 5 groups of DBH were selected: <15cm, 15-20 cm, 20-25 cm, 25-30 cm and >30 cm. Finally, funneling ratios were calculated following Herwitz (1986).

$$F = \frac{V}{B \cdot P} \qquad (2)$$

where **V** is the volume of stemflow (L), B is the trunk basal area (m^2), P is incident rainfall (mm), and F is the funneling ratio. Funneling ratios above 1 indicate that trees start to concentrate precipitation as stemflow.

Analysis of the variance (ANOVA) in conjunction with a Tukey-Kramer *post-hoc* analysis was performed to check possible differences between relative stemflow and mean funneling ratios between stands; a *p*-value ≤ 0.05 was used as a threshold for statistical significance. To ensure data symmetry, only rainfall events which produced stemflow were used and all stemflow values were log-transformed to guarantee normality of the error distribution and homoscedasticity of the errors.

3.5. Abiotic factors affecting stemflow and funneling ratios

To assess the influence of all measured abiotic factors, and to rule out the marked correlation between gross rainfall and stemflow, an unrotated principal component analysis (PCA) with normalized data was done with the following variables: maximum rainfall intensity measured in 30 minutes, event duration, vapour pressure deficit (VPD) and wind speed. The PCA also permitted the detection of groups of events with similar stemflow volumes and funneling ratios.

3.6. Biotic factors affecting stemflow and funneling ratios

An ANOVA test was conducted to detect statistical differences in stemflow volumes and funneling ratios between trees of each species. Moreover, to reduce the amount of factors affecting stemflow and funneling ratios, a PCA with all the normalized measured biotic factors in each tree (DBH, basal area, height, crown area, crown volume, branch angle, branch diameter, bark depth, trunk lean, stem bark surface and bark storage capacity) was performed. From these factors, DBH, crown volume, mean branch angle, bark storage capacity and tree lean explained most of the variability and were used to compare and analyse the effect of each factor over each tree.

3.7. Interaction of biotic and abiotic factors that affect stemflow dynamics

To analyse the combined effect of biotic and abiotic factors on the stemflow dynamic, and in order to rule out the influence of the rainfall volume, 12 events of similar magnitude (≈30 mm) but with marked differences in their maximum rainfall intensity measured in 30 minutes and in their duration were selected. Among the biotic variables measured, DBH was selected to represent tree biotic factors, because it was found to be correlated with most of the other biotic factors measured, stronger in pines. Therefore, in order to generalise and compare results, and keeping in mind the complexity of oak morphology compared with pines', trees were separated in two DBH classes (<25cm and >25cm).

4. Results

4.1. Gross rainfall

Total rainfall measured during the study period was 519 mm and 528 mm in the pine and oak stands, respectively. The study period was the second rainiest year over the last 20 years in the study area. From the 33 rainfall events measured, 66% were smaller than 15 mm, 28% between 15 and 40 mm, and 6% were larger than 40 mm, these percentages matched with the distribution of rainfall events measured in the medium-term period in the study site (Latron et al., 2010a). At the event scale, differences in gross rainfall between the two forested stands were in general less than 1 mm and differences in maximum intensity were less than 0.5 mm h^{-1}, but differences tended to be larger for rainfall events with a higher intensity. This was the case of the July 23rd thunderstorm, for which rainfall differed by 14 mm between the two stands. This was a short duration event (less than 2 hours) with a maximum intensity of 41 mm in 30 minutes and rainfall amounts of 72 mm and 58 mm for the pine and oak stands, respectively.

4.2. Stemflow and funneling ratios

Relative stemflow ($S_{(\%R)}$) was low in both stands, with mean $S_{(\%R)}$ values of 1.2% (±1.4) for pine and 1.1% (±1.4) for oak. Nonetheless, it was highly variable among events, for example in some events $S_{(\%R)}$ reached up to 6% of the gross rainfall (Figure 1a). No statistical significant differences in the relative stemflow were found between forest stands. For both species, stemflow volumes increased with rainfall (Figure 1b), our data suggested 3 types of stemflow responses: (1) events with less than 15 mm of rainfall produced small stemflow volumes, on average 0.4 ±0.7 L, with the largest coefficient of variation between trees (~100%); (2) events between 15 and 40 mm of rainfall produced a mean stemflow volume of 7.0 ±4.1 L, with coefficient of variation ~60%; and (3) events greater than 50 mm of rainfall produced on average 25 ±16 L of stemflow and presented the lowest coefficient of variation between trees (~50%) (Figure 1b). At the intra-event scale, the 5-min data showed that relative stemflow presented a higher variability under lower intensities and that it decreased with increasing rainfall intensities (Figure 1d). Besides, it was observed that for intensities lower than 4 mm in 5 minutes (48 mm h^{-1}), stemflow volumes increased (Figure 1e), beyond this threshold, stemflow volume no longer increased with increasing rainfall intensity.

< Figure 1 here please >

Funneling ratios of both species increased with the rainfall amount until a plateau of ~20 mm of rainfall. Beyond 20 mm of rainfall, more rainfall did not necessarily equate with a major concentration of stemflow at the base of the trees (Figure 1c). No statistical differences were observed between the mean funneling ratios measured of each stand. On the other hand, examining the 5-min rainfall intensity, we observed that funneling ratios decreased as the intensity increased (Figure 1f). Mean funneling ratios smaller than 10 were produced when rainfall intensity was higher than 5 mm in 5 minutes, below this threshold, mean funneling ratios were generally higher, with values up to 20. Statistical significant differences between species were found for the lag time, the rainfall needed to produce stemflow, and the stemflow produced after rainfall. Results showed that the mean lag time between the start of rainfall and the start of stemflow was 1 h for pine and 1 h 30 min for oak; however median values were 30 min and 48 min respectively (Figure 2a). The mean amount of gross rainfall needed to produce stemflow was 4 mm for pine and 6 mm for oak (Figure 2b). Nonetheless, during some rainfall events, stemflow did not begin until the gross rainfall was approximately 17 mm. Once the rainfall ceased, the volume of stemflow produced was greater for oak than for pine

(Figure 2c), indicating that oak remained wet longer and diverted more stemflow (0.9±1.2 L) compared to pine (0.5±0.4 L) after the rainfall.

< Figure 2 here please >

The intra-event stemflow dynamics (5-min step) of 4 rainfall events with similar rainfall volumes, but differing in rainfall duration and intensity revealed that for all kinds of events and sizes of trees, maximum stemflow intensities were much higher than maximum rainfall intensities (Table 2, Figure 3). For long duration and low intensity events (Figure 3 a and b), there was a delay between the beginning of the rainfall and the start of stemflow. Furthermore, the time series of oaks suggested that stemflow matched the rainfall pattern better than for pines (e.g. Figure 3a from 15:35 h). Moreover, for two consecutive periods of similar rainfall intensities, stemflow intensity was higher during the second period (e.g. first and second peak in Figure 3a, third and four peaks in Figure 3b). On the other hand, shorter and more intense rainfall events (Figure 3 c and d) resulted stemflow intensities almost 10 times higher than long duration-low intensity events (Figure 3 a and b). We also observed that when the peak of rainfall was at the onset of the event, the lag time was reduced considerably (e.g. in Figure 3a the lag time was 5h and for the events in Figure 3 b, c and d only 30-45 minutes). In general, during low intensity events (<2 mm/h), pines and oaks with DBH < 25 cm presented respective peaks of stemflow up to 12 and 9 times greater than larger trees. For higher rainfall intensities, these figures were up to 80 and 60. However, at the end of the event, oaks with DBH > 25 cm produced more stemflow.

< Table 2 here please >

< Figure 3 here please >

4.3. Abiotic factors affecting stemflow and funneling ratios

Stemflow increased linearly with gross rainfall, but the differences between events of similar magnitude depended on other abiotic factors. The PCA (Figures 4a and 4b) explained 78.2 and 76.3% of the variance for the pine and oak, respectively. For both species, the first component contrasted short events, with high VPD and high wind speeds, against long events, with wet atmospheric conditions and low wind speeds. The second component was demarcated by rainfall intensity. This analysis generally suggests that relative stemflow was higher for long rainfall events and for rainfall events with high rainfall intensities. On the other hand, rainfall events with high wind speed and with a high VPD tended to produce less stemflow. In the same way, events with the highest intensity also tended to produce less stemflow. Despite no statistical significant differences were found between rainfall intensities and stemflow volumes or funneling ratios, PCA results suggest three types of rainfall events generating different stemflow responses: (1) events with moderate intensities and long durations greatly increased stemflow production in oak (9 ±16 L) more than in pine (3 ±6 L), additionally we observed funneling ratios of ~7 and ~4 in oak and pine respectively; (2) events of high intensity and short duration produced similar stemflow volumes (4 ±5 L in pine and 3 ±4 L in oak) and similar funneling ratios (~6); and (3) events of low intensity and short duration produced low stemflow in both stands (0.5 ±0.4 L pine and 1 ±2 L oak) and higher funneling ratios were measured in the oak stand (~6) than the pine stand (~2).

< Figure 4 here please >

4.4. Biotic factors affecting stemflow and funneling ratios

The intra-species tree comparison of stemflow volumes and funneling ratios showed statistical significant differences in funneling ratios among some trees. The PCA of biotic factors (Figures 4b and 4c) explained 80.7 and 83.4% of the variance for the pine and oak trees, respectively, and suggested that funneling ratios were highly influenced by the DBH. Moreover, the PCA results along with the comparison of the distribution of funneling ratios and the biotic factors (Figure 5) showed that pine trees with less than 25 cm DBH and with smaller crown volumes (P1, P2, P3 and P6) presented funneling ratios statistically significant greater than larger trees (P4, P5 and P7), which had horizontal or downwards inclined branches and higher bark storage capacities. Tree lean (2º-5º) increased funneling ratio, however, larger tree lean (>5º) decreased it. For oaks, tree Q7 produced the highest funneling ratio, and it was statistically significant different from the other oaks. This tree had the smallest DBH, a voluminous crown, branch inclinations between 20º and 25º and the lowest bark storage capacity. But, on the other hand, trees Q1, Q2, Q5 and Q6 produced low funneling ratios, compared to Q7, these trees had higher storage capacities (>0.50 mm). Trees with the lowest funneling ratios (Q3 and Q4) were moderately sized trees (DBH 24.8 and 20.5 cm) and flow paths were obstructed (big nodules in the trunk observed *in situ*). Tree Q4 also produced statistically significantly less volume than the other oaks. A detailed response of each tree for each rainfall event can be seen in Figure A1 (Supplementary material).

< Figure 5 here please >

4.5. Interaction of biotic and abiotic factors that affect stemflow dynamics

The interaction between biotic and abiotic factors was checked for 12 events of similar magnitude (~30 mm). Among these events, 6 were of low intensity, with mean rainfall intensity of 6 mm h^{-1} and mean duration of 17 hours and the other 6 events were of high intensity, with a mean rainfall intensity of 17 mm h^{-1} and mean duration of 5 hours. Smaller pines, regardless the rainfall intensity, produced slightly more stemflow than larger pines. In contrast, larger oaks produced more stemflow than smaller oaks, and higher rainfall intensities increased stemflow volumes for all oaks (Figure 6a). There were not differences in funneling ratios for oak trees. On the contrary, larger differences were observed in the funneling ratios of pines depending on their size (i.e. lowest values for larger trees), especially for low intensity events (Figure 6b). Lag times were longer during high rainfall intensities for both species; this lag time was higher for oaks (Figure 6c). Stemflow duration once rainfall had ceased was similar between pines, although slightly longer for larger pines during low intensity events (on average 30 more minutes). Big oaks produced stemflow over a longer duration, with larger stemflow volumes stemming from low intensity events (Figure 6d).

< Figure 6 here please >

5. Discussion

5.1. Stemflow production and funneling ratios

On average, stemflow produced by oak and pine represented only about 1% of the total gross rainfall over the study period. This percentage agrees with the previous values reported for *Pinus sylvestris* and *Quercus pubescens* under Mediterranean climate (Llorens and Domingo, 2007; Muzylo et al., 2012b). In both stands similar stemflow volumes were produced after each rainfall event, but different dynamics were observed. The different stemflow dynamics between species was attributed to a complex interaction of biotic and abiotic factors, similar observations were made by Levia et al. (2010). However, the largest differences were found within trees of the same species, with significant differences in their funneling capabilities.

5.2. Abiotic factors affecting stemflow and funneling ratios

Our study found that stemflow and funneling ratios were highly influenced by the gross rainfall, the duration of the rainfall, the rainfall intensity, the vapour pressure deficit and the wind speed. The role of one or several of these factors in stemflow production have been previously described in other studies (e.g. Dunkerley, 2014; Reid and Lewis, 2009; Van Stan et al., 2014), but the comparison between species and the high frequency of the stemflow measurements revealed new insights into some of these factors. As pointed out by Herwitz (1987), high intensity rainfall events may agitate foliar surfaces, create splash, disrupt canopy interception and divert more rainfall into throughfall, resulting in a decrease of stemflow. In this sense, we observed that rainfall intensity peaks greater than 4 mm in 5 minutes decreased the capacity of trees to funnel water. A similar effect was observed by Levia *et al.* (2010), who also linked this effect to an excess of the branches' flow capacity, causing water detachment and resulting in throughfall. This phenomenon was further reflected by a steady stemflow production and a decrease of the funneling ratio at increasing rainfall intensities. Moreover, we detected that stemflow volumes varied greatly depending on the position of the peaks of high intensity along the event. Similar to Dunkerley (2014) we observed that events with high intensity peaks produced more stemflow than those of uniform rain and the lag time was reduced when the maximum peak of intensity was at the onset of the event. When successive intensity peaks occurred there was an increase of the stemflow volume and of the funneling ratio, which could be explained by a rapid diversion of water through the early created stemflow paths. For rainfall events with a high intensity peak (>5 mm in 5 minutes) stemflow intensities could exceed 100 times the intensity of open rainfall. As a consequence, and as observed by Spencer and van Meerveld (2016), during some precise moments of a rainfall event, the amount of water that reached the base of the tree as stemflow could enhance infiltration rates and groundwater recharge.

Unlike Van Stan *et al.* (2011), in this study, we observed that increasing wind speed resulted in lower stemflow volumes and lower mean funneling ratios. This effect was attributed to an increase of the VPD linked to higher wind speeds; in these conditions evaporative demand was enhanced and, as a consequence, interception loss increased reducing stemflow volumes. Moreover, for the same evaporative demand, the evaporation of intercepted water in pine is higher because the canopy of pine is aerodynamically rougher than oak (Jarvis, 1976). Previous studies in the same study site (Llorens et al., 1997; Muzylo et al., 2012a) observed higher interception losses for pines (24%) than for oaks (15%). This higher interception loss in pines could explain why the synchronicity between rainfall and stemflow was weaker for pine than oak.

5.3. Biotic factors affecting stemflow and funneling ratios

Likewise, as in other recent studies (Germer et al., 2010; Levia et al., 2010; Siegert and Levia, 2014; Spencer and van Meerveld, 2016), we observed an effect of the tree size, where trees with DBH between 15 and 25 cm had higher funneling ratios. The higher efficiency of small pine trees was attributed to a combination of different biotic factors: more branches tilted vertically, smaller crown and less bark surface. Smaller oaks, in general, also presented higher funnelling ratios, but more differences were found. For example, some small trees presented flow paths obstructions, such as big nodules, or had a high tree lean, factors that would divert more water as throughfall and would reduce their funneling ratios. Levia et al. (2015) also found that trunk lean was a factor affecting stemflow amount from European beech saplings.

Despite producing similar volumes of stemflow, there were differences in the timing and dynamics of stemflow for the two species, expressed by different funneling ratios. One of the factors determining funneling ratios is the canopy architecture; as observed by Reid and Lewis (2009) the canopy represents a dynamic storage where rainfall can be evaporated or diverted as stemflow during and after rainfall events depending on the meteorological conditions. We observed higher funneling ratios for pine trees with smaller canopies. These trees have also fewer branches and more tilted vertically that could ease the formation of preferential flow paths and reduce the diversion of stemflow, leading this way to a faster response in stemflow production. Likewise, and as observed by Liang et al. (2009), we observed that a certain tree lean, between 2º and 5º, favoured the formation of flow paths and therefore increased funneling ratios; however, tree lean greater than 5º would divert more water to throughfall. When flow paths are created stemflow can wet the trunk and it can be enhanced or lessen, depending on the bark storage capacity (Levia and Herwitz, 2005; Van Stan and Levia, 2010), therefore, trees with thicker rough bark would produce less stemflow. In agreement with these studies, we observed that oak, whose bark storage capacity was larger than pine, had longer lag times and required more rainfall to trigger stemflow.

5.4. Interaction of biotic and abiotic factors that affect stemflow dynamics

Biotic factors clearly determined the funneling ratio of each tree, but abiotic factors determined the magnitude of the stemflow response. In our study, biotic factors were constant; however abiotic factors were variable between and within events. Stemflow, as described in previous literature (Levia and Frost, 2003), increased with gross precipitation, even though, we observed that for the same amount of rainfall, the response was different for small or big trees. Events of high rainfall intensity were associated to short duration, high wind speed and low VPD; during these events more splash could be produced (Herwitz, 1987), higher evaporation rates would enhance the interception losses, and as observed by Reid and Lewis (2009), a higher retention of water in the bark would be possible. These conditions resulted in longer lag times in all trees regardless their biotic characteristics. However, small pines, in contrast to oaks, had higher funneling ratios for all ranges of rainfall intensity, which demonstrate that the architecture of small pines is more efficient at collecting stemflow. On the other hand, the higher bark water storage capacity of oaks in combination with low intensity and long duration events increased the content of water stored on their stems that was released slowly after the rainfall.

6. Conclusions

Stemflow produced by pine and oak forests in the Vallcebre research catchments represented only a small portion of the gross rainfall (~1%), although it may be a substantial source of water at the tree base (ranging from 0.5 ±0.6 L to 25 ±16 L per event). Stemflow volumes and funneling ratios varied greatly at the intra- and inter-storm scales and it was the result of a complex combination of biotic and abiotic factors. Stemflow increased with the event size but its variability depended on the duration of the event, the evaporative demand of the atmosphere, the rainfall intensity, the distribution of the rainfall intensity peaks along the event and on the biometric characteristics of each tree. In general, smaller trees were more efficient in funneling stemflow per unit area and time. The lag times were longer and more rainfall was required to initiate stemflow for the oak trees. These differences, between species and tree size, can partly be explained by the bark storage capacity and the effect of evaporation on stemflow. Stemflow should be taken into account when analysing infiltration processes, soil moisture dynamics and groundwater recharge in forested catchments, because, as presented here, it can be a very large point input/source of water, but its amount depends on the biotic and abiotic factors. Thus, future work should consider the variability induced by stemflow in hydrological and biogeochemical processes that occur at the tree base during rainfall events, as well as the relevance of stemflow as a locally concentrated input source of water at the catchment scale.

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FIGURE CAPTIONS

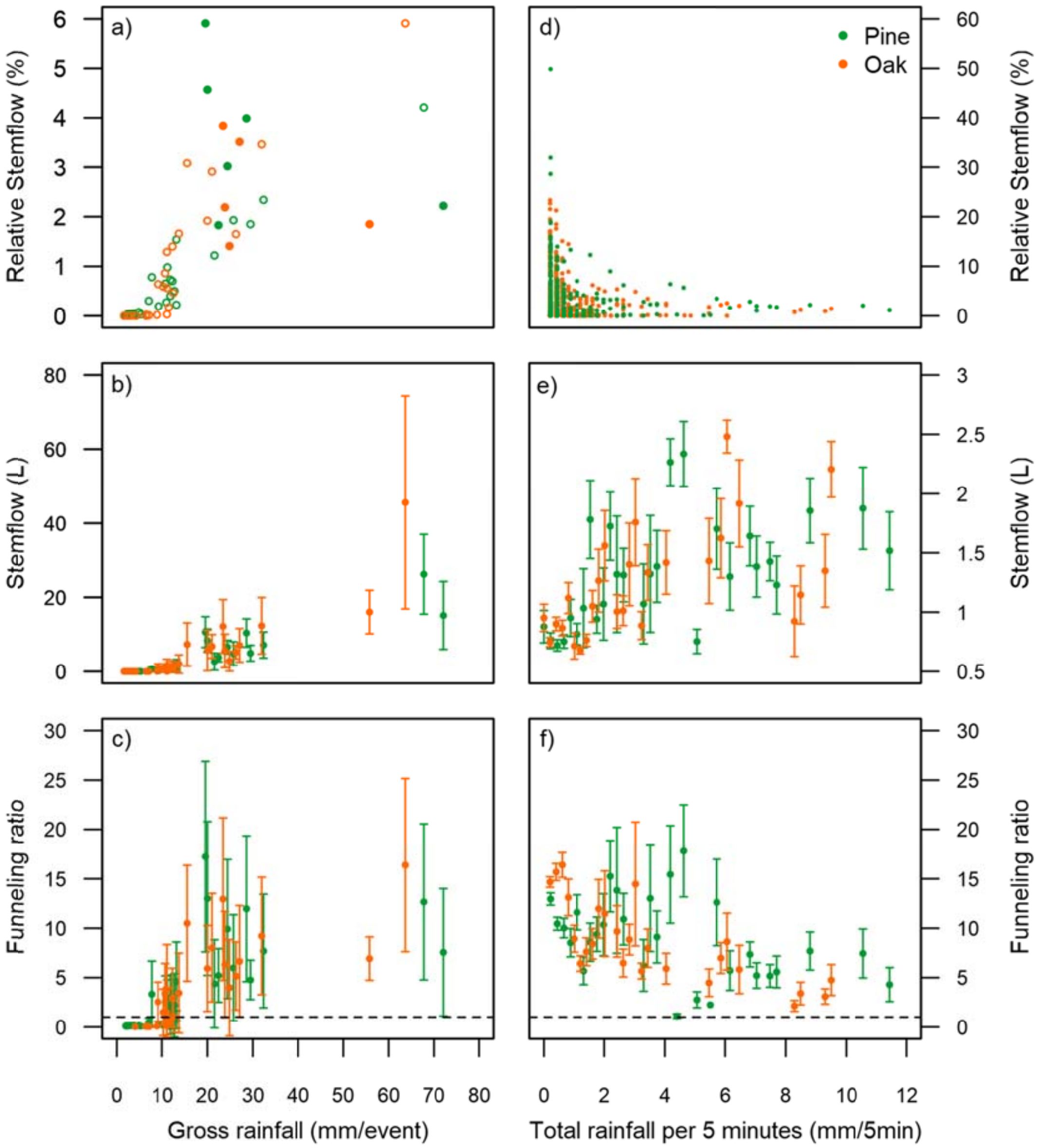

Figure 1. (Left) Relationship between gross rainfall and (a) relative stemflow ($S_{(\%R)}$), empty dots indicate events with maximum rainfall intensities in 30 minutes below 10 mm h^{-1}, and full dots above 10 mm h^{-1} (b) stemflow volume (L) and (c) funneling ratio. (Right) Relationship between total rainfall at 5 minutes interval and (d) relative stemflow ($S_{(\%R)}$) (e) stemflow volume (L) and (f) funneling ratio.

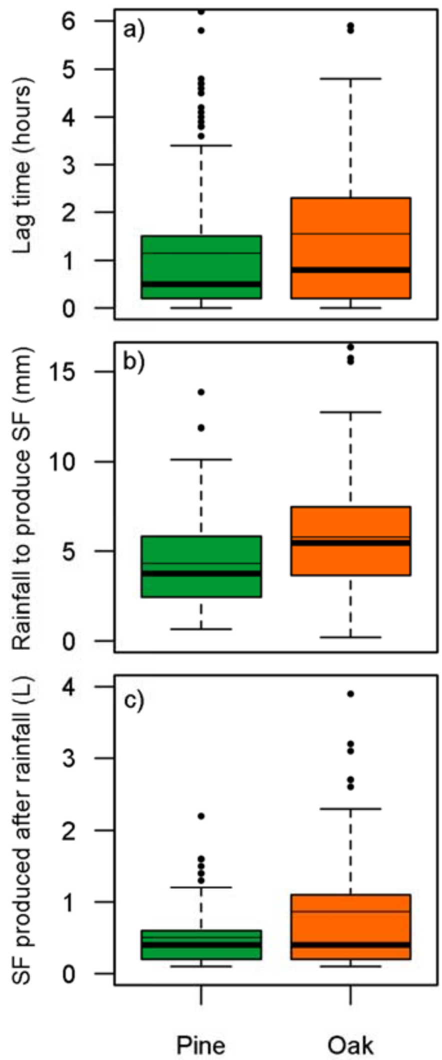

Figure 2. Box-plots (a) of the lag time between the beginning of rainfall and the beginning of stemflow, (b) of the volume of rainfall needed to produce stemflow and (c) of the stemflow produced once rainfall ended. The horizontal thick black line indicates the median, boxes correspond to the 25th and 75th percentiles, whiskers represent values that fall within 1.5 times the interquartile range and circles represent outliers. Mean values are represented with the thin black line.

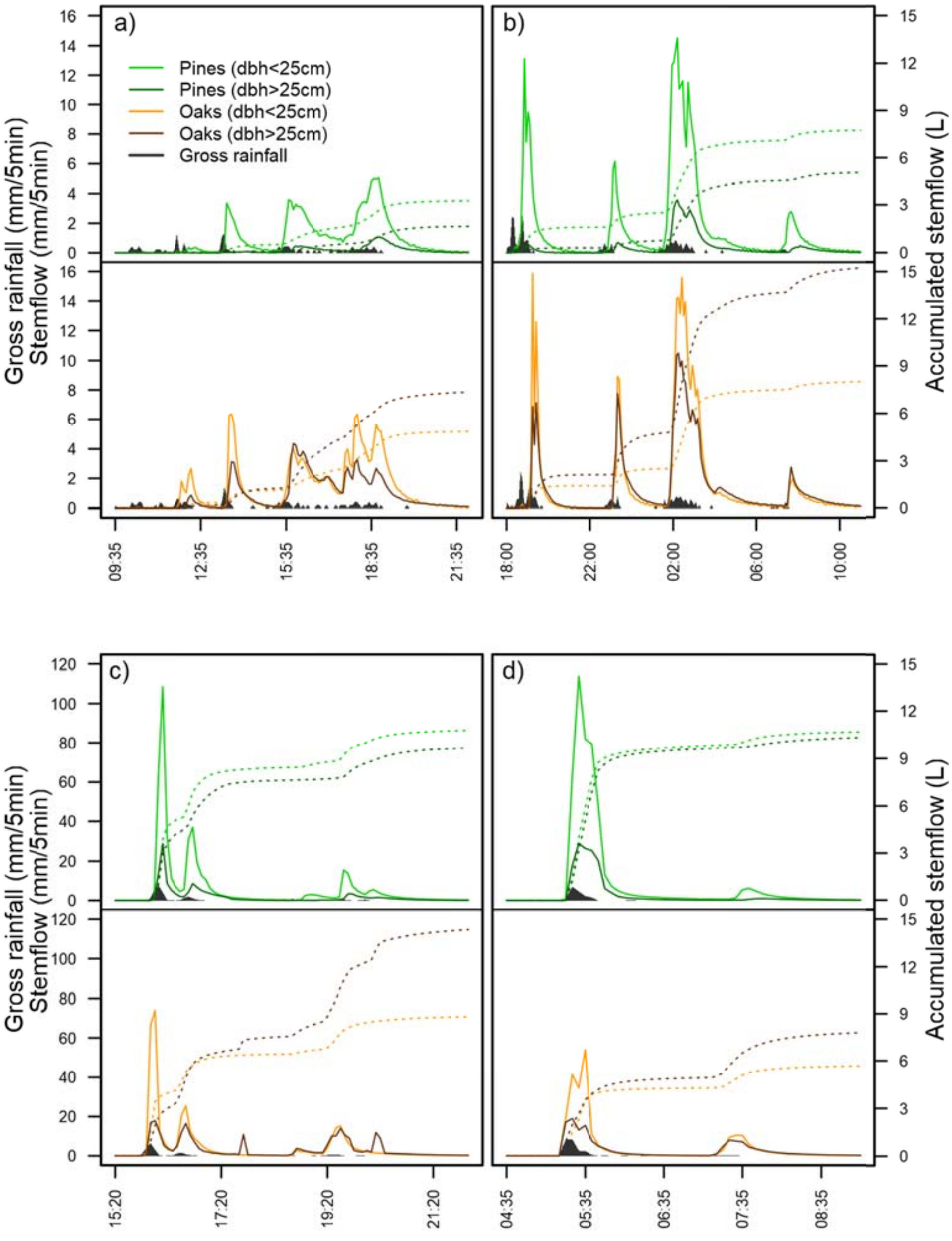

Figure 3. Time series (5-min interval) of four rainfall events. (a and b) are events of long duration and low mean rainfall intensity and (c and d) are events of short duration and high intensity. Rainfall depth is represented by a gray area, continuous lines represent the stemflow evolution in mm and the dotted lines indicate the accumulated stemflow in litres.

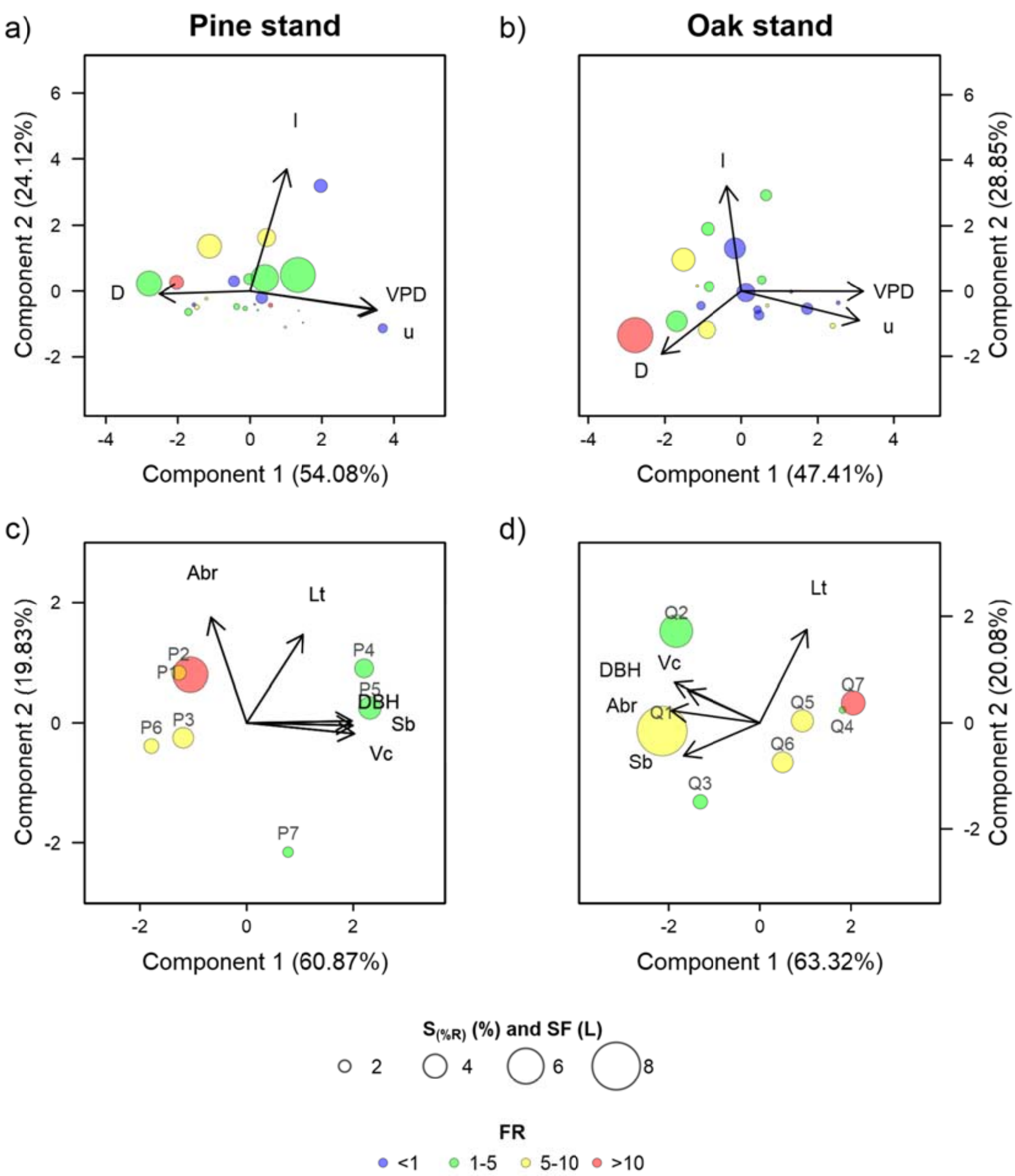

Figure 4. Bi-plots of the Principal Component Analysis (PCA). Figures a and b plot the PCA performed with the abiotic variables measured in the pine (a) and oak (b) stands. Size of circles is proportional to the relative stemflow ($S_{(\%R)}$). Figures c and d plot the PCA performed with the biotic variables measured in the pine (c) and oak (d) stands. Size of circles is proportional to mean stemflow volume produced by tree (Sf (L)). D = event duration, I = maximum rainfall intensity measured in 30

minutes, VPD = vapour pressure deficit, and u = wind speed. DBH = diameter at breast height, Vc = crown volume, Abr = mean branch angle, Sb = Bark storage capacity, and Lt = tree lean.

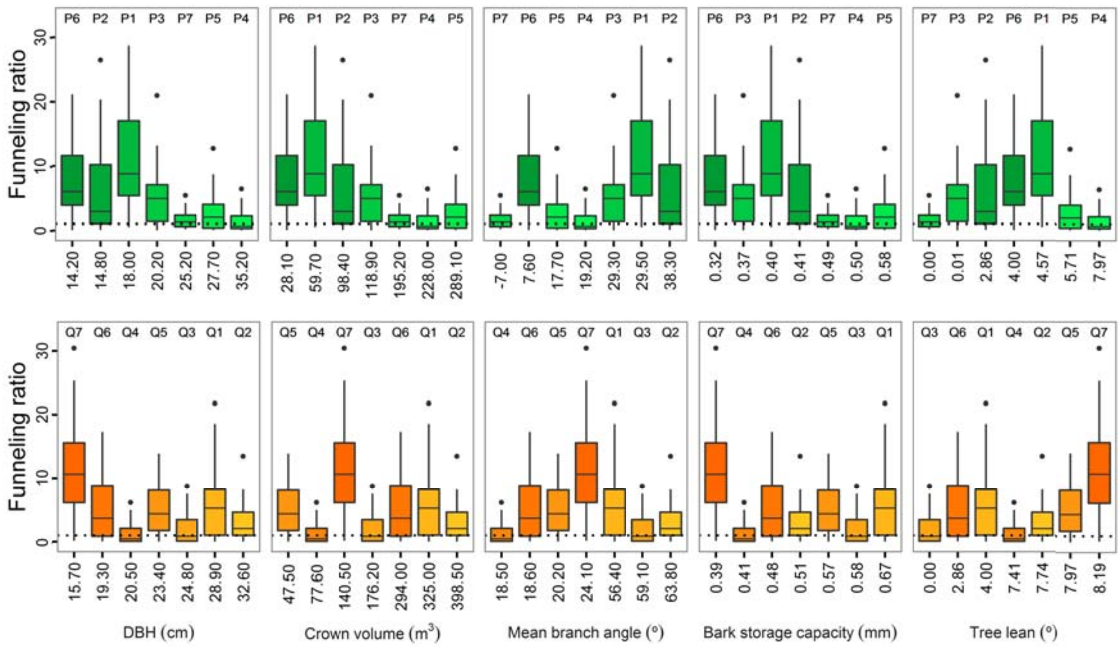

Figure 5. Box-plots of funneling ratios in relation to biotic factors for Scots pine (top) and downy oak (bottom). The horizontal black line indicates the median, boxes correspond to the first and third quartiles (the 25th and 75th percentiles), whiskers represent values that fall within 1.5 times the interquartile range and circles represent outliers. The dotted line indicates FR=1.

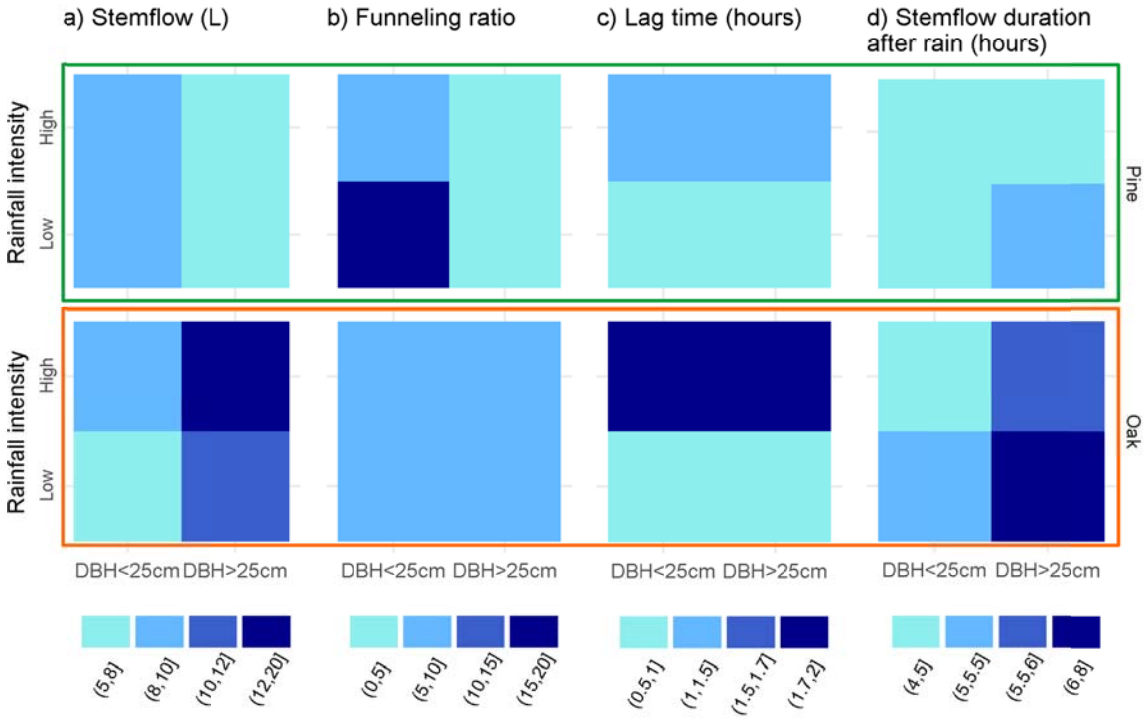

Figure 6. Relationship between rainfall intensity (Low/High), and (a) stemflow volume (L), (b) funneling ratio, (c) lag time (hours) and (d) stemflow duration after rainfall (hours), for small (DBH < 25 cm) and large (DBH > 25 cm) pine and oak trees for events of rainfall amount ≈30 mm. From light to dark, colors represent the increase of each stemflow variable studied (volume, FR, lag time and duration).

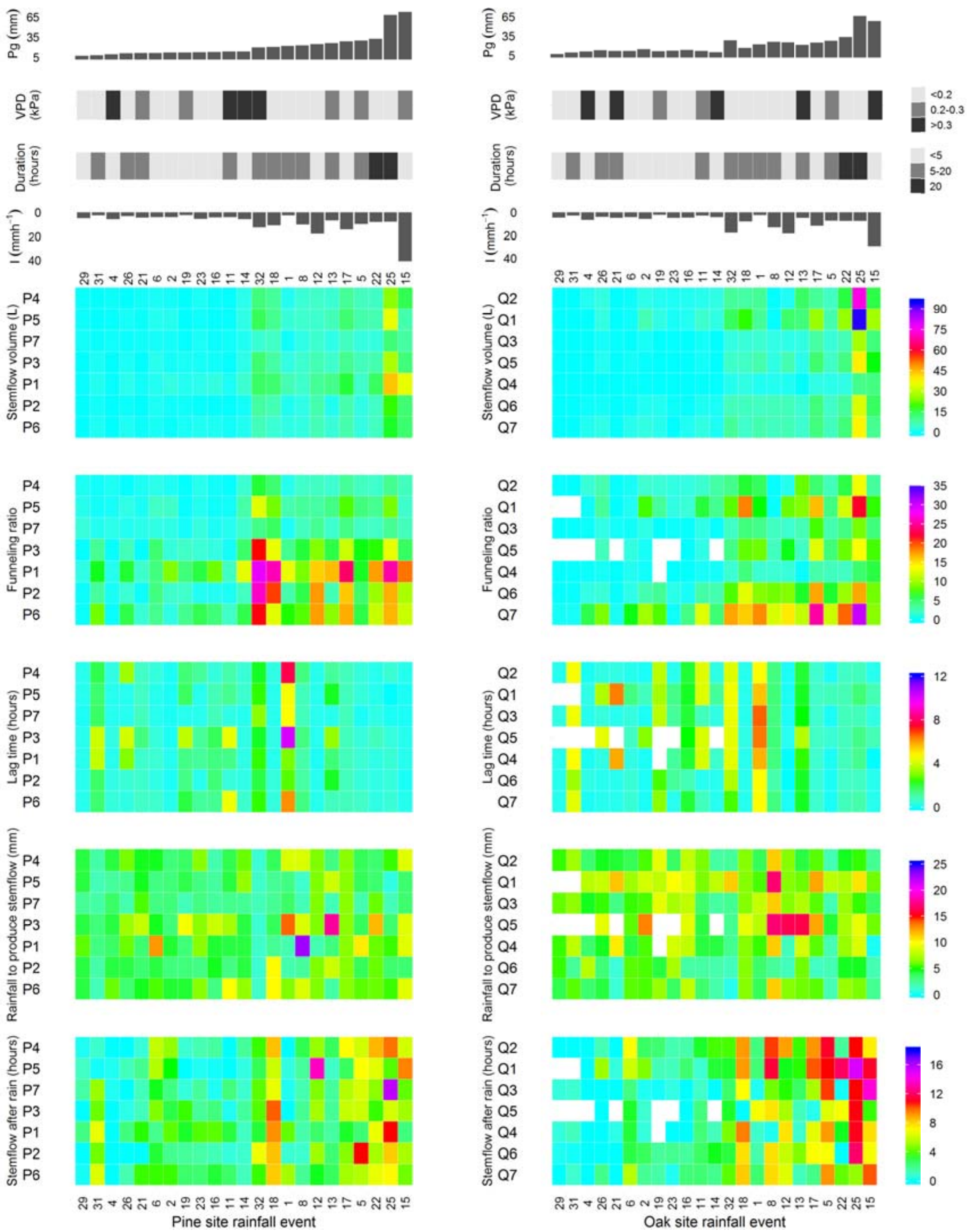

Figure A1. Tile plots for all trees and events with more than 6 mm of gross rainfall. From top to bottom: gross rainfall (Pg, mm), vapour pressure deficit (VPD, kPa), rainfall duration (hours), rainfall intensity (mm h^{-1}), stemflow volume (L), funneling ratio, lag time between rainfall and stemflow (hours), rainfall volume necessary to produce stemflow (mm) and stemflow duration after rainfall ceased (hours). Trees are ordered by DBH and events by the rainfall volume measured in the pines stand. White colours represent NA values.

Table 1. Biometric characteristics of the monitored trees.

Species	Tree number	DBH (cm)	Basal area (cm^2)	Height (m)	Crown area (m^2)	Crown volume (m^3)	Mean branch angle (°)	Mean branch diameter (cm)	Bark depth (cm)	Stem bark surface (m^2)	Bark storage capacity (mm)	Tree lean (°)
Scots pine	P1	18.0	254.5	17.5	7.5	59.7	29.5	3.1	1.5	6.3	0.40	4.6
	P2	14.8	172.0	16.9	10.8	98.4	38.3	3.3	1.5	4.9	0.41	2.9
	P3	20.2	320.5	21.2	11.9	118.9	29.3	2.8	2.1	7.3	0.37	0.0
	P4	35.2	973.1	22.3	17.3	228.0	19.2	4.4	3.3	15.0	0.50	7.9
	P5	27.7	602.6	18.3	23.8	289.1	17.7	5.6	2.9	11.0	0.58	5.7
	P6	14.2	158.4	15.5	4.7	28.1	7.6	2.1	1.0	4.7	0.32	4.0
	P7	25.2	498.8	18.1	20.1	195.2	-7.0	4.3	2.6	9.8	0.49	0.0
	Mean (+/-1 SD)	**22.2 +/-8**	**425.7 +/-292**	**18.5 +/-2**	**13.7 +/-7**	**145.3 +/-95**	**19.2 +/-15**	**3.7 +/-1**	**2.1 +/-1**	**8.4 +/-4**	**0.44 +/-0.1**	**3.6 +/-3**
Downy oak	Q1	28.9	656.0	11.7	28.0	325.0	56.4	6.2	1.8	11.6	0.67	4.0
	Q2	32.6	834.7	13.2	39.9	398.5	63.8	4.4	1.0	13.6	0.51	7.7
	Q3	24.8	483.1	15.6	13.1	176.2	59.1	5.2	0.9	9.6	0.58	0.0
	Q4	20.5	330.1	10.6	7.5	77.6	18.5	3.3	1.0	7.5	0.41	7.4
	Q5	23.4	430.1	11.2	9.1	47.5	20.2	5.1	1.1	8.9	0.57	7.9
	Q6	19.3	292.6	13.3	22.3	294.0	18.6	4.1	1.1	6.9	0.48	2.8
	Q7	15.7	193.6	10.8	13.5	140.5	24.1	3.1	0.8	5.3	0.39	8.2
	Mean (+/-1 SD)	**23.6 +/-6**	**460.0 +/-222**	**12.3 +/-2**	**19.0 +/-12**	**208.5 +/-133**	**37.2 +/-21**	**4.5 +/-1**	**1.1 +/-0.3**	**9.1 +/-3**	**0.52 +/-0.1**	**5.5 +/-3**

Table 2. Rainfall characteristics and stemflow production at 5-min interval of 4 rainfall events. Mean Pg = mean gross rainfall, Mean I = mean rainfall intensity, I_{max} = maximum peak of rainfall intensity, Duration = rainfall duration, VPD = vapour pressure deficit, $S_{(\%R)}$ = relative stemflow, DBH = diameter at breast height, Mean S = mean stemflow volume, S_{Imax} = maximum peak of stemflow intensity, Mean FR = mean funnelling ratio. P refers to Scots pine and Q refers to Downy oak.

Event	Mean Pg (mm)	Mean I (mm h^{-1})	I_{max} (mm 5min^{-1})	Duration (h)	VPD (kPa)	$S_{(\%R)}$		DBH (cm)	Mean S (L)		S_{Imax} (mm 5min^{-1})		Mean FR	
						P	*Q*		*P*	*Q*	*P*	*Q*	*P*	*Q*
a	22	1.2	1.3	18	0.12	1.2	2.9	<25	3.3	4.9	5.0	6.3	6.7	10.0
								>25	1.7	7.3	1.1	4.4	1.2	6.5
b	33	1.3	2.5	25	0.07	2.3	3.4	<25	7.7	8.0	14.5	15.9	11.5	10.8
								>25	5.1	15.2	3.6	10.5	2.5	7.9
c	26	5.2	7.7	5	0.07	3.9	3.8	<25	10.8	8.8	108.6	73.9	17.1	15.8
								>25	9.7	14.3	29.0	17.9	5.1	10.8
d	24	4.0	8.1	6	0.30	5.9	3.5	<25	10.7	5.7	113.9	54.0	24.4	9.2
								>25	10.3	7.8	29.0	19.0	7.7	4.7