Assessing canopy rainfall partitioning by Mediterranean dryland shrubs under extreme rainfall

Assessing Canopy Rainfall Partitioning by Mediterranean Dryland Shrubs under Extreme Rainfall

Running title: *Extreme Rainfall Partitioning in Mediterranean Dryland Shrubs*

Manuel Esteban Lucas Borja [1], John T. Van Stan II [2], María Dolores Carmona Yáñez [1], Carlos Alberto García López [1], and Demetrio Antonio Zema [3,*]

[1] Department of Agroforestry Technology, Science and Genetics, School of Advanced Agricultural and Forestry Engineering, Campus Universitario s/n, Castilla La Mancha University, E-02071 Albacete, Spain

[2] Department of Biological, Geological, and Environmental Sciences, Cleveland State University, 2121 Euclid Ave., Cleveland, 44115, OH, United States

[3] Department AGRARIA, “Mediterranea” University of Reggio Calabria, Località Feo di Vito, I-89122 Reggio Calabria, Italy

Corresponding Author: Demetrio Antonio Zema, Department AGRARIA, “Mediterranea” University of Reggio Calabria, Località Feo di Vito, I-89122 Reggio Calabria, Italy, dzema@unirc.it

Abstract

Intense rain events have become more frequent in some regions due to climate change, and this trend is particularly concerning in dryland regions where the ecological and geomorphological impacts of rainfall are intimately tied to its intensity. The interception of rainfall by vegetation is a critical process in the water balance of drylands; thus, this study estimated the canopy interception capacity and interception rates as well as stemflow of three typical Mediterranean shrub species (*Rosmarinus officinalis*, *Thymus vulgaris*, and *Macrochloa tenacissima*) of three size classes in Spain under a simulated extreme rainfall rate (~8 mm min^{-1}, historical return period of >100 years). Given that these plants’ canopy structures markedly differ from taller woody plants (i.e., trees), a novel method was developed to assess the stemflow fraction. Results showed significant differences in interception amount, rates, and storage capacity among the shrub species, with variations in plant morphology, such as shrub height and canopy diameter, being the key factors determining interception capacity. *R. officinalis* had the highest interception fraction per unit canopy area, or 'specific interception,' (18.4%). In contrast, the lowest specific interception fraction was measured for *M. tenacissima* (6.5%*). Thymus vulgaris* was characterized by the highest stemflow yields per unit canopy area (4.85 mm) and fraction (up to 29.6% of rainfall), which was the lowest for *M. tenacissima* (1.09 mm, ~1-4%). Strong linear correlations were found between canopy interception and shrub canopy diameter (|r| > -0.51, max = -0.90), when observations were grouped for size class. These linear correlations between shrub morphology and partitioning enabled multiple-regression linear models to be developed that predicted canopy interception and stemflow with good accuracy ($r^2 > 0.64$, with a maximum of 0.82) from shrub height, canopy diameter, dry biomass, size class, and species. Despite these measurements being conducted under one extreme storm depth and intensity, the results provide: (i) values of rainfall partitioning for important shrub species in Mediterranean dryland environments; and (ii) a simple but reliable model that may be further developed (e.g., embedding variable rainfall values as weather input or incorporating other morphological parameters) and may be integrated into complex hydrological models.

Keywords: canopy interception capacity; canopy interception rate; plant morphology; hydrological models; multiple-regression analysis; rainfall simulation.

1. INTRODUCTION

Rainfall interception is an essential process in the hydrological cycle (Arnell, 2003), as it affects the interplay between infiltration and runoff as well as soil erosion via droplet impacts and overland flow generation (Calder, 2001). This process regulates the amount of rainwater that directly falls on the ground (Muzylo *et al.*, 2009) by temporarily retaining a portion of the gross rainfall that contacts vegetation surfaces and evaporating it into the atmosphere ("interception"), while the remaining portion either falls to the ground as drops ("throughfall") or as flows down branches and stems ("stemflow"). Together, throughfall and stemflow are net rainfall (Muzylo *et al.*, 2009). Although throughfall, interception and stemflow are highly variable across vegetation structure and climate condition, their global average proportions of gross rainfall over forests are estimated as 77%, 22% and ~1% of gross rainfall, respectively (Porada *et al.*, 2018; Van Stan and Gordon, 2018; Magliano *et al.*, 2019a). These processes alter the quantity, quality, and distribution of precipitation that reaches the ground (Wood *et al.*, 1998; Van Stan *et al.*, 2020), thereby affecting the amount and spatial distribution of rainwater that enters and leaves a catchment.

Rainfall partitioning by plant canopies into these fluxes is influenced by several factors, primarily related to each storm's meteorological conditions and the canopy's architectural characteristics. Rainfall amount and intensity generally determine whether a canopy saturates and when this saturation occurs (Coenders-Gerrits *et al.*, 2020; Klamerus-Iwan *et al.*, 2020), thus influencing the fraction of rainfall that is intercepted, as well as the amount and timing of throughfall and stemflow (Sadeghi *et al.*, 2020). The amount of rainfall needed to saturate the canopy (its water storage capacity), however, is generally controlled by the canopy's leaf, branch and bark characteristics (Carlyle-Moses and Gash, 2011) and, when present, the vegetation residing on these canopy surfaces epiphytically (Mendieta-Leiva *et al.*, 2020). These same canopy architectural characteristics appear to also influence the effect of rainfall intensity by modulating in-canopy flows and storage elements, like leaf and stem water impoundments (Klamerus-Iwan *et al.*, 2020). Results from indirect investigations of canopy-rainfall interactions applying multivariate statistical approaches to include other storm variables, like wind characteristics and atmospheric moisture demand (i.e., vapour pressure deficits), suggest that such variables influence rain amount- and intensity-driven interactions with canopy structure (Van Stan *et al.*, 2014, 2017).

Climate change is altering rain events and their partitioning by plant canopies in ways relevant to ecosystem functioning (Di Nuzzo *et al.*, 2022; Lian *et al.*, 2022), thus, much research has explored rainfall interception. However, interception research has been overwhelmingly focused on forest environments (Carlyle-Moses and Gash, 2011; Levia *et al.*, 2019), while croplands, shrublands, and grasslands have received less attention (Belmonte Serrato and Romero Diaz, 1998; Dunkerley, 2000; Snyder *et al.*, 2022). This is surprising as shrublands account for a meaningful fraction of land cover, ~11% (Ritchie and Roser, 2013), shrubs can compose a substantial fraction of understory communities in many forests (Sun *et al.*, 2022), shrub encroachment is a global area of research interest and conservation concern (Maestre *et al.*, 2016), and the interception by shrubs can be even greater compared to forest stands within a given area. This demonstrates that shrubs may have a similar influence as trees on the local water cycle (if not larger). Still, the paucity of data on shrub interception to date suggests that rainfall interception by shrubs plays an important role in ecohydrological processes of arid or semi-arid ecosystems, which cover 40% of the Earth's surface (Zhang *et al.*, 2017). Examining shrub interception for dryland ecosystems is, therefore, likely to inform our understanding of drylands ecosystem services (Maestre *et al.*, 2012; Magliano *et al.*, 2019a).

Mediterranean regions contain substantial drylands with shrub cover; however, a review of 90 papers on vegetation interception in this region concluded that only 11% of studies focused on shrubs or bushes (Llorens and Domingo, 2007; Zhang *et al.*, 2015). This is a problematic knowledge gap for the Mediterranean, as water is a limiting factor that controls plant productivity and economic development in this region (Dunkerley, 2000; Zhang *et al.*, 2017) yet annual rainfall interception by dry shrublands exhibits large variability, ranging from 3% to 37% (Zhang *et al.*, 2017). A major reason for this knowledge gap is that obtaining accurate interception data for various shrub species (and herbaceous species) is difficult due to the challenges in measuring interception flows (Díaz and Serrato, 1994; Belmonte Serrato and Romero Diaz, 1998; Gordon *et al.*, 2020). Still, this magnitude and uncertainty in shrubland interception indicates that studies seeking to improve understanding of this topic may yield valuable insights into semi-arid and arid ecosystem hydrology (Zhang *et al.*, 2017). Accurate estimation of interception by shrubs may also aid in efforts to predict water flow dynamics, sediment movement, vegetation growth, and impacts of vegetation restoration on stream flow and water quality. Constraining the uncertainty in shrubland interception processes may also inform global climate change scenarios (Gutmann, 2020).

In Mediterranean Spain, climate change scenarios project alarming alterations to rainfall frequency and intensity, with the latter being a critical factor in determining whether a storm is beneficial or hazardous (Camarasa-Belmonte *et al.*, 2020). Multiple studies have shown an increasing trend in meteorological conditions that can result in extremely intense rainfall events (Sumner *et al.*, 2003; Cantos, 2017; Camarasa-Belmonte *et al.*, 2020; Ferreira, 2021; Llasat *et al.*, 2021). Global circulation models suggest greater frequency of severe thunderstorms in the region due to increased incidence of moist easterly atmospheric flows (Sumner *et al.*, 2003), and recent rain intensity observations indicate that this has occurred (Camarasa-Belmonte *et al.*, 2020). These atmospheric flows can intersect with upper-tropospheric cut-off low systems, locally called 'gota fría', which can generate intense and widespread rain episodes (Porcù *et al.*, 2007)—and have been attributed to ~1/3 of the catastrophic floods on record for the region (Llasat *et al.*, 2007). Recent projections suggest that cut-off lows and related extreme rainfall may increase in frequency by 60-80% for the region (Ferreira, 2021). A warming climate also contributes to increased convective activity, resulting in more intense rainfall, concentrated in fewer, more extreme events, across Mediterranean Spain (Llasat *et al.*, 2021). Given these alarming current and projected meteorological conditions, there is a need for research on the response of the region's shrubland ecohydrology. As the shrub canopy is literally at the forefront of rainfall intensification, understanding the shrub interception response to intense rainfall is of particular interest.

To begin addressing these fundamental knowledge gaps, this study estimates the rainfall interception of three shrub species (*Rosmarinus officinalis*, *Thymus vulgaris* and *Macrochloa tenacissima*) that are typical of the Mediterranean semi-arid landscape in Castilla La Mancha (Central Eastern Spain). The interception estimates are based on observations during simulated rainfall at high intensity and, then, associated with major morphological characteristics of each study species. Stemflow is rarely examined for shrubs, especially grassy shrubs, due to the physical difficulties of collecting water at the base of the canopy—which is immediately above the ground (Sadeghi *et al.*, 2020). However, the limited data available suggests that woody and grassy shrubs are capable of substantial stemflow generation (exceeding 50% of rainwater across the canopy, (Sadeghi *et al.*, 2020). Thus, a novel method was developed where measurements were taken from two simulations; first, with an impermeable sheet fit around the stem that left a gap of open soil for the stemflow water to infiltrate; then, with this sheet-stem gap being sealed. The difference allows estimation of stemflow. Simple prediction models are also developed using multiple regression analysis. To the authors' knowledge, while interception magnitudes for *R. officinalis* and *T. vulgaris* have been previously studied by Belmonte Serrato and Romero Diaz (1998), this process has never been explored with reference to plant morphology for all study species. Furthermore, no previous investigations have estimated interception for *M. tenacissima*, and for *R. officinalis* and *T. vulgaris* under extreme rainfall.

2. MATERIALS AND METHODS

2.1 Study area

The investigation was carried out in a shrubland close to the municipality of Villamalea (39,36422° N, −1,59689° E, province of Albacete, region of Castilla La Mancha, Spain) (Figure 1).

1. [Insert Figure 1]

The climate of the area, typically Mediterranean, can be classified as “Csa” type, according to the Köppen-Geiger classification (Kottek *et al.*, 2006). The mean rainfall is 407 mm per year and the mean temperature is 14 °C, according to the historical data of the last 20 years, recorded at the nearest weather station (Hellín) by the Spanish Meteorological Agency (AEMET). Rainfall is mainly concentrated in spring and autumn, and a long dry period occurs in summer (usually from June to September). These dry climate conditions reduce the natural vegetation cover in the landscape.

Elevation of the area, a flat terrain that is typical for the Iberian Plateau (Meseta), is close to 765 m a.s.l. The natural tree vegetation mainly consists of *Pinus pinea* L. and *Pinus halepensis* M. The main shrub species are *Rosmarinus officinalis* L., *Thymus vulgaris* L., and *Macrochloa tenacissima* (L.), but *Brachypodium retusum* (Pers.) Beauv., *Lavandula latifolia* Medik., *Quercus coccifera* L. and *Plantago albicans* L. are also present. The mean density/cover of the three shrub species examined in this study is ~2.5 plants m^{-2}. According to the Soil Map of the World of FAO-UNESCO (FAO-UNESCO, 1981) and the International Soil Classification System proposed by IUSS Working Group WRB (WRB-IUSS, 2015), the prevalent soils are *Calcic cambisols* with sandy-clay-loamy texture over a limestone parent material and an average organic matter content of 1.1 g dm^{-3}.

2.2 Experimental design

Canopy rainfall interception under extreme rain intensity was measured for *R. officinalis*, *T. vulgaris*, and *M. tenacissima* using a rainfall simulator (see section 2.3) and according to the experimental procedure depicted in Figure 2. The frame of the rainfall simulator was placed over the ground supporting an individual of each species on a surface area of 0.33 m x 0.33 m (the net area receiving simulated rainfall is 0.1089 m^2). Care was taken to avoid disturbing the soil and its cover. Attention was paid to ensure that all simulated rainfall fell onto the runoff collecting device, placing a plastic screen close to each side of the simulator (but outside of the plant canopy). These screens also avoided wind disturbance to the rainfall drops. For plants having larger canopy area compared to the rainfall area, the centres of simulator frame and plant horizontal projection were made coincident. In this case, the plastic screens contained all the plant canopy; however the canopy edges were unavoidably pushed slightly against these plastic sides. For plants with smaller canopy, the experiment was carried out on sites with no more than one individual per species.

[Insert Figure 2]

Two series of rainfall simulations (hereafter S_1 and S_2) were carried out on the same plant individual, to measure separately throughfall and stemflow.

To both prevent infiltration of simulated rainwater and divert the portion of water that reached the surface to a collection system, a thin plastic sheet was first weighted and then placed over the ground inside the frame of the simulator and around the plant stem. In the S_1 series, the plastic sheet was placed, caring that stemflow could infiltrate (Figure 3). In the S_2 series, the sheet was sealed around the plant stem using silicone, in order to convey also the stem flow to the collection system. After rainfall simulation, the plastic sheet and screens were carefully removed and weighed, in order to estimate the fraction of water stored (e.g., due to the presence of folds and small ponds on ground) and not diverted to the collecting device. Five experiments of rainfall simulation were carried out for each species.

2.

3. [Insert Figure 3]

2.3 Simulations of extreme rainfall

The rainfall rate applied in this study represents observed extrema reported in past literature (Quinn and Laflen, 1983; Carlyle-Moses and Gash, 2011; Lin *et al.*, 2011; Zheng *et al.*, 2012, 2018; Ma *et al.*, 2016). Importantly, extreme rainfall rates are difficult to observe for various reasons. Principally, extreme rainfall rates can damage equipment due to accompanying hazards (like wind and lightning) or flooding. If rain gauges are able to collect observations through periods of extreme rainfall, these observations suffer from substantial under-catch—especially for the more affordable gauge designs that rely on tipping bucket mechanisms

(Duchon and Biddle, 2010; Duchon *et al.*, 2014; Pollock *et al.*, 2018). Still, throughout Mediterranean Spain, extreme rainfall rates are being more frequently recorded (Camarasa-Belmonte *et al.*, 2020). In the Prebaetic Mountains near the southern coastline, Mount Aitana (1558 m) can experience rainfall rates that surpass 800 mm in 24 h (Peñarrocha *et al.*, 2002). In Júcar (Cuenca, Spain), rainfall rates have been observed to reach 1000 mm in 24 h (Llasat *et al.*, 2021). Of course, this extreme rainfall rate is not consistent for 24 h. Rather, it varies throughout the storm and, according to a recent analysis of high temporal resolution (5-min) rainfall observations in the eastern Iberian Peninsula, rainfall rates may reach sustained intensities that exceed 35 mm in a 5-min period. Thus, we selected an extreme rainfall rate near this maximum that was achievable using an off-the-shelf rainfall simulator: 36 mm over 4.5 minutes. This equates to a mean intensity of 432 mm h^{-1}—an intensity with a historical return period of >100 years in the studied area, simulating an extremely heavy event, as representative of a worst-case scenario for the study area (Lucas-Borja *et al.*, 2022).

In each experiment, artificial rainfall (raindrop size of 5.9 mm) was produced using an Eijkelkamp® rainfall simulator from 40 cm height over the top canopy of plants (Iserloh *et al.*, 2013; Hlavčová *et al.*, 2019), and the resulting surface runoff was measured.

Both rainfall simulations and surface runoff measurements were done according to the methodology proposed by Carrà *et al.*, (2021) and Lucas-Borja *et al.* (2022), where more details can be found. To summarize, a hole was dug in the experimental area, where a small bucket was placed to collect runoff water. The frame of the simulator was then installed upslope of the hole. A gutter, installed downslope of the frame, conveyed all runoff into the bucket. The sprinkler, whose tank was filled with 2.2 L of clean water, was ten placed on top of the frame, for the immediate rainfall simulation. During the rainfall simulation, the runoff volume was measured at every 30 s with a meterstick. The experiment ended 30 s after the end of rainfall, when no more runoff was coming into the bucket. In S_1 series, the interception was estimated by subtracting the instantaneous runoff from gross rainfall. Then, the interception graph was built, reporting the flow rate over time.

2.4 Estimation of canopy rainfall interception and its components

Rainfall interception, throughfall and stemflow are reported at various scales, yet studies must take care that the observations recorded from *specific* study plants in an experimental setting—like *specific* water storage capacity of an individual canopy or canopy component—

be scaled to representative landscape values—actual water storage capacity of the plant community—to enable study intercomparison (Klamerus-Iwan *et al.*, 2020) and integration of scaled results into modelling efforts (Gutmann, 2020). In this study, which was performed at the individual shrub scale, volume observations for precipitation (P_V, [L] and runoff (R_V, [L] were recorded. Then, the volume of interception (I_V, [L] was calculated as the difference between P_V and R_V in the S_2 series of rainfall simulations. The specific interception of the study plant (Is [mm]) was calculated dividing I_V by C, and its fraction [%], was estimated as:

$$I_S = I_V/(P \times C) \quad (1)$$

where P is the simulated precipitation amount [36.8 L m^{-2}] and C is the canopy area of the study plant [m^2] over which the simulation was conducted.

Rainfall intercepted by the plant canopies per m^2 at the landscape scale, I_C, was estimated based on the plant density [2.5 plants m^{-2}]. First, assuming each experimental shrub represented the 2.5 plants m^2 of the landscape, the projected plant canopy cover [PC, m^2 canopy area per m^2 ground area] was estimated by multiplying the experimental shrub canopy area [m^2 plant^{-1}] by the plant density. The total amount of rainfall supplied to PC within a single m^2 of landscape area (P_{PA}, [L]) could then be estimated by multiplying this PC by P. The product of P_{PA} and I_S results in a volume of water intercepted within 1 m^2 of the landscape (I_C [mm]).

The same process was applied to the estimation of stemflow from the second simulation. Unscaled stemflow (SF, [L]) was calculated as the difference between the surface runoff collected in S_1 (equal to throughfall) and S_2 (equal to throughfall and stemflow) series, respectively. Its specific value (SFs, [mm]) was determined as for Is. The fraction of SF_C on P ([%]) as well as the landscape-scale stemflow (SF_C) were also calculated. Specific throughfall fraction (TF_S, [%]) was then estimated as the total recovered rainfall minus the stemflow, divided by P.

2.5 Measurement of shrub morphology

The following morphological parameters for the surveyed plant individuals were measured: total height (cm), canopy diameter (cm), dry biomass (g). Canopy area was estimated by considering its horizontal projection as an ellipse, of which we measured the shortest and the longest axes by a meterstick. The meterstick was also used to manually estimate plant height. For plants having canopies larger than area receiving simulated rainfall, the latter was considered equal to the canopy area as the canopy was constrained to the simulation area. After the rainfall simulations, each plant was cut (therefore, with a destructive sampling) and brought to the laboratory. Leaves and branches were dried in oven, and dry biomass was determined by weighing after at least 48 h at 72 ° C.

Plant size was classified in small (*R. officinalis* height < 30.0 cm; *T. vulgaris* height < 20.0 cm; *M. tenacissima* height < 35.0 cm), medium (*R. officinalis* height between 30.0 cm and 40.0 cm; *T. vulgaris* height between 20.0 cm and 35.0 cm; *M. tenacissima* height between 35.0 cm and 50.0 cm) and large (*R. officinalis* height between 40.0 cm and 42.2 cm; *T. vulgaris* height between 35.0 cm and 51.0 cm; *M. tenacissima* height between 50.0 cm and 68.5 cm).

2.6 Statistical analysis

A two-way ANOVA was applied to the measurement of interception, stemflow and throughfall (unscaled, landscape scale, and fraction values) , in order to evaluate statistically significant differences among the three species according to the size. I_S, I_C, $I_{\%}$, SF_S, SF_C, $SF_{\%}$, and $TF_{\%}$ were the response variables, while species and size were the independent factors of ANOVA. Whenever significant differences were identified for a given variable, a Tukey's test (at $p < 0.05$) was used to identify which species and size were different. Prior to the ANOVAs, normality and homogeneity of variance were evaluated by Shapiro-Wilk's and Levene's tests, respectively. When the tests were not satisfied, the data were square root-transformed prior to re-running the ANOVAs.

Moreover, a Pearson's correlation analysis was carried out between I_0 on one side and one of the morphological characteristics of plants on the other side.

Finally, multiple-regression prediction models between $I_{\%}$, SF%, and $TF_{\%}$ (predicted variables) and these morphological characteristics (predictors) were setup, and the predictions were evaluated for "goodness-of-fit" with the corresponding observations using a scatterplot and the coefficient of determination (r^2, ranging from zero, in the case of no agreement between model and data variance, to one, for perfect agreement (Parhizkar *et al.*, 2021)). All statistical analyses were carried out using the XLSTAT 2019 software (Addinsoft, Paris, France).

3. RESULTS

3.1 Shrub morphological variability

The two-way ANOVA revealed that all the surveyed morphological parameters were significantly different among the three species ($F < 42.035$, $p < 0.0001$), size classes of plants ($F < 314.024$, $p < 0.0001$) as well as interaction between these two factors ($F < 10.321$, $p < 0.0001$). Regarding the plant size, as expected, height, canopy diameter and dry biomass followed the pattern: small < medium < large for all species. On average, *M. tenacissima* had the highest height and canopy diameter (48.1 ± 0.78 cm and 39.9 ± 0.62 cm, respectively), while the highest dry biomass was measured for *T. vulgaris* (60.9 ± 1.12 g). Height (31.7 ± 0.79 cm) and canopy diameter (23.8 ± 1.16 cm) were the smallest for *T. vulgaris* and *R. officinalis*, respectively, while the latter species evidenced the lowest dry biomass (51.4 ± 0.61 g) (Figure 4).

4. [Insert Figure 4]

3.2 Shrub partitioning of extreme rainfall

The (unscaled) specific interception, throughfall and stemflow fractions (I_S, SF_S, and TF_S [%]) for any study shrub varied significantly among the three species ($F < 9.590$, $p < 0.0001$), size ($F < 6.293$, $p < 0.0001$), while the interaction between these factors was significantly different only for SF_S ($F = 4.332$, $p < 0.01$). The interception and stemflow magnitudes (I_S and SF_S [mm]) were also different significant among the three species ($F < 9.590$, $p < 0.0001$) and size ($F < 8.066$, $p < 0.0001$). The interaction between these factors was significant only for SF_S ($F = 4.332$, $p < 0.01$).

Regarding unscaled values derived from individual plant canopies of all species and canopy size, interception volumes ranged from 40 – 720 mL over the simulation period. This volume of intercepted rainwater equated to a specific interception magnitude of 0.18 – 1.11 mL cm^{-2} of projected canopy area and an I_S ranging from 4.9 – 30.1%. This was generally highest for *R. officinalis*, with the greatest mean ± SE I_S being observed for the moderate-sized shrub (18.4 ± 3.8%) and was generally lowest for the *M. tenacissima* with the smallest-sized shrub producing a mean I_S of 6.5 ± 0.5%. *Thymus vulgaris* showed a relatively intermediate value that was consistent across sizes (13.7 ± 0.8%), yet this species produced the largest mean specific stemflow fraction, 13.6%, and the greatest variability in stemflow across shrub sizes, ± 22.2% (Figures 5 and 6). In fact, a statistically significant gradient in specific stemflow yield was found for *T. vulgaris* (4.85 ± 0.76 mm) > *R. officinalis* (3.37 ± 0.43 mm) > *M. tenacissima* (1.09 ± 0.09 mm), which, furthermore, was significantly higher on small plants compared to both medium and large individuals. The maximum stemflow was measured for medium-size plants of *T. vulgaris* (6.17 ± 1.21 mm), while the minimum value was detected for small plants of *M. tenacissima* (0.89 ± 0.11 mm) (Figure 5). As a result of the generally large specific fraction of interception and stemflow, *T. vulgaris* exhibited the lowest specific throughfall fractions. The largest specific throughfall fractions were indirectly estimated for *M. tenacissima*, which had low stemflow and interception (Figure 6).

5. [Insert Figure 5]
6.
7. [Insert Figure 6]
8.

Landscape-scale estimates of interception (I_C) and stemflow (SF_C) varied significantly among the three species ($F < 11.570$, $p < 0.0001$), size ($F < 39.461$, $p < 0.0001$), while its interaction was significantly different only for I_C ($F = 7.391$, $p < 0.0001$). In more detail, I_C increased with increasing canopy size for all shrub species. The larger canopy diameters of *M. tenacissima* (Figure 3) enabled this species to produce the largest I_C values for two size classes, being 0.50 ± 0.19 mm (small) and 1.24 ± 0.22 mm (medium). The large shrubs for *M. tenacissima* and *T. vulgaris* were similarl in their I_C magnitudes, being 1.55 ± 0.27 mm and 1.59 ± 0.23 mm, respectively. Small *R. officinalis* produced the lowest I_C, being 0.17 ± 0.03 mm; yet, this was similar to the small *T. vulgaris* shrub estimate of 0.19 ± 0.02 mm. Medium-sized *R. officinalis* and *T. vulgaris* shrubs produced I_C magnitudes around 0.6-0.8 mm (Figure 7).

9. [Insert Figure 7]

3.3 Interception modelling for shrub species and size

All the surveyed morphological parameters showed high, positive and significant correlations each other. The values of r were 0.94 (height vs. canopy diameter), 0.81 (height vs. dry biomass), and 0.71 (canopy diameter vs. dry biomass).

The separate analysis of the linear correlations between each shrub characteristic and the (unscaled) specific interception, throughfall and stemflow fractions (I_S, SF_S, and TF_S [%]) for plant size class confirmed high and significant values for both height (with a maximum absolute value of 0.91 for small plants in the case of TF_S) and canopy diameter (peak of 0.92 for large shrub, again in the case of TF_S), while low coefficients of correlation were again found between these values and dry biomass (in the range -0.46 to 0.50). When the correlation analysis was carried out for plant species, SF_S, and TF_S were highly correlated only to *T. vulgaris* species (r between -0.71 and 0.60 for canopy diameter, and between -0.71 and 0.60 for dry biomass, while the correlation with height was noticeable for canopy diameter, r = -0.71, and for dry biomass, r = 0.61, but low, r = 0.21, for I_C), while the correlations for the other species were always very low and non-significant ($|r| < 0.50$) (Table 1).

10. [Insert Table 1]

The multi-regression analysis proposes linear equations to predict I_S, SF_S, and TF_S from two of the surveyed plant morphological parameters (height and canopy diameter) as well as the size class and species. These equations assume the following structure:

I_S (%) = 31.450 x Height - 0.65 x Canopy diameter + 0.16 x Dry biomass + 15.265 x Species(*M. tenacissima*) + 2.365 x Species(*R. officinalis*) + 14.692 x Size(Large) + 11.340 x Size(Medium) (2)

SF_S (%) = 28.41 + 0.219 x Height - 1.077 x Canopy diameter + 1.160 x Species(*M. tenacissima*) - 6.925 x Species(*R. officinalis*) + 10.451 x Size(Large) + 7.188 x Size(Medium) (3)

TF_S (%) = 38.670 + 0.444 x Height + 1.768 x Canopy diameter - 0.182 x Dry biomass - 18.028 x Species (*M. tenacissima*) + 4.303 x Species(*R. officinalis*) - 25.078 x Size(Large) - 18.701 x Size(Medium) (4)

where species (*R. officinalis*), species (*M. tenacissima*), size class (Medium) and size class(Large) are equal to one for the corresponding species or size class and zero otherwise. The analysis of goodness-of-fit of this model shows a r^2 of 0.642 for Eq. (2), 0.793 for Eq. (3), and 0.823 for Eq. (4), which means that these equations have an acceptable to good accuracy in reproducing I_S, SF_S, and TF_S from morphological characteristics of plants. The related scatterplot also shows how most of the pairs of observations vs. predictions of I_S, SF_S, and TF_S are close to the line of perfect agreement (Figure 8).Moreover, only two pairs (one for I_S and one for SF_S) are out of the confidence interval.

11. [Insert Figure 8]

4. DISCUSSION

4.1 Shrub canopy rainfall interception under an extreme storm intensity

The study's findings demonstrate that shrubs with varying canopy structures can intercept a significant portion of rainfall per unit canopy area (up to28%) during a simulated extreme storm intensity in a Mediterranean dryland site in Spain. However, we note that this is a localized estimate, specific to the shrub canopies themselves—not a value achieved at the landscape scale. Still, this is particularly relevant in semiarid and arid shrublands of the Mediterranean region where large storms with high intensity and short duration can lead to the highest hydrological and erosive responses of soil and vegetation (Lucas-Borja *et al.*, 2020). Therefore, the regulation of extreme rainfall and localized runoff and erosion events may be mitigated by shrubland interception. Although rainfall simulation experiments are not exactly representative of spatial and temporal variability of precipitation, they are one of the most common methods to measure interception (Iserloh *et al.*, 2013) and allow estimation of the amount of rainwater intercepted by plant individuals where field methods are extraordinarily challenging (like beneath shrub canopies). The extreme rates typically produced by rainfall simulators have been (rightly) criticized for not representing realistic rain event properties under typical conditions (Dunkerley, 2008, 2021); however, this study demonstrates how these simulations may be useful in assessing the response of vegetation (and localized soils) to the extreme rainfall conditions projected for some regions under climate change (and increasingly observed in Mediterranean Spain) (Duchon and Biddle, 2010; Duchon *et al.*, 2014; Pollock *et al.*, 2018; Camarasa-Belmonte *et al.*, 2020; Llasat *et al.*, 2021). Additionally, these experiments can help to identify associations between the canopy interception capacity, the size, and the species of the shrubs.

Several authors have also measured canopy interception fractions from shrub canopies that were in a similar range to those estimated our study, with values ranging from 3% to 28% and high variability due to rainfall and plant characteristics. For instance, Belmonte Serrato and Romero Diaz (1998) reported an interception fraction of 22.5% for *R. officinalis*, while Magliano *et al.* (2019) found an average value of 9.4% for 68 woody plant species in drylands. Additionally, Zheng *et al.* (2018) showed that the measured interception fraction of maize was on average 12.6% of cumulative gross rainfall during the whole growing season. Finally, interception fractions of *Caragana korshinski* were highly variable according to available studies, ranging from 11.7% (Wang *et al.*, 2005) to 28% (Jian *et al.*, 2012).

At the landscape scale, the fraction of interception for shrublands can significantly decrease when a sparse shrub density results in partial canopy cover. In our study, the scaled interception magnitudes ranged from 0.1 – 1.8 mm event^{-1}, which reduces landscape scale interception fraction to 0.3 – 5.0% and, thereby, severely limits the benefit of shrub interception at this scale. This interception fraction agrees with previous work showing that the intensity of rainfall significantly decreases the interception fraction—resulting in substantial decreases in rainfall interception across all canopies regardless of vegetation attributes (e.g., Lian et al., 2022). This may be due to the rapid overwhelming of the shrubland canopy water storage capacity. Storage capacity estimates from past literature agree well with the range of landscape-scale interception losses reported here.

For example, in Mediterranean conditions, Garcia-Estringana *et al.* (2010) found S_C values of 0.35 to 3.24 mm for *Medicago strasseri* and *Lavandula latifolia*, respectively. In tallgrass prairie, Zou *et al.* (2015) reported highly variable S_C values of shrub species, ranging from 0.27 mm (early growing season) to 3.86 mm (senescence). The canopy interception capacity of *Hippophae rhamnoides* and *Syringa pubescens* ranged from 1.07 to 1.28 mm and from 0.88 to 1.07 mm, respectively (Zhang *et al.*, 2017). Yang *et al.* (2019) reported interception losses for *Caragana intermedia* in the range of 0.1 mm to 3 mm, with an average value of 1 mm.

Since shrub size significantly affects aspects of canopy rainfall interception process for these species (which plays important ecosystem regulatory roles), future work may benefit from more directly assessing the S_C for these shrubs under extreme rainfall intensities.

Indeed, observations and estimates of rainfall interception shows a large variability that depends on weather characteristics and plant morphology (Zhang *et al.*, 2017). However, accurately quantifying interception remains a challenge due to the indirect estimation of related fluxes by subtracting throughfall and stemflow from gross rainfall, resulting in large errors in estimated net rainfall values (Zhang *et al.*, 2015; Magliano *et al.*, 2022). In this study, we employ a relatively novel approach to disentangling the throughfall and stemflow contributions during rainfall simulations (i.e., the sealing of the impervious sheet to the stem base after an initial simulation). Stemflow estimates generated agree with those from previous work, ranging from ~2% to 30% of simulated rainfall (Belmonte Serrato and Romero Diaz, 1998; Shou *et al.*, 2017; Magliano *et al.*, 2019a, 2019b, 2022; Yue *et al.*, 2021; Zhang *et al.*, 2023). These stemflow estimates agree with past reviews of stemflow across plant functional types, showing that shrubs often generate greater stemflow fractions than other woody plants (Sadeghi et al., 2020). The higher stemflow rates observed in this study may offset the local interception benefits under extreme rainfall by increasing erosion at the stem base (Dunkerley, 2020). If large stemflow fluxes were running off at the stem base, this may have underestimated stemflow fluxes due to a portion of this water not infiltrating at the stem base (as assumed). Moreover, measurements of interception over long time scales (typically a season or a year) are less problematic than estimations at the event scale, which are affected by high variability over short periods (e.g., the intensity and angle of rainfall, and wind speed and direction, Crockford and Richardson, 2000). Still, future work focused on shorter time scales and simulations that align with projected climate changes may yield important insights.

4.2 Variability in canopy rainfall interception with shrub species and size

The three species in the study exhibited significantly different morphological parameters, indicating that each species may respond differently to rainfall and intercept variable amounts of rainwater. *T. vulgaris* and *R. officinalis* showed the highest average specific canopy interception fraction compared to *M. tenacissima*, intercepting 27% to 37% more rainwater, respectively. However, the specific canopy interception fraction of *M. tenacissima* was higher, at 60% and 37% more than *R. officinalis* and *T. vulgaris* , respectively. Since the three species were exposed to the same rainwater input/experiment, the observed differences in interception can be attributed to variations in canopy structure (Zhang *et al.*, 2017), which generally correlates with shrub height and canopy area. Taller and larger shrubs have denser foliage with more stratified layers, resulting in higher interception per unit of incident rainfall. Additionally, larger foliage, often measured as Leaf Area Index (LAI), leads to a decrease in throughfall and stemflow, resulting in higher interception loss (Zhang *et al.*, 2017). The temporal variability of rainfall interception rate for all size classes and shrub species was found not noticeably variable over time in this study. This is contrary to some previous studies that showed higher interception at the start of rainfall, progressively decreasing until a steady value is reached, as predicted by relevant models (e.g., Friesen et al., 2015). The lack of variability in this study may be due to the extreme depth of the simulated precipitation, which has a return interval of many decades in the study area. The high amount of rainwater on the plants from the beginning of the rainfall event may lead to the interception reaching its final and steady value without significant temporal variability. Future studies under different rainfall conditions and at different temporal scales are needed to confirm these findings.

4.3 Linear modelling of extreme rainfall interception by shrubs

Our correlation analysis found strong associations between shrub morphological parameters and rainfall partitioning fractions, suggesting that these parameters can serve as good predictors of this hydrological variable. In contrast, the results of correlation analyses conducted by other authors have been more mixed. For example, Garcia-Estringana *et al.* (2010) found generally low and non-significant correlations between canopy interception and morphological parameters (i.e., < 0.19 for fresh total biomass), except for LAI ($r = 0.30$) and canopy projection area ($r = -0.38$). Meanwhile, Zou et al. (2015) did not find a significant relationship between canopy interception ratio and canopy area. Plant height and breast diameters were classified as significant predictors in determining interception loss in forests by a review of Chinese field studies. Zhang *et al.* (2017) indicated that interception loss from one species, *H. rhamnoides* is better predicted using rainfall amount, while the canopy structure should be considered when predicting interception loss for another differently-structured species, *S. pubescens*.

Although this study found that plant height is a reliable predictor of canopy interception, canopy area is also an important factor. Combining multiple parameters may provide a more comprehensive estimate of a canopy's ability to intercept rainfall. Linear functions are often the best-fit functions for predicting interception capacity, and the regression slopes differ among plant species and size classes. Therefore, our study agrees with others that linear models with different parameters may be used to predict canopy interception loss. These correlations are particularly high for *T. vulgaris*, and especially when canopy diameter is chosen as morphological predictor of interception. In contrast, interception for both *R. officinalis* and *M. tenacissima* can not be accurately predicted by those morphological parameters. This also supports that, at least for these species, interception strongly depends on plant size class, and no reliable models can be built, if this size is not taken into consideration. The results of this study are in close agreement with the findings of Shou et al.

(2017), who found different correlation coefficients between shrub height or canopy area and interception (from -0.02 to 0.7) for different species (*C. microphylla*, *H. fruticosum* and *S. gordejevii*). The lack of correlation between canopy interception capacity and dry biomass, found in this study, contrasts to the results of Wood *et al.* (1998), who reported that dry biomass has the strongest relationship with the rainwater intercepted for many species.

The linear equations proposed in this study accurately predict rainfall partitioning variables for the three main species in the study area using two easily measurable morphological parameters, plant type and size class. This finding is consistent with previous research (Zheng *et al.*, 2012, 2018; Zhang *et al.*, 2015), stating that the canopy interception loss can be predicted reasonably better using multiple linear regression models compared to single regressions, due to the interactions of multiple factors affecting rainfall partitioning among stemflow, throughfall and interception. Following the statement of (Magliano *et al.*, 2022), the good accuracy of the linear multiple-regression models suggests its feasibility for incorporation into complex hydrological models (e.g., Hydrus 2D, Skaggs *et al.*, 2004, SPLASH, Urgeghe *et al.*, 2010, or CREST, Wang *et al.*, 2011), to enhance the prediction accuracy of water amount reaching the soil surface.

Although this study provides important insights into the role of shrub morphological parameters in predicting canopy interception capacity, there are three limitations that should be addressed in future research. First, in all simulations, the study used a constant amount and intensity of rainfall, but the temporal dynamics of these two storm characteristics can affect interception process and associated water flow (e.g., Carlyle-Moses and Gash, 2011; Zhang *et al.*, 2017; Snyder *et al.*, 2022). Therefore, although the study gives indications about the magnitude of this hydrological process under the water input of one extremely intense rainfall condition, the effect of time-varying depth and intensity on the interception process needs to be further explored and incorporated into the proposed prediction model (Yang *et al.*, 2019). Secondly, the study focused on a limited number of shrub species and further investigations are needed to evaluate the effects of interception loss on the water cycle in other dominant shrub species in dry environments, where rainfall is crucial for plant growth and yield. Similar investigations, also using very simple measuring devices, such as the portable rainfall simulators, are in general useful to identify the relationships between canopy interception, water storage capacity, or interception rate with shrub morphology. Finally, although this study measured three important plant morphological parameters, including shrub height and canopy area, several studies have indicated that LAI may be a more effective metric for predicting canopy interception. For instance, (Yue *et al.*, 2021) showed a significant positive relation between LAI and interception. This suggests future research should include LAI measurements in models of canopy rainfall interception. Moreover, more precise methods to estimate the canopy area are suggested (such as destructive sampling and analysis of morphometry of leaves and branches or image analysis methods applied to high-resolution photographs), in order to increase the estimation accuracy compared to the use of a meterstick.

5. CONCLUSIONS

Under simulated extreme rainfall, observations of canopy interception for three species typical of Mediterranean drylands were of magnitudes relevant to the localized surface water balance (interquartile range: 12-20%) and significantly different for plant species and size. However, in applying a novel method (using simulation scenarios that left an open soil gap for stemflow water infiltration, and another with the sheet-stem gap sealed), stemflow rates exceeding 10% of simulated rainfall were observed. Considering the extreme rainfall rate, these local stemflow rates are likely to offset the interception effects and enhance local erosion.

Strong linear correlations were found for canopy interception and the studied shrubs' height and canopy diameter. Linear models were developed capable of predicting canopy interception and stemflow using plant height, canopy diameter, dry biomass, size class, and species. Limitations of the study are rooted in the use of only one value of extreme rainfall depth and intensity and the limited set of shrub species. Despite these limitations, the results provide valuable information on canopy interception magnitude, rates, and the stemflow inputs for important shrub species in Mediterranean arid lands under high intensity rainfall, as well as simple linear models that may be further developed and integrated into hydrological models. In these ways, this study contributes to our understanding of the response of dryland environments to intensified rain events and provides useful information on the canopy rainfall partitioning` of Mediterranean shrub species.

DATA AVAILABILITY

Data will be made available upon request to the authors.

REFERENCES

Arnell NW. 2003. Relative effects of multi-decadal climatic variability and changes in the mean and variability of climate due to global warming: future streamflows in Britain. *Journal of Hydrology* **270** (3–4): 195–213

Belmonte Serrato F, Romero Diaz A. 1998. A simple technique for measuring rainfall interception by small shrub: “interception flow collection box”. *Hydrological Processes* **12** (3): 471–481 DOI: 10.1002/(SICI)1099-1085(19980315)12:3<471::AID-HYP586>3.0.CO;2-E

Calder IR. 2001. Canopy processes: implications for transpiration, interception and splash induced erosion, ultimately for forest management and water resources. In *Tropical Forest Canopies: Ecology and Management: Proceedings of ESF Conference, Oxford University, 12–16 December 1998*Springer; 203–214.

Camarasa-Belmonte AM, Rubio M, Salas J. 2020. Rainfall events and climate change in Mediterranean environments: an alarming shift from resource to risk in Eastern Spain. *Natural Hazards* **103**: 423–445

Cantos JO. 2017. Incremento de episodios de inundación por lluvias de intensidad horaria en el sector central del litoral mediterráneo español: análisis de tendencias en Alicante. *Sémata: Ciencias Sociais e Humanidades* (29)

Carlyle-Moses DE, Gash JH. 2011. Rainfall interception loss by forest canopies. *Forest hydrology and biogeochemistry: Synthesis of past research and future directions*: 407–423

Carrà BG, Bombino G, Denisi P, Plaza-Àlvarez PA, Lucas-Borja ME, Zema DA. 2021. Water Infiltration after Prescribed Fire and Soil Mulching with Fern in Mediterranean Forests. *Hydrology* **8** (3): 95

Coenders-Gerrits M, Schilperoort B, Jiménez-Rodríguez C. 2020. Evaporative processes on vegetation: an inside look. *Precipitation partitioning by vegetation: A global synthesis*: 35–48

Crockford RH, Richardson DP. 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. *Hydrological Processes* **14** (16–17): 2903–2920 DOI: 10.1002/1099-1085(200011/12)14:16/17<2903::AID-HYP126>3.0.CO;2-6

Di Nuzzo L, Benesperi R, Nascimbene J, Papini A, Malaspina P, Incerti G, Giordani P. 2022. Little time left. Microrefuges may fail in mitigating the effects of climate change on epiphytic lichens. *Science of the Total Environment* **825**: 153943

Díaz MAR, Serrato FB. 1994. Distribución de flujos de agua en el proceso de interceptación en cuatro especies vegetales mediterráneas y su relación con la cantidad de agua disponible

en el suelo. In *Geomorfología En España: III Reunión de Geomorfología, Logroño 14 a 16 de Septiembre de 1994*Sociedad Española de Geomorfología; 201–210.
Duchon C, Fiebrich C, Grimsley D. 2014. Using high-speed photography to study undercatch in tipping-bucket rain gauges. *Journal of Atmospheric and Oceanic Technology* **31** (6): 1330–1336
Duchon CE, Biddle CJ. 2010. Undercatch of tipping-bucket gauges in high rain rate events. *Advances in Geosciences* **25**: 11–15
Dunkerley D. 2000. Measuring interception loss and canopy storage in dryland vegetation: a brief review and evaluation of available research strategies. *Hydrological Processes* **14** (4): 669–678 DOI: 10.1002/(SICI)1099-1085(200003)14:4<669::AID-HYP965>3.0.CO;2-I
Dunkerley D. 2008. Rain event properties in nature and in rainfall simulation experiments: a comparative review with recommendations for increasingly systematic study and reporting. *Hydrological Processes* **22** (22): 4415–4435 DOI: 10.1002/hyp.7045
Dunkerley D. 2021. The case for increased validation of rainfall simulation as a tool for researching runoff, soil erosion, and related processes. *CATENA* **202**: 105283 DOI: 10.1016/j.catena.2021.105283
FAO-UNESCO. 1981. *FAO-Unesco soil map of the world, 1: 5,000,000*. Unesco.
Ferreira RN. 2021. Cut-off lows and extreme precipitation in eastern Spain: Current and future climate. *Atmosphere* **12** (7): 835
Garcia-Estringana P, Alonso-Blázquez N, Alegre J. 2010. Water storage capacity, stemflow and water funneling in Mediterranean shrubs. *Journal of Hydrology* **389** (3–4): 363–372 DOI: 10.1016/j.jhydrol.2010.06.017
Gordon DAR, Coenders-Gerrits M, Sellers BA, Sadeghi SM, Van Stan II JT. 2020. Rainfall interception and redistribution by a common North American understory and pasture forb, Eupatorium capillifolium (Lam. dogfennel). *Hydrology and Earth System Sciences* **24** (9): 4587–4599
Gutmann ED. 2020. Global modeling of precipitation partitioning by vegetation and their applications. *Precipitation partitioning by vegetation: A global synthesis*: 105–120
Hlavčová K, Danáčová M, Kohnová S, Szolgay J, Valent P, Výleta R. 2019. Estimating the effectiveness of crop management on reducing flood risk and sediment transport on hilly agricultural land – A Myjava case study, Slovakia. *CATENA* **172**: 678–690 DOI: 10.1016/j.catena.2018.09.027
Horton RE. 1919. Rainfall interception. *Monthly weather review* **47** (9): 603–623
Iserloh T, Ries JB, Arnáez J, Boix-Fayos C, Butzen V, Cerdà A, Echeverría MT, Fernández-

Gálvez J, Fister W, Geißler C. 2013. European small portable rainfall simulators: A comparison of rainfall characteristics. *Catena* **110**: 100–112

Jian S-Q, Zhao C-Y, Fang S-M, Yu K, Wang Y, Liu Y-Y, Zheng X-L, Peng S-Z. 2012. Characteristics of rainfall interception by Caragana korshinskii and Hippophae rhamnoides in Loess Plateau of Northwest China. *Ying Yong Sheng tai xue bao= The Journal of Applied Ecology* **23** (9): 2383–2389

Klamerus-Iwan A, Link TE, Keim RF, Van Stan II JT. 2020. Storage and routing of precipitation through canopies. *Precipitation partitioning by vegetation: A global synthesis*: 17–34

Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. 2006. World map of the Köppen-Geiger climate classification updated

Levia DF, Nanko K, Amasaki H, Giambelluca TW, Hotta N, Iida S, Mudd RG, Nullet MA, Sakai N, Shinohara Y. 2019. Throughfall partitioning by trees. *Hydrological Processes* **33** (12): 1698–1708

Lian X, Zhao W, Gentine P. 2022. Recent global decline in rainfall interception loss due to altered rainfall regimes. *Nature Communications* **13** (1): 7642

Lin D, Zheng Z, Zhang X, Li T, Wang Y. 2011. Study on the effect of maize plants on rainfall redistribution processes. *Scientia Agricultura Sinica* **44** (12): 2608–2615

Llasat M-C, Martín F, Barrera A. 2007. From the concept of "Kaltlufttropfen"(cold air pool) to the cut-off low. The case of September 1971 in Spain as an example of their role in heavy rainfalls. *Meteorology and Atmospheric physics* **96**: 43–60

Llasat MC, del Moral A, Cortès M, Rigo T. 2021. Convective precipitation trends in the Spanish Mediterranean region. *Atmospheric Research* **257**: 105581

Llorens P, Domingo F. 2007. Rainfall partitioning by vegetation under Mediterranean conditions. A review of studies in Europe. *Journal of Hydrology* **335** (1): 37–54 DOI: 10.1016/j.jhydrol.2006.10.032

Lucas-Borja ME, Bombino G, Carrà BG, D'Agostino D, Denisi P, Labate A, Plaza-Alvarez PA, Zema DA. 2020. Modeling the Soil Response to Rainstorms after Wildfire and Prescribed Fire in Mediterranean Forests. *Climate* **8** (12): 150 DOI: 10.3390/cli8120150

Lucas-Borja ME, de las Heras J, Moya Navarro D, González-Romero J, Peña-Molina E, Navidi M, Fajardo-Cantos Á, Miralles Mellado I, Plaza-Alvarez PA, Gianmarco Carrà B, et al. 2022. Short-term effects of prescribed fires with different severity on rainsplash erosion and physico-chemical properties of surface soil in Mediterranean forests. *Journal of Environmental Management* **322**: 116143 DOI: 10.1016/j.jenvman.2022.116143

Ma B, Li CD, Ma F, Li ZB, Wu FQ. 2016. Influences of Rainfall Intensity and Leaf Area on Corn Stemflow: Development of a Model. *CLEAN – Soil, Air, Water* **44** (8): 922–929 DOI: 10.1002/clen.201500050

Maestre FT, Eldridge DJ, Soliveres S. 2016. A multifaceted view on the impacts of shrub encroachment. *Applied Vegetation Science* **19** (3): 369–370

Maestre FT, Quero JL, Gotelli NJ, Escudero A, Ochoa V, Delgado-Baquerizo M, García-Gómez M, Bowker MA, Soliveres S, Escolar C. 2012. Plant species richness and ecosystem multifunctionality in global drylands. *Science* **335** (6065): 214–218

Magliano PN, Whitworth-Hulse JI, Baldi G. 2019a. Interception, throughfall and stemflow partition in drylands: Global synthesis and meta-analysis. *Journal of Hydrology* **568**: 638–645 DOI: 10.1016/j.jhydrol.2018.10.042

Magliano PN, Whitworth-Hulse JI, Cid FD, Leporati JL, Van Stan JT, Jobbágy EG. 2022. Global rainfall partitioning by dryland vegetation: Developing general empirical models. *Journal of Hydrology* **607**: 127540 DOI: 10.1016/j.jhydrol.2022.127540

Magliano PN, Whitworth - Hulse JI, Florio EL, Aguirre EC, Blanco LJ. 2019b. Interception loss, throughfall and stemflow by *Larrea divaricata* : The role of rainfall characteristics and plant morphological attributes. *Ecological Research* **34** (6): 753–764 DOI: 10.1111/1440-1703.12036

Mendieta-Leiva G, Porada P, Bader MY. 2020. Interactions of epiphytes with precipitation partitioning. *Precipitation Partitioning by Vegetation: A Global Synthesis*: 133–146

Muzylo A, Llorens P, Valente F, Keizer JJ, Domingo F, Gash JHC. 2009. A review of rainfall interception modelling. *Journal of Hydrology* **370** (1–4): 191–206 DOI: 10.1016/j.jhydrol.2009.02.058

Parhizkar M, Shabanpour M, Lucas-Borja ME, Zema DA, Li S, Tanaka N, Cerda A. 2021. Effects of length and application rate of rice straw mulch on surface runoff and soil loss under laboratory simulated rainfall. *International Journal of Sediment Research* **36** (4): 468–478

Peñarrocha D, Estrela MJ, Millán M. 2002. Classification of daily rainfall patterns in a Mediterranean area with extreme intensity levels: the Valencia region. *International Journal of Climatology: A Journal of the Royal Meteorological Society* **22** (6): 677–695

Pollock MD, O'donnell G, Quinn P, Dutton M, Black A, Wilkinson ME, Colli M, Stagnaro M, Lanza LG, Lewis E. 2018. Quantifying and mitigating wind - induced undercatch in rainfall measurements. *Water Resources Research* **54** (6): 3863–3875

Porada P, Van Stan JT, Kleidon A. 2018. Significant contribution of non-vascular vegetation to global rainfall interception. *Nature Geoscience* **11** (8): 563–567

Porcù F, Carrassi A, Medaglia CM, Prodi F, Mugnai A. 2007. A study on cut-off low vertical structure and precipitation in the Mediterranean region. *Meteorology and Atmospheric Physics* **96**: 121–140

Quinn NW, Laflen JM. 1983. Characteristics of raindrop throughfall under corn canopy. *Transactions of the ASAE* **26** (5): 1445

Ritchie H, Roser M. 2013. Land use. *Our world in data*

Sadeghi SMM, Gordon DA, Van Stan II JT. 2020. A global synthesis of throughfall and stemflow hydrometeorology. *Precipitation partitioning by vegetation: A global synthesis*: 49–70

Shou W, Musa A, Liu Z, Qian J, Niu C, Guo Y. 2017. Rainfall partitioning characteristics of three typical sand-fixing shrubs in Horqin Sand Land, north-eastern China. *Hydrology Research* **48** (2): 571–583 DOI: 10.2166/nh.2016.177

Skaggs TH, Trout TJ, Šimůnek J, Shouse PJ. 2004. Comparison of HYDRUS-2D simulations of drip irrigation with experimental observations. *Journal of irrigation and drainage engineering* **130** (4): 304–310

Snyder DK, Stringham TK, Snyder KA. 2022. Rainfall interception by mountain big sagebrush (*Artemisia tridentata* spp. *vaseyana*): Dryland shrub canopy cover affects net precipitation. *Hydrological Processes* **36** (1) DOI: 10.1002/hyp.14441

Sumner GN, Romero R, Homar V, Ramis C, Alonso S, Zorita E. 2003. An estimate of the effects of climate change on the rainfall of Mediterranean Spain by the late twenty first century. *Climate dynamics* **20**: 789–805

Sun X, Wang X, Wang C, Zhang Q, Guo Q. 2022. Filling the "vertical gap" between canopy tree species and understory shrub species: biomass allometric equations for subcanopy tree species. *Journal of Forestry Research*: 1–11

Urgeghe AM, Breshears DD, Martens SN, Beeson PC. 2010. Redistribution of Runoff Among Vegetation Patch Types: On Ecohydrological Optimality of Herbaceous Capture of Run-On. *Rangeland Ecology & Management* **63** (5): 497–504 DOI: 10.2111/REM-D-09-00185.1

Van Stan JT, Gordon DA. 2018. Mini-review: stemflow as a resource limitation to near-stem soils. *Frontiers in Plant Science* **9**: 248

Van Stan JT, Hildebrandt A, Friesen J, Metzger JC, Yankine SA. 2020. Spatial variability and temporal stability of local net precipitation patterns. *Precipitation Partitioning by*

Vegetation: A Global Synthesis: 89–104

Van Stan JT, Norman Z, Meghoo A, Friesen J, Hildebrandt A, Côté J-F, Underwood SJ, Maldonado G. 2017. Edge-to-stem variability in wet-canopy evaporation from an urban tree row. *Boundary-Layer Meteorology* **165** (2): 295–310

Van Stan JT, Van Stan JH, Levia DF. 2014. Meteorological influences on stemflow generation across diameter size classes of two morphologically distinct deciduous species. *International journal of biometeorology* **58**: 2059–2069

Wang J, Hong Y, Li L, Gourley JJ, Khan SI, Yilmaz KK, Adler RF, Policelli FS, Habib S, Irwn D, et al. 2011. The coupled routing and excess storage (CREST) distributed hydrological model. *Hydrological Sciences Journal* **56** (1): 84–98 DOI: 10.1080/02626667.2010.543087

Wang X-P, Li X-R, Zhang J-G, Zhang Z-S, Berndtsson R. 2005. Measurement of rainfall interception by xerophytic shrubs in re-vegetated sand dunes / Mesure de l'interception de la pluie par des arbustes xérophiles sur des dunes de sable replantées. *Hydrological Sciences Journal* **50** (5): 12 DOI: 10.1623/hysj.2005.50.5.897

Wood MK, Jones TL, Vera-Cruz MT. 1998. Rainfall Interception by Selected Plants in the Chihuahuan Desert. *Journal of Range Management* **51** (1): 91 DOI: 10.2307/4003570

WRB-IUSS. 2015. *World Reference Base for Soil Resources. World Soil Resources Reports 106*.

Yang X, Chen L, Wang L, Wang X, Gu J, Qu W, Song N. 2019. Dynamic rainfall-partitioning relationships among throughfall, stemflow, and interception loss by Caragana intermedia. *Journal of Hydrology* **574**: 980–989 DOI: 10.1016/j.jhydrol.2019.04.083

Yue K, De Frenne P, Fornara DA, Van Meerbeek K, Li W, Peng X, Ni X, Peng Y, Wu F, Yang Y, et al. 2021. Global patterns and drivers of rainfall partitioning by trees and shrubs. *Global Change Biology* **27** (14): 3350–3357 DOI: 10.1111/gcb.15644

Zhang Y, Li X-Y, Li W, Wu X-C, Shi F-Z, Fang W-W, Pei T-T. 2017. Modeling rainfall interception loss by two xerophytic shrubs in the Loess Plateau. *Hydrological Processes* **31** (10): 1926–1937 DOI: 10.1002/hyp.11157

Zhang Y, Wang X, Hu R, Pan Y, Paradeloc M. 2015. Rainfall partitioning into throughfall, stemflow and interception loss by two xerophytic shrubs within a rain-fed re-vegetated desert ecosystem, northwestern China. *Journal of Hydrology* **527**: 1084–1095 DOI: 10.1016/j.jhydrol.2015.05.060

Zhang Y, Yuan C, Chen N, Levia DF. 2023. Rainfall partitioning by vegetation in China: A quantitative synthesis. *Journal of Hydrology* **617**: 128946 DOI:

10.1016/j.jhydrol.2022.128946

Zheng J, Fan J, Zhang F, Yan S, Xiang Y. 2018. Rainfall partitioning into throughfall, stemflow and interception loss by maize canopy on the semi-arid Loess Plateau of China. *Agricultural Water Management* **195**: 25–36 DOI: 10.1016/j.agwat.2017.09.013

Zheng ZC, Li TX, Zhang XZ, Wang YD, Lin CW. 2012. Differentiation characteristics and influencing factors of rainfall interception in maize plants. *J Soil Water Conserv* **26** (04): 208–211

Zou CB, Caterina GL, Will RE, Stebler E, Turton D. 2015. Canopy Interception for a Tallgrass Prairie under Juniper Encroachment (CA Hagen, ed.). *PLOS ONE* **10** (11): e0141422 DOI: 10.1371/journal.pone.0141422

TABLES

Table 1 – Coefficients of correlation of linear regressions between specific interception fractions and morphological characteristics (classified for shrub species and size) measured in rainfall simulations (Villamalea, Castilla La Mancha, Spain).

	Is			SFs			TFs		
	Height	Canopy diameter	Dry biomass	Height	Canopy diameter	Dry biomass	Height	Canopy diameter	Dry biomass
	Species								
R. officinalis	0.31	-0.50	-0.37	-0.42	-0.50	-0.16	-0.09	-0.04	-0.37
T. vulgaris	0.21	**-0.71**	**0.61**	**-0.68**	**-0.71**	**-0.71**	**0.56**	**0.60**	**0.61**
M. tenacissima	0.26	0.22	-0.14	0.17	0.22	0.09	-0.26	-0.25	-0.14
All	-0.11	-0.20	0.20	**-0.62**	**-0.70**	-0.31	0.47	**0.57**	0.09
	Size								
Small	**-0.69**	**-0.82**	0.47	**-0.90**	**-0.82**	-0.46	**0.91**	**0.84**	0.47
Medium	-0.41	**-0.79**	-0.39	**-0.80**	**-0.79**	0.19	**0.77**	**0.81**	-0.39
Large	**-0.84**	**-0.82**	0.50	**-0.81**	**-0.82**	-0.45	**0.87**	**0.92**	0.50
All	-0.11	-0.20	0.20	**-0.62**	**-0.70**	-0.31	0.47	**0.57**	0.09

Note: I_S = specific interception; SF_S = specific stemflow; TF_S = specific throughfall; bold characters evidence significant values ($p < 0.05$).

FIGURE LEGENDS

12. Figure 1 – Geographic location of the study area (Villamalea, Castilla La Mancha, Central Eastern Spain) (left) and individuals of the three shrub species considered in this study (*M. tenacissima*, *T. vulgaris* and *R. officinalis*) (right).

Figure 2 – Flow-chart of the novel method to measure rainfall partitioning at the local scale (S1 and S2 refer to the two rainfall simulation series separately carried out, in order to measure rainfall interception and stemflow).

Figure 3 – Pictures of the rainfall simulation experiments (rainfall simulation series S_1, left, and S_2, right) on a small plant of *M. tenacissima*.

Figure 4 – Main morphological characteristics of vegetation according to shrub species and size in the experiments simulating rainfall and interception (Villamalea, Castilla La Mancha, Spain). *Different lowercase letters indicate significant differences in the interaction plant species x size after Tukey's test ($p < 0.05$).*

Figure 5 –Specific (unscaled) interception (I_S) and stemflow (SF_S) for different shrub species and size after rainfall simulations (Villamalea, Castilla La Mancha, Spain). *Different lowercase letters indicate significant differences in the interaction plant species x size after Tukey's test ($p < 0.05$).*

Figure 6 – Fractions of specific interception (I_S), stemflow (SF_S) and throughfall (TF_S) on simulated rainfall for different shrub species and size in the experiments (Villamalea, Castilla La Mancha, Spain). *Different lowercase letters indicate significant differences in the interaction plant species x size after Tukey's test ($p < 0.05$).*

Figure 7 –Landscape-scale interception (I_C) and stemflow (SF_C) for different shrub species and size after rainfall simulations (Villamalea, Castilla La Mancha, Spain). *Different lowercase letters indicate significant differences in the interaction plant species x size after Tukey's test ($p < 0.05$).*

Figure 8 - Scatterplot of observed fractions of specific interception (I_S), stemflow (SF_S) and throughfall (TF_S) vs. values predicted by multi-regression models for different shrub species and size after rainfall simulations (Villamalea, Castilla La Mancha, Spain).