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Rainfall partitioning within semiarid juniper communities: effects of event size and canopy cover

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Abstract:

Partitioning bulk rainfall into canopy interception, litter interception, stemflow and throughfall allows an estimate of the physical impact of trees on the local hydrologic budget. Despite recognition of the potentially large effect of interception and associated processes on the hydrologic budget, few, if any, studies have quantitatively evaluated the multiple components simultaneously in semiarid savannas, nor have the effects of rainfall intensity within storms been rigorously evaluated. We monitored interception and rainfall partitioning in individual Ashe juniper (*Juniperus ashei* Buchholz) canopies at ten sites over a 3-year period. Averaged over all ten sites for 2700 total rain events, about 35% of the bulk rainfall falling on juniper trees was intercepted by the tree canopy, 5% was intercepted by the coarse litter and duff beneath the tree, 55% reached the ground surface as direct and released throughfall, and 5% was redirected to the base of the tree as stemflow. Small amounts of rainfall ($<2\cdot5$ mm) were entirely captured by the canopy and evaporated to the atmosphere, contributing nothing to soil water under juniper trees. Low intensity rainfall (e.g. 13 mm over a 19-h period) that could conceivably benefit the local plant community was largely intercepted by the tree canopy ($>60\%$ interception). High intensity rainfall was less influenced by juniper canopies. At high intensities (e.g. >70 mm over a 15-h period) only 20% of the bulk precipitation was intercepted by the canopy and litter. The hourly pattern of rainfall within extended storms demonstrated periods with low intensity and periods with high intensity. The interception rates during these periods closely mimic the rates seen in similar intensity short duration storms. Canopy and litter interception effectively reduced the beneath-canopy precipitation from 600 to 360 mm in the western region and from 900 to 540 mm in the eastern region. Copyright © 2006 John Wiley & Sons, Ltd.

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INTRODUCTION

Spatial allocation of resources in semiarid and arid environments is one of the most critical factors affecting plant distribution. The redistribution of nutrients into 'islands of fertility' has been demonstrated repeatedly in many different systems (Schlesinger *et al.*, 1996; Reynolds *et al.*, 1999). In arid and semiarid environments where potential evapotranspiration is many times greater than precipitation, water is the most limiting nutrient. Redistribution of precipitation through banded vegetation (Dunkerley, 1997) or vegetation patches (Reid *et al.*, 1999), where runoff from bare areas is directed towards woody plants where infiltration occurs, or by funneling water from the canopy towards the base of the plant (Herwitz, 1986; Martinez-Meza and Whitford, 1996; Devitt and Smith, 2002), has been shown to increase the moisture available to individual plants. The canopy structure and leaf morphology of different species can alter the distribution of bulk precipitation and modify the amount of water that actually reaches the ground surface beneath woody plants (Hester, 1996; Carlyle-Moses, 2004). The amount of rainfall intercepted by tree canopies and lost to evaporation is species-specific and may be a function of rainfall intensity (Schowalter, 1999; Silva and Rodriguez, 2001).

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How the size and frequency of pulsed events such as precipitation affect ecosystem processes has recently attracted attention (Schwinning *et al*., 2004). Very small pulses of precipitation may not be important for vascular plants but may be critical for microflora (Schwinning and Sala, 2004). Tree canopies can impact this by altering the vertical and horizontal spatial distribution of water within the plant community. Canopy interception generally exerts a negative effect on the horizontal distribution of water by retaining small pulses of precipitation in the canopy (Loik *et al*., 2004) and preventing water from reaching the ground surface. Stemflow can particularly affect the vertical distribution of water by funneling water to the base of the tree where it can infiltrate rapidly (Devitt and Smith, 2002) or be redistributed less rapidly through diffusion or hydraulic redistribution (Schwinning and Sala, 2004). In either case, the vertical and spatial heterogeneity of water within the plant community can be drastically altered by the physical presence of trees.

Ignoring the amount of precipitation intercepted by tree canopies, or lumping it with evapotranspiration, can lead to large errors in the estimation of the other parts of the hydrologic budget (Savenije, 2004). If interception is ignored, this amount of precipitation would be lumped with the soil water pool and, consequently, lead to overestimation of transpiration. In fact, Guevara-Escobar *et al*. (2000) reported that evapotranspiration from a poplar (*Populus deltoides* Bart. *ex* March) forest in New Zealand during the spring growing period averaged 2·7 to 3·0 mm d^{-1} and of that 1·4 mm d^{-1} was lost as canopy interception. Not accounting for interception could have led to a dramatic overestimation of transpiration.

The morphology of juniper trees (*Juniperus* sp.) is ideally suited for intercepting and retaining precipitation. The scale-like leaf structure and the large leaf area combine to hold a significant amount of water in the canopy. The impact of juniper trees on the local and regional hydrologic budget is hotly debated as water demands from rangelands increase. For instance, the density and aerial cover of Ashe juniper (*Juniperus ashei* Buchholz) in central Texas has increased over the last 200 years. Originally limited to rocky outcrops or areas of low fuel availability, Ashe juniper now covers almost 2·7 million hectares on the Edwards Plateau. Water demands from this area have increased owing to agricultural irrigation and municipal growth. Aggressive shrub and tree control has been touted as the solution to provide more water for aquifer recharge, although its feasibility has not been demonstrated at a regional or landscape scale (Wilcox *et al*., 2006).

Understanding both the physiological and physical impact of juniper trees on water availability is crucial; this study investigates the physical impact of juniper trees on the local hydrologic budget. Our objectives were to: (1) determine how rainfall is partitioned within juniper trees over a wide geographic region, and (2) determine how rainfall intensity alters the patterns of rainfall partitioning. This study focused explicitly on individual trees rather than on a closed forest canopy.

METHODS

Ten study sites were selected over a 280-km range from the western to the eastern portion of the Edwards Plateau in central Texas (Table I). Long-term precipitation ranges from 600 mm on the western sites to 900 mm on the eastern sites. Shallow soils (<15 cm) at all sites were underlain with a karst geology. The highly fractured limestone allows rapid water movement when rainfall reaches the soil surface. At each site, two Ashe juniper trees were selected for instrumentation. The trees were subjectively selected as being representative of the site, within 30 m of each other, and without overlapping canopies with other trees. Each tree was instrumented to collect rainfall, throughfall, stemflow, and litter moisture on an hourly interval by an electronic datalogger (CR10X, Campbell Scientific, Logan, UT). Rainfall above the canopy (hereafter referred to as bulk rainfall) was measured to the closest 0·25 mm using a tipping bucket rain gauge (Texas Electronics).

Throughfall was collected using a system of four 20-cm funnels connected to a 20-cm diameter collection tube. A float in the tube was connected to a potentiometer, and as the throughfall was collected the potentiometer measured the increasing water level in the tube. The change in millivolts of the instrument was calibrated to record the actual height of the water column. After the rain stopped, the datalogger tripped

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Table I. Research site location and establishment date for juniper interception

Site	Latitude	Longitude	Date established
Uvalde	29·44°	99·69°	Aug. 7, 2000
Bexar-1	29·66°	98·78°	Sep. 16, 2000
Bexar-2	29·74°	98·41°	Nov. 22, 2000
Blanco	30·28°	98·41°	Nov. 16, 2000
Comal	29·86°	98·16°	Dec. 15, 2000
Hays	29·94°	98·01°	Sep. 15, 2000
Kendall	29·96°	98·80°	Dec. 18, 2000
Kerr	30·09°	99·49°	Oct. 3, 2000
Medina-1	25·54°	99·16°	Nov. 2, 2000
Medina-2	29·56°	99·45°	Dec. 19, 2000

a solenoid to drain the tube and make it ready for the next rainfall event. The funnel collectors were placed on a transect through the canopy of the tree such that they were at least 1·5 m apart, and two of the collectors were in the interior portion of the canopy and two were in the exterior portion. They were moved to different locations periodically to account for spatial variability in throughfall.

Litter moisture was measured using water content reflectometers (Campbell Scientific CS615) after they were calibrated to the high organic matter. The amount of litter was determined by measuring litter depth near the base of the tree, mid-way through the canopy, and at the drip line of the canopy on eight equally spaced transects radiating from the base of each tree. Litter depth was measured by carefully removing a small section of the litter and measuring from the top surface of the litter to the organic soil beneath the litter, after measurement the displaced litter was returned to its original location. The coarse litter layer did not contain any roots from the trees. The area of the tree was combined with litter depths to determine the volume of litter under each tree. Bulk density samples were collected to convert litter volume to litter mass. Additional samples were taken to calibrate the reflectometer probes. For calibration purposes, the litter was oven-dried and weighed to determine the mass of the sample. Ten percent of that mass of distilled water was then added to the litter and a measurement was taken using the CS615 probe. This process was repeated to measure from 10 to 80% gravimetric moisture. This whole process was repeated six times and a regression was calculated to convert the millivolt reading from the probes to gravimetric litter moisture. Litter moisture (M_l) was calculated as

$$M_l = -4681{\cdot}93 + 14416{\cdot}18 * V - 14600{\cdot}62 * V^2 + 4942{\cdot}83 * V^3 \quad (1)$$

where V = millivolt reading from the CS615 probe. The calibration procedure was repeatable because we calculated a similar equation using different litter samples, but the equation was not tested against an independent data set.

Stemflow was collected by constructing a narrow collar around the main trunk of each tree about 70 cm above the ground surface. The collar collected all the water that flowed on the outside of the stem and diverted it to a tipping bucket measuring device. The bucket held 1 l of water before it tipped, representing about 0·1 mm of rain for an average sized juniper tree. This stemflow measurement represented all the water directed to the base of the tree, although some portion of stemflow water may have fallen before it reached the base. This portion was considered as part of the throughfall measurement.

Canopy interception (I_c) cannot be measured directly, but must be estimated by subtraction using the formula

$$I_c = P_b - (T + S) \quad (2)$$

where P_b is bulk precipitation, T is throughfall, and S is stemflow.

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Then the amount of water reaching the soil surface (W_s) was calculated as

$$W_s = P_b - I_c - I_l \tag{3}$$

where I_l is the litter interception.

During the 3-year study, data were collected from over 2700 rainfall events (over all ten sites). A rainfall event was considered as a separate event if there was at least a 1-h gap between recorded rainfall events. Bulk rainfall was partitioned to canopy interception, evaporation, soil litter interception, and soil water on a percentage basis. Data were analysed by creating classes of rainfall based on 2·54-mm increments and using curvilinear regression techniques to calculate the best fit model. Separate models were constructed for each of the ten sites, and a single model was calculated for all ten sites combined. Throughfall was estimated using a 2-parameter hyperbolic regression, interception was regressed with a 2-parameter hyperbolic decay curve, and both litter interception and stemflow were regressed with a 2-parameter exponential rise to a maximum. Regression coefficients from the models for each site were compared with the model for all sites combined using confidence interval estimation. In addition, the hourly time-step of rainfall partitioning for different intensity storms was calculated to determine how rainfall intensity and duration affected canopy and litter interception.

RESULTS

The average tree over all ten sites was 5·4 m tall (range of 3·8–7·6 m) and had a canopy area of 21·4 m^2 (range of 8·1–64·1 m^2) (Table II). Generally, the taller and larger trees were from the eastern portion of the study area while the smaller trees were from the western area.

Rainfall distribution

The research sites were operational for different lengths of time depending on access to the private properties. The Comal site was instrumented for the shortest length of time (505 days) while the Uvalde site was in place the longest (1122 days) (Table II). During the time the Comal site was in place we recorded 158 rainfall events with a total rainfall of 1176 mm. At the Uvalde county site we recorded 355 rainfall events with a total rainfall of 2245 mm. The wettest site was the Hays site with 3208 mm of rain in 361 storms. There were no statistical differences between the rainfall frequency histograms for the ten sites, so the average histogram is presented in Figure 1. Sixty percent of the storms at all the sites had less than 2·54 mm of rain.

Table II. Tree size and litter amounts for the ten research sites

Site	Tree 1				Tree 2				Total rainfall (mm)	Length of observation (d)
	Height (m)	Canopy area (m^2)	Litter depth (cm)	Litter weight (kg)	Height (m)	Canopy area (m^2)	Litter depth (cm)	Litter weight (kg)		
Uvalde	6·10	11·69	2·62	28·3	6·10	22·48	4·01	61·2	2246	1122
Bexar-1	4·57	14·82	3·38	46·5	7·00	18·10	4·93	82·6	2569	757
Bexar-2	5·79	20·09	4·06	75·9	5·79	31·27	2·39	69·1	1472	702
Blanco	3·81	12·03	1·85	20·6	4·57	9·62	1·32	13·6	1711	685
Comal	7·32	36·03	1·68	64·4	4·72	17·77	2·34	33·2	1176	505
Hays	7·62	34·55	6·10	66·1	4·57	15·21	3·86	59·2	3209	1084
Kendall	7·32	64·15	0·41	56·2	6·25	33·61	2·21	52·8	3054	1006
Kerr	4·57	22·48	3·86	80·7	4·27	20·51	2·67	50·9	1983	1084
Medina-1	4·57	11·71	3·35	36·2	4·27	8·10	4·55	69·7	2244	933
Medina-2	4·27	14·11	2·11	29·3	4·27	9·62	4·75	32·6	2105	863

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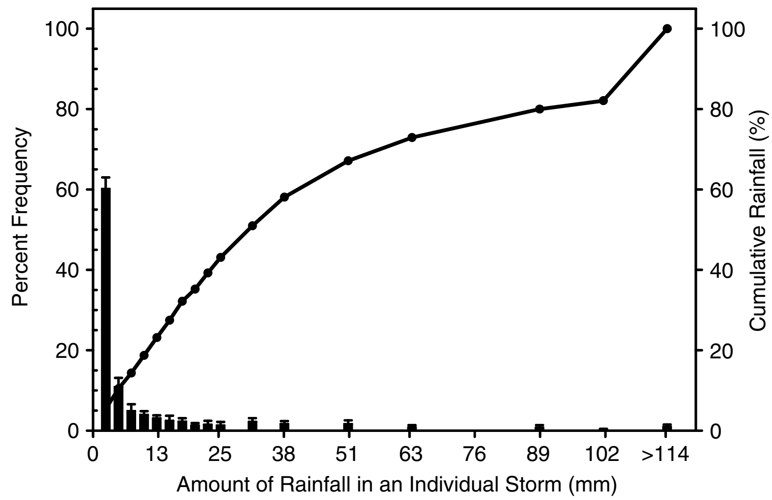

Figure 1. Frequency distribution of rainfall (bars) and cumulative rainfall amount (line) summed over ten sites on the Edwards Plateau, TX

Although these storms were numerous, they contributed only 5·4% of the total rainfall at each site. Storms >63·5 mm were less numerous, accounting for only 2·7% of the total number of storms, but they contributed over 27% of the total rainfall. The recording equipment was designed to measure a single rainfall event up to 127 mm, and there was 1 event greater than that during the study. That storm was dropped from the analysis because we could not accurately measure the throughfall.

Cumulative rainfall partitioning

Averaged over all the storms during the 3-year study, about $60{\cdot}8 \pm 2{\cdot}7\%$ (mean ± SE) of the bulk rainfall reached the soil surface beneath juniper trees while the remaining $39{\cdot}2 \pm 2{\cdot}9\%$ was intercepted by either the canopy or the coarse litter and then lost to evaporation. There were significant differences ($P < 0{\cdot}05$) in the amount of water intercepted versus that reaching the soil surface among the ten sites, but there was no clear impact from the long-term precipitation gradient on the amount of water reaching the soil surface (data not shown). The high canopy interception and evaporation was mainly due to the large number of small storms that experienced total, or nearly total, interception. The low intensity storms were numerous but contributed little moisture to the soil surface (Figure 2). Most of the precipitation from storms with <2·54 mm rain was either intercepted by the canopy (96%) or the litter layer (2%), leaving only 2% of the bulk rainfall to reach the soil surface beneath the juniper trees. At the highest rainfall levels in these low intensity storms, at least 15% of the bulk rainfall was intercepted by the tree canopy. The litter layer became saturated at fairly low levels of rain and absorbed about 5% of the bulk rainfall, leaving about 80% of the bulk rainfall reaching the soil surface.

As storm size increased, the proportionate amount of water intercepted by the canopy and lost to evaporation decreased (Figure 2). Curvilinear regression analysis demonstrated the high interception from small rainfall events. Approximately 50% of direct throughfall did not occur until at least 11 mm of rain had occurred. At this time, about 43% of the rain was intercepted by the canopy, 5·6% was intercepted by the litter, and 2% occurred as stemflow. The remaining 50% directly reached the soil surface. At the highest rainfall levels, over 80% of the rain directly reached the soil surface as throughfall, nearly 5·6% was intercepted by the litter layer, 4% occurred as stemflow, and 10% was intercepted by the canopy. Interception by the litter layer peaked quickly and remained constant after saturation, resulting in a low coefficient of determination for that regression.

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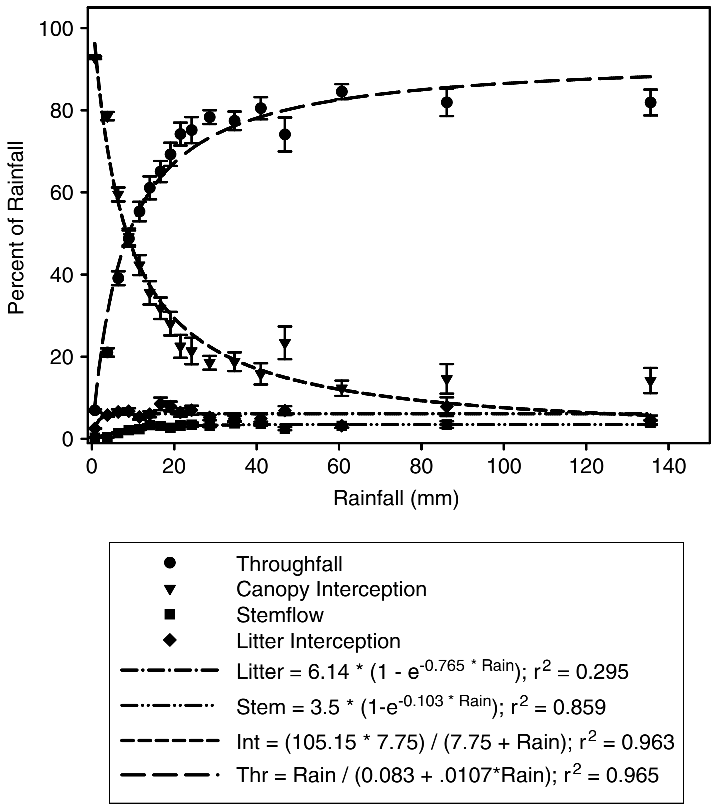

Figure 2. Bulk rainfall partitioned into canopy interception (Int), litter interception (Litter), stemflow (Stem), and throughfall (Thr) in Ashe juniper trees

Rainfall intensity and partitioning within juniper canopies

Low intensity storms. Low intensity storms were defined as storms yielding <12·5 mm of rain over a 24 h period. During low intensity rainfall events, most of the initial rainfall was intercepted by the canopy and the litter layer. Figure 3(a) depicts the hourly partitioning of rainfall during a 13-mm storm that lasted for 29 h. During the first 16 h of the storm, canopy interception and litter interception were the dominant factors. After accumulation of 7·6 mm of rain (at hour 17), throughfall became the dominant factor in partitioning the rainfall. Overall stemflow was a negligible factor in low intensity storms. The cumulative partitioning (Figure 3(b)) demonstrates that over 60% of the rain received during a typical low intensity storm is intercepted by either the tree canopy or the litter layer.

High intensity storms. High intensity storms can deposit more than 25 mm of rain over a very short time. The hourly pattern of rainfall within high intensity events dictates how rainfall is partitioned within tree canopies. Figure 3(c) and (d) depict a 68-mm storm over a 16-h period, which began with a light rain. The hourly time steps (Figure 3(c)) show that periods of low rainfall typically have high interception and low throughfall. During the first 7·6 mm of the storm, most rainfall was captured by either the canopy or the litter (up to hour 3 in Figure 3(c)), but throughfall was the dominant factor after that. The hours within the storms that had high intensity rainfall (for example, hours 6 to 8, and 11 to 13) experienced greater throughfall than other periods. Stemflow seemed to lag behind rainfall by about 1 h. The cumulative partitioning (Figure 3(d)) demonstrates that only about 30% of the bulk rainfall received during a mixed intensity storm is intercepted

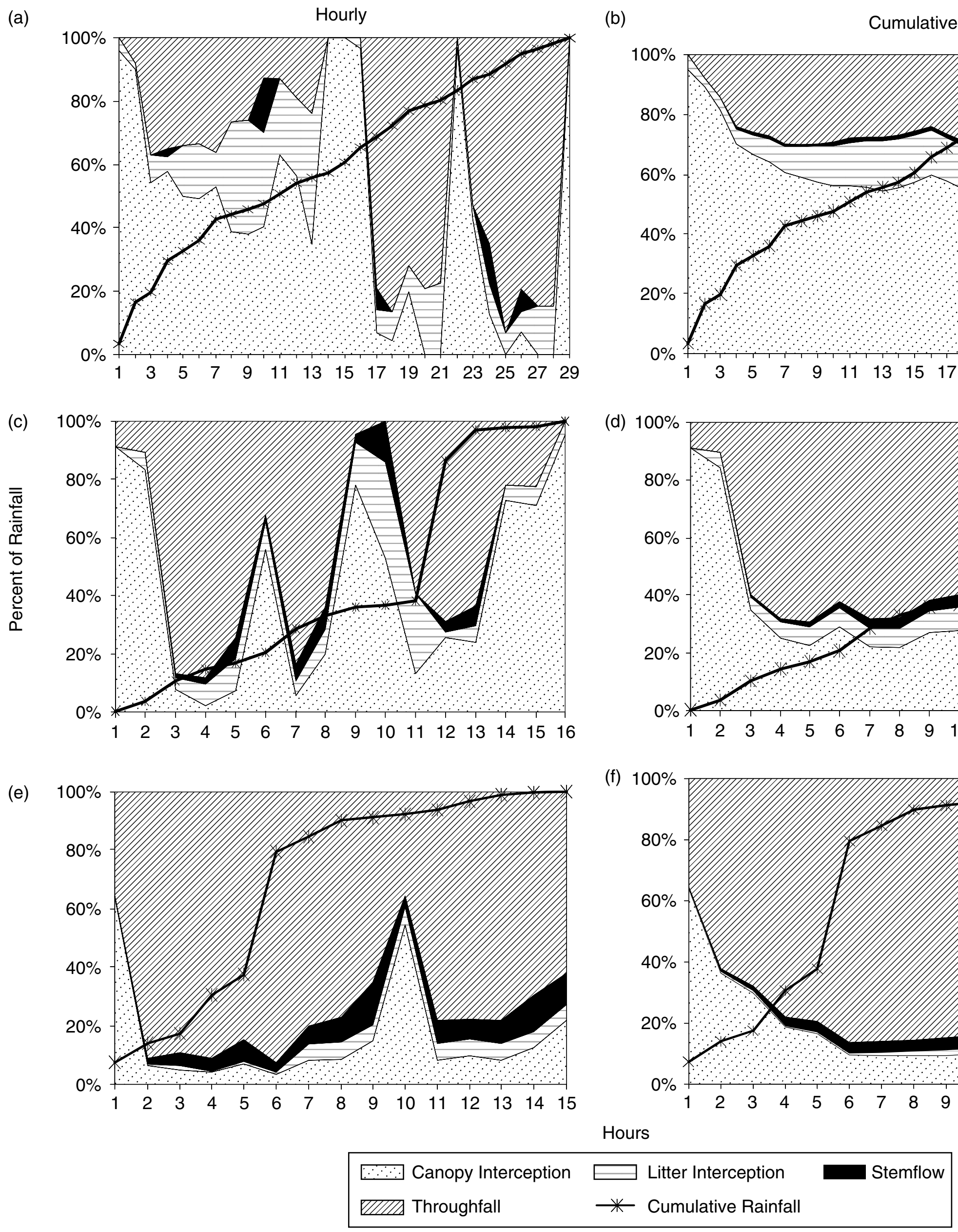

Figure 3. Hourly and cumulative rainfall partitioning for 13 mm (a), (b), 68 mm (c), (d), and 73 mm (e), (f) storms of various durations in an Ashe juniper community

by the tree canopy or litter layer. This particular storm started rather gently with only 7·6 mm of rain over a 3-h period, but more intense storms behaved differently.

During a 73-mm rainfall event over a 15-h period, the storm began with over 7·6 mm of rain in the first hour. The canopy and litter were quickly saturated and throughfall was dominant early in the storm (Figure 3(e) and (f)). Stemflow still lagged behind the precipitation, but was an important factor. During a

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1-h interval (hour 5 to 6) about 29 mm of rain fell, but very little of this rain was intercepted and retained in the canopy. Significant stemflow also occurred during this hour. The cumulative partitioning (Figure 3(f)) demonstrates that only about 15% of the rain received during a typical high intensity storm is intercepted by either the tree canopy or the litter layer. Overall, these events have a greater proportion of throughfall than either lower or mixed intensity events.

DISCUSSION

Interception of rainfall, rather than cumulative evapotranspiration, may better reflect the physical impact of individual trees on the local hydrologic budget (Savenije, 2004). Accurate partitioning of rainfall into evaporation, transpiration, soil water storage, and deep infiltration can aid the development and testing of many hydrologic models. The data must be species-specific because of the different leaf morphologies and canopy structure. Shortgrasses such as curleymesquite (*Hilaria belangieri* (Steud.) Nash) may intercept less (~11%) of the bulk rainfall than mid-grasses such as sideoats grama (*Bouteloua curtipendula* (Michx.) Torr.) (~18%) (Thurow *et al.*, 1987). Shrubs in semiarid systems have been reported to intercept from 13 to 40% of bulk rainfall, deciduous trees from 9 to 20%, and coniferous trees from 20 to 48% (Carlyle-Moses, 2004). When growing in the same environment, conifers typically exhibit a higher interception than plants with broad leaves (Moreno *et al.*, 1993; Silva and Rodriguez, 2001). We found that the Ashe juniper canopy and litter intercepted ~40% of the total bulk precipitation, combined over all ten study sites and for all intensities of rainfall, during a 3-year period. This proportion is much lower than the 79% interception reported by Thurow and Hester (1997) but greater than the 7 to 16% interception reported by Slaughter (1997). The large discrepancy between this study and the Thurow and Hester study results from the different definitions of litter. We measured interception only by the coarse litter fraction, which was typically only 0·4 to 6·0 cm thick and amounted to an average of ~51 kg $tree^{-1}$ (Table II). Hester (1996) measured interception by the organic soil layer (~25 cm thick; T. Thurow, pers. comm. 2005) and recorded a litter biomass >127 000 kg ha^{-1}. We excluded the 6 to 26 cm depth because plant roots were prevalent and water use from this layer would be largely impacted by transpiration. The lower estimate of Slaughter (1997) resulted from considering only canopy interception and not litter interception. A portion of the water initially intercepted by the tree canopy is redirected towards the base of the plant through stemflow. The amount and timing of stemflow is dependent on the plant species and the amount of rainfall. In environments where precipitation occurs rapidly, such as rainforests, stemflow represents a small portion of the bulk precipitation. Marin *et al.* (2000) found that only 1·1% of the bulk precipitation was redirected as stemflow in an Amazon rainforest, and Fujieda *et al.* (1997) reported stemflow of 1·2% in a Brazilian rainforest. In more semiarid environments, stemflow may account for as little as 0·06% in a pine/oak forest (Silva and Rodriguez, 2001) to as much as 45% in some shrubs (Mauchamp and Janeau, 1993). The high interception recorded for creosote tarbush (*Flourensia cerna* DC.), a semiarid land shrub in Mexico, resulted from the simulation of an intense storm and the inverted cone shape of the plant (Mauchamp and Janeau, 1993). A thorough review of woody plants shows that an average of 8·2% of bulk precipitation can be accounted for by considering stemflow (Carlyle-Moses, 2004), although there is great variability between plant species. This average is slightly greater than the 5% we observed (Figure 2), but the branching pattern and shaggy bark of the Ashe juniper can cause stemflow to be deposited as throughfall before the water reaches the main trunk of the tree. Bulk rainfall that was held in the canopy for a short time, or that was slightly redirected before it fell to the ground, was considered as part of the total throughfall.

The redirection of bulk precipitation via stemflow can result in 5 (Slaughter, 1997) to 30 (Bellot and Escarre, 1998) times greater concentration of water near the stem than ambient rainfall. In more tropical rainforest settings the funneling ratio may be as high as 140 (Herwitz, 1986). If we assume that the stemflow would impact an area of 0·5 m^2 around the base of the tree, our study indicates that the funneling of stemflow water results in a 21 to 1 ratio for concentration of rainfall near the trunk when compared to bulk rainfall. For

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example, during a 140-mm rainfall this 0·5 m^2 area would receive 14·9 l of rainfall rather than the 0·7 l that a similar sized area would receive just from bulk rainfall. The higher recorded infiltration rates under juniper trees would allow this water to remain on the site beneath the tree rather than being lost as overland flow (Thurow and Hester, 1997). This additional water could be used to increase the competitive effectiveness of the plant (Ndawula-Senyimba *et al*., 1971) or it could quickly pass by the root system and enter the deeper portions of the soil profile (Martinez-Meza and Whitford, 1996). Given the current density of Ashe juniper trees on the Edwards Plateau, the funneling effect of stemflow could have a large impact on the local and regional water budget.

Environmental effects on rainfall partitioning

Interception in tree canopies is affected by the amount, intensity, and duration of precipitation, as well as the air temperature and wind speed (Schowalter, 1999; Crockford and Richardson, 2000). This relationship may also change with the season as plants lose leaves or as precipitation changes from rain to snow (Breshears *et al*., 1998; Devitt and Smith, 2002). Small rainfall events (<5 mm) are typically captured and held by the tree canopy, almost regardless of the shrub or tree species (Navar *et al*., 1999; Carlyle-Moses, 2004). These storms typically do not produce any stemflow (Silva and Rodriguez, 2001), so the water remains in the canopy. In Ashe juniper canopies, all the precipitation of a 2·5-mm storm is held in the canopy and only 50% of an 11-mm storm reaches the soil surface (Figure 2). The water held in the canopy is lost to evaporation, although there is some possibility that the water may be absorbed by the plant. We found that Ashe juniper effectively stops transpiration when precipitation begins and does not start transpiring for about 3 h after the rain has stopped (data not shown). In fact, if the intercepted rainwater was being absorbed by the plant rather than remaining on the leaf surface, we hypothesize that transpiration would have begun sooner after the rain stopped. By having a 3-h lag, it appears that the water must be evaporated before there is a sufficient moisture gradient for transpiration to begin.

The interaction among the intensity, duration, and amount of rainfall is best shown with the hourly time steps during storms of varying intensities. Many of the storms in semiarid areas are short duration storms that produce low amounts of rainfall (Figure 1), but even in the longer storms, the hourly time step reveals periods with low intensity and periods with high intensity (Figure 3). The interception rates during these periods closely mimic the rates seen in similar intensity short duration storms. Unfortunately, the hourly time-step of our measurements precluded differentiating between free throughfall and released throughfall described by Dunkerley (2000). The most significant difference between storm intensities was in the pattern of stemflow. Small storms did not generate stemflow, and there was a 1-h lag between precipitation and stemflow during high intensity storms. Stemflow would also continue for ~1 h after precipitation had stopped in high intensity storms.

Canopy impact on local water budget

We created a simple model combining average tree size (Table I), the frequency distribution of rainfall events (Figure 1), and the regression equations from Figure 2 to calculate the impact of juniper trees on the local hydrological budget at each of the ten research sites. These estimates are based on solitary trees, although the canopies may influence one another to some extent as tree density increases. The model includes a range from 20% canopy cover, which would be an open savanna, to 100% canopy cover, which would represent a juniper dominated site (cedar break). When juniper cover was low (20%), the amount of water lost to canopy and litter interception averaged 60 mm y^{-1} (Figure 4), regardless of the site. Intuitively this makes sense because the types of storms and the amount of rainfall should not affect canopy or litter interception when tree cover is low. As tree cover increased from 20 to 100%, the amount of water lost to interception increased to an average of 320 mm yr^{-1}. The site that received the most precipitation (Bexar-1) had the greatest amount of water lost to interception (390 mm yr^{-1}). At drier sites, or at sites with little litter under the trees (e.g. Kerr), interception averaged 270 mm yr^{-1} with a closed juniper canopy.

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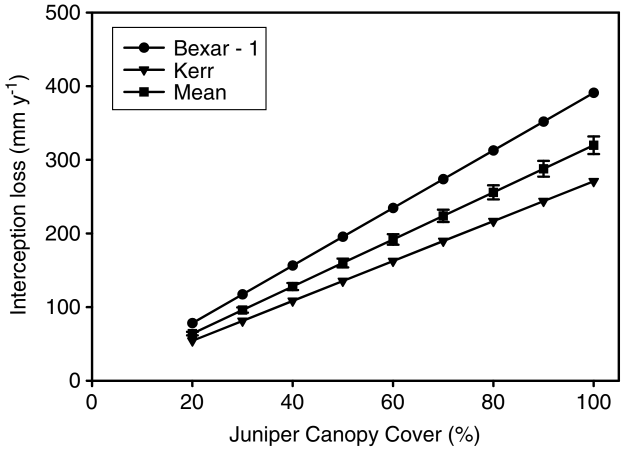

Figure 4. Canopy and litter interception in a juniper community on an annual basis for the wettest (Bexar-1), driest (Kerr) and mean of all ten research sites. The bars on the mean values represent ±1 standard error

Ecohydrologic implications

The amount of water allocated to the physiological process of transpiration by Ashe juniper has been demonstrated in previous studies (Owens and Schreiber, 1992; Owens, 1996; Dugas *et al*., 1998). This study demonstrates the clear impact of the physical presence of Ashe juniper on the local hydrologic budget. Over a 3-year period, nearly 40% of the bulk rainfall failed to reach the soil surface beneath juniper trees across a broad geographic region, effectively changing the annual precipitation under juniper trees in the western region from 600 to 360 mm yr^{-1} and in the eastern region from 900 to 540 mm yr^{-1}. The tree canopies introduced a great deal of horizontal spatial heterogeneity in rainfall within these plant communities.

Low intensity rainfall that conceivably affects local ecosystem processes was entirely intercepted by the juniper trees. High intensity rainfall that supplies most water to the system was less influenced by juniper canopies. The redirection of bulk rainfall to the base of the tree via stemflow may benefit the tree by concentrating water near the root system or, conversely, it may serve to funnel water to preferential flowpaths beneath the trees. Determining the fate of this water is essential for understanding the impact of juniper trees on both the overall site water balance and on the vertical heterogeneity of soil water within the site. If transpiration does not increase, or just marginally increases, after a rainfall, then we can infer that the water must have passed the rooting zone and is not available for the plant. This would be the water ultimately available for deep drainage and aquifer recharge.

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