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# Intra-storm evaporation as a component of canopy interception loss in dryland shrubs: observations from Fowlers Gap, Australia

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## Abstract:

Interception losses from the canopies of dryland plant taxa remain poorly understood, especially the relative contributions of intra-storm and post-storm evaporative losses. Employing a new measuring apparatus, this study uses low-intensity simulated rain, matched to the properties of local rain, to explore interception processes in bluebush shrubs at an Australian dryland site. Five shrub specimens were exposed to simulated rain for 60–90 min. Experiments were repeated at three rainfall intensities (10, 15, and 20 mm $h^{-1}$). Canopy evaporation was found from the difference between the flux of water delivered to the shrub and the flux of throughfall, once equilibrium had been established. The results show that evaporation from the wet foliage during rain proceeds at an average rate of 3·6 mm $h^{-1}$. This figure is for relatively cool spring-season conditions; evaporation rates in hot summer conditions would be larger. Intra-storm evaporation is shown to exceed post-rain evaporation from interception storage on the shrubs, and this differentiates dryland shrub interception processes from those of the better-studied wet forest environment. Implications of the high dryland shrub canopy evaporation rates for aspects of dryland ecology are highlighted. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS dryland shrubs; canopy interception; evaporation; Fowlers Gap

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## INTRODUCTION

Interception of rain on foliage remains less well researched for dryland plants than for forest ecosystems in the humid zone (Dunkerley, 2007). Community-level interception losses are likely to be relatively low in drylands because the plant cover itself is low (often <20–30% canopy cover). However, this does not mean that the interception loss for individual plants is also small, or that interception is of little significance in dryland ecosystems. Indeed, the same general conditions are present in urban environments, where isolated trees, but grown in large numbers, can significantly influence hydrologic processes, including catchment runoff (e.g. Xiao *et al.*, 1998; Xiao and McPherson, 2002). At least three lines of reasoning suggest that in Australian dryland shrub taxa, which form the subject of this paper, and dryland shrubs elsewhere, interception losses may also be quite large. First, in some taxa, shrub canopies are dense, with no or very few canopy gaps. The many fine twigs and abundant, small and densely packed leaves provide a large intercepting surface. Second, the intensity, duration, and total rain depth of storms in the drylands are often small. For example, Návar *et al.* (1999) report that, at a study site in Mexico, 44% of rainfall events delivered <5 mm. At a semi-arid site near Lanzhou, China, 61% of rain events delivered <5 mm and only 2% of events were >20 mm (Wang *et al.*, 2005). Similarly, at this site, 94% of rain events exhibited $I_{10} < 5$ mm $h^{-1}$. Mean event intensities were not reported, but would have been proportionally lower. At a second site in China, 57·5% of events delivered <5 mm (Cheng *et al.*, 2006). From Texas, Owens *et al.* (2006) report that 60% of 2700 rainfall events analysed from a 3-year study delivered <2·54 mm. From southeast Spain, Belmonte Serrato and Diaz (1998) reported that, from 3 years of rainfall data, average event intensities were always <3·1 mm $h^{-1}$. In 1994, the average event depth was only 4·7 mm. These total storm depths are of the same order of magnitude as might be expected of the canopy interception storage depth in dense plant canopies. Furthermore, there are often rainless breaks during dryland storms, when evaporation can partially empty interception stores before rain resumes (e.g. Cecchi *et al.*, 2006), potentially increasing aggregate storm interception losses. For example, Wildy *et al.* (2004) reported that trees in Western Australia resulted in a high interception loss of 49% during a period in which 122 mm of rain fell, mainly in very small rainfall events.

The third factor likely to contribute to relatively large dryland interception losses is the high afternoon temperatures and low relative humidities. It is well documented that the largest concentration of rain events occurs in the late afternoon and early evening, as a result of the lapse of time needed for the dryland surface to warm sufficiently to trigger strong convective uplift. For

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example, data from a very large network of recording rain-gauges in Saudi Arabia show that few storms start before noon, with a clear peak between 15:00 and 19:00, and most events last <1 h (Wheater *et al.*, 1991). Because of this, the small rain events just described deliver their limited amounts of water to hot and dry environments where strong evaporative losses can be expected.

In the light of these dryland characteristics, it is somewhat surprising that many early studies of canopy interception in dryland plants paid little attention to intra-storm evaporative losses, focusing instead on the idea that interception primarily involved the filling of a notional canopy interception store during rain, which would then empty by evaporation once the rain had ended. It was the view of many studies that if the canopy could retain, for example, a volume of water equivalent to a depth of 2·5 mm over the projected canopy area, then the interception loss in storms of a depth at least sufficient to fill this store would be 2·5 mm. This amount could then be subtracted from the open-field rainfall to estimate the net or effective rainfall. This measure of the interception storage capacity is referred to in the remainder of this paper as the static canopy storage capacity (sCSC). (The term 'static' is used because there is also a component of dynamic storage, which is not often measured. This results when an increase in rainfall intensity causes an associated increase in the retained water depth, the volume of water in detention as stem and branch flow, etc. See Dunkerley (2007) for further explanation). One explanation for the focus on sCSC was the frequent reliance on simulated rain, and the experimental use of high intensities and large associated rain depths. Short experimental rain events probably also diminished the apparent relevance of evaporative losses during rain.

The work of West and Gifford (1976) exemplifies the focus on static interception storage and post-rain drying. They tested shrubs under simulated rain at 10 mm $h^{-1}$ and 50 mm $h^{-1}$, noting weight gain (as a measure of sCSC) after 0·5, 1, 2, 5, 10, and 15 min. Mean sCSC derived from these data for the test taxa (big sagebrush and shadscale) was 1·5 mm. Given canopy covers of 19·1% and 16·8% respectively, and in light of the occurrence of about 21 storms of depth >1·5 mm annually, West and Gifford (1976) estimated an annual interception of about 5·9 mm of rain in these communities. No attention was paid to storm duration or rain gaps or to evaporative losses from wet foliage under field conditions.

Using the same approach, Tromble (1983) studied sCSC in 12 specimens of tarbush (*Flourensia cernua*), using simulated rain at 60 mm $h^{-1}$ for 30 min. Tromble stated that a high intensity was used to minimize evaporative losses and so reveal '... actual rainfall interception and storage on the canopy' (Tromble 1983: 525). Intercepted water was quantified from weight gain following the artificial rain. The mean result was an sCSC of 3·0 mm. To estimate seasonal interception losses to the plant community, Tromble then followed the method of West and Gifford (1976). He subtracted the sCSC depth from each of the 17 summer rainfall events in the Las Cruces experimental site that exceeded 3 mm depth (the mean number being derived from 10 years of records), and allowing for only 15% canopy cover by the shrubs at landscape scale (and a little rounding of results), estimated 8·5 mm of total interception ($17 \times 3$ mm $\times 0{\cdot}15 = 7{\cdot}65$ mm) in an average summer season. This amounted to 6·7% of the summer rainfall.

Both of these studies thus adopt the idea that the depth of water that can be held in the sCSC is the amount of interception loss in a storm sufficient to fill that store. But it is clear that if evaporation from the wet canopy proceeds at a significant rate, then the filling of the interception store is actually the net result of water accumulation exceeding the rate of water vapour loss (together with some leaf and branch drip). The higher the intra-storm evaporation rate, the longer will be the time needed to fill the interception store. Such a longer filling time would of necessity be associated with a water loss larger than the sCSC. Thus, the studies just cited almost certainly underestimated the annualized interception losses in the plant communities that were studied.

Thurow *et al.* (1987) made a more sophisticated study that combined field results from natural rain with laboratory work under simulated rain. Their study targeted canopy interception on grass and shrub taxa in Texas, and used a range of simulated rain intensities (25, 50, 90, 114, 150 and 175 mm $h^{-1}$) with rain durations from 1 to 20 min. For samples tested under simulated rain, sCSC was determined by weighing. For field observations, interception was estimated by subtracting stemflow and throughfall from open-field rainfall. For grass samples tested in the laboratory, Thurow *et al.* (1987) found that interception (expressed as a percentage of the dry weight of the vegetation) stabilized after 5–8 min of simulated rain. Longer rain events exhibited no increase in interception loss. They estimated that this reflected the overflow of an sCSC of 1·0–1·8 mm for the taxa tested. The indoor tests would have been made without direct solar heating, and restricted ventilation may have limited evaporation during the short tests, so that the failure of interception losses to continue after 5–8 min may not reflect field interception processes adequately. Moreover, in contrast to the laboratory data, for oak shrubs under natural rain, measured interception loss in millimetres increased with increasing storm depth (though the proportion of the open-field rain lost to interception declined in larger storms; see Thurow *et al.* (1987: figure 5)). Thus, the outdoor results do not suggest that interception losses exclusively reflect the filling and overflowing of a defined sCSC, but rather are consistent with greater total evaporative loss in deeper (and, presumably, longer) rain events. Unfortunately, Thurow *et al.* (1987) did not report data on storm durations, nor did they offer an explanation of their outdoor results, nor a means to adapt their laboratory estimates of sCSC to field conditions.

Tromble (1988a,b) reported studies of interception in creosotebush (*Larrea tridentata*) from New Mexico, and also reviewed earlier studies. Though the work was aimed at understanding canopy interception losses, the work again focuses on quantifying water held in static interception storage. Test shrubs were exposed to intense simulated rain (60 mm h$^{-1}$ for 30 min) and sCSC was found by weight gain. Tromble (1988a: 66) noted that this high intensity was deliberately employed to minimize the significance of evaporation losses, and allow the interception loss (static storage) to be identified. He estimated the average sCSC for individual creosotebush plants to be 3·6 mm rain depth over the projected canopy area. Tromble reasoned that storms of 3·6 mm depth or less would be fully intercepted, whereas larger storms would deliver an effective rainfall equal to the open-field rainfall minus the 3·6 mm intercepted.

A similar approach was adopted by Dunkerley and Booth (1999), in the first published work on canopy interception in Australian chenopod shrubs. Dunkerley and Booth (1999) estimated sCSC by weight gain on cut specimens exposed to simulated rain, and reported values of 1·3–2·0 mm for several taxa. Their remote field site lacked rainfall records, but using an estimated average rain-day total of 5·7 mm, Dunkerley and Booth (1999) estimated that community-level interception losses were likely to be a small fraction ($< 6\%$) of rain-day depths. In the absence of detailed information on rain event properties, they were unable to evaluate the part played by intra-storm gaps and associated evaporative losses.

More recent work has highlighted the role of ongoing evaporation during rain events. Návar and Bryan (1990) showed that the Gash interception model (Gash, 1979; Gash *et al.*, 1995) is quite sensitive to the figure used for the ongoing wet canopy evaporation rate. From field data on open-field rainfall and interception loss, they estimated a mean evaporation rate during rain of 2·95 mm h$^{-1}$. However, because this rate was higher than had been found in interception studies in other environments, they considered that this rate might be an overestimate and that some water might have been absorbed by leaves rather than evaporated. Návar *et al.* (1999) used the Gash interception model to estimate that mean evaporation rate from a wet canopy in the Tamaulipan thornscrub of Mexico lay in the range 2·51–3·31 mm h$^{-1}$, depending upon the kind of field data used for parameterization (throughfall cylinder collectors or throughfall troughs). Návar *et al.* (1999) recommended that evaporation be measured directly, but noted that there are technical difficulties in doing this in the field.

Domingo *et al.* (1998) applied the Rutter interception model (Rutter *et al.*, 1971) to several dryland taxa at a semi-arid site near Almería, Spain. Interception loss was measured directly by subtracting the sum of stemflow and throughfall from the open-field rainfall. This was combined with laboratory work in which cut specimens were fully wetted with a sprayer, and their weight monitored as the canopy dried. The results of the evaporation trials are not presented. However, graphs showing the output from the calibrated interception model (Domingo *et al.*, 1998: figure 6) show intra-storm evaporation rates of up to 5–8 mm h$^{-1}$, with the highest values from *Stipa tenacissima*, a tall tussock grass that has a thick mat of dead leaves around its base. These leaves probably provide a substantial area from which evaporation can proceed.

Apart from the studies just cited, there appear to be no published studies of the intra-storm evaporation rate from the wet canopies of dryland shrubs. Consequently, it is difficult to apportion the relative contributions of intra-storm evaporation and post-storm evaporation in the interception process in dryland shrubs. Wood *et al.* (1998: 92) have suggested that most evaporation takes places after rain events have ceased. The foregoing discussion, however, suggests that the storm event properties of drylands, and the afternoon temperatures and relative humidities, may increase the relative significance of evaporation during rain events. Indeed, the relative dominance of intra- and post-event evaporation may be a factor that differentiates the mechanisms of dryland shrub canopy interception from those of the much-studied canopies of forests in humid environments. In the latter, many studies suggest that ongoing wet canopy evaporation rates are small, certainly $\ll 1$ mm h$^{-1}$ (e.g. Klassen *et al.*, 1998; Klassen, 2001), notably lower than the 3–8 mm h$^{-1}$ noted above from dryland studies.

In the light of the foregoing brief overview of prior studies of interception in dryland shrubs, the objectives of the present work were:

1. To develop and test a simple method for monitoring intra-storm evaporation from shrub canopies during rain.
2. To apply this method using simulated rain at intensities and rain event durations comparable to those occurring naturally in the field area, so as to quantify the evaporation rate from the wet canopy of typical Australian dryland shrubs.
3. To compare the magnitude of intra-storm evaporative losses to post-storm evaporative losses from static interception stores.

## THE FIELD AREA

The canopy interception experiments were carried out at the Fowlers Gap Arid Zone Research Station, which is located in western New South Wales, Australia, about 110 km north of the city of Broken Hill. Climatic characteristics include cool winters and hot summers, and a mean annual rainfall of about 230 mm. The rainfall is highly variable from year to year, and long droughts occur. Summer temperatures can exceed 38 C, and under these conditions the afternoon relative humidity may fall to <5%. The terrain is dominated by low, open shrubland in which various hardy chenopod shrubs are common. Black bluebushes (*Maireana pyramidata*) form the subject of the present study. In this area, these drought-resistant shrubs typically grow to a height of 0·5–1·0 m, though they are often smaller, and have small obovoid leaves a few millimetres in length. The leaves have a rough surface texture, arising from a covering of small hairs, and are typically 2–4 mm in length (Figure 1).

To provide information on the properties of rain events in the area as needed for several ongoing research projects, the author has established a number of recording rain-gauges. Storm properties reported here have been derived from a tipping-bucket rainfall record spanning the period late 2002–early 2006. This was done with computer routines written by the author. In the analysis, a storm event was defined as a period of rain separated from other periods of rain by at least 12 rainless hours. Shorter gaps within a storm event were allowed. The 2002–2006 rainfall record was analysed for storm event sizes and durations. In addition, the relationship between intensity and measurement period was examined through the whole record. Intervals for which maximum intensity was determined ranged from 1 min to 24 h, and included $I_{30}$ and $I_{60}$. The daily distribution of storm start times was also noted.

The analyses show that, at Fowlers Gap, the fewest rain events begin in the early hours of the morning, with an uneven rise to a peak between 18 : 00 and 19 : 00. This means that most rain falls during the warm and dry afternoon hours (sunset in summer not occurring until after 20 : 00), when relative humidity is often very low, and considerable sensible heat is stored in the warm soil. Such a temporal distribution of rain is of clear relevance to the behaviour of evaporation from shrub canopies.

In the available rainfall record spanning 1288 days (data collection is ongoing), the total recorded rainfall was 697·5 mm. This fell on only 117 days, so that about 9% of days had rain. The average daily rainfall was just under 6 mm. Average storm duration was 6 h 18 min. The largest storm, in 2003, lasted nearly 32 h and delivered 56 mm of rain. The average intensity through this storm, however, was only 1·75 mm $h^{-1}$. Maximum intensities from the entire period of record for several storm durations relevant to the experimental programme are as follows: $I_{30}$, 30 mm $h^{-1}$; $I_{60}$, 21 mm $h^{-1}$ $I_{120}$, 13·2 mm $h^{-1}$; $I_{180}$, 9·0 mm $h^{-1}$. The simulated rain used in the experiments was designed to accord with these field data on rain occurrence in the local area. These intensities are maxima for the time intervals specified, so that most storms in the study area involve smaller intensities than those just listed. Therefore, in the experiments to be described next, the maximum $I_{60}$ used in rainfall simulation experiments was 20 mm $h^{-1}$. Several lesser intensities were also used.

Figure 1. The small rounded leaves of bluebush shrubs used in the interception experiments. The covering of fine hairs, which restrict surface wetting, can be seen in the photograph. The leaves are about 3 mm in length

## EXPERIMENTAL METHODS

Multiple canopy interception experiments were carried out on each of five cut specimens of entire bluebush shrubs collected on the Fowlers Gap Arid Zone Research Station. The shrubs were chosen to be typical of those growing in this area in terms of height and canopy thickness. Shrub dimensions, including height and dry weight, were recorded. The rainfall simulation work was done in September, when daily temperatures only reached 25–30 C. The water used was from the reticulated residential supply on the research station. The water is derived from surface dams, and is non-saline. Each shrub was subjected to multiple rainfall simulations at differing intensities and durations, after being allowed to dry completely for 24 h. These shrubs suffered no visible changes in canopy properties during the week of experimentation. To maintain canopy properties, the shrubs were stored in the shade and the stems were placed in water.

Each shrub specimen was weighed dry and then mounted in growth position on a large sheet metal tray, which had vertical sides 10 cm tall and a floor that sloped to direct all throughfall runoff toward an outlet pipe (Figure 2). Suspended 1·9 m above the shrub and tray was a Perspex chamber 0·5 m × 0·5 m × 0·05 m, which carried 361 drip-forming modules set on a grid of 2·5 cm × 2·5 cm. However, in the present experiments, only 190 of the drippers were used, the remainder being closed. This created an array on a 2·5 m × 5 cm grid. The drip modules were standard plastic irrigation drippers (Figure 3). Water was fed into this enclosed chamber by a peristaltic pump whose speed was digitally controlled and set to deliver flows equivalent to rainfall intensities of 10, 15 and 20 mm $h^{-1}$ over the area below the drip-forming chamber. The sheet-metal tray was coated with water-repellent furniture wax prior to each experiment. This treatment caused water to bead on the surface and run off rapidly over the sloping floor of the tray, toward the outlet drain, where flow was caught and weighed every 5 min during simulated rain. The waxing was done to minimize evaporative losses from water retained on the metal tray and to minimize detention of water on the tray surfaces.

Figure 2. A bluebush shrub in test position on the throughfall tray. The outlet pipe is concealed behind the front wall of the tray, but the runoff collecting container can be seen in the small pit at the lower right of the image. The tray measures 1 m × 1 m

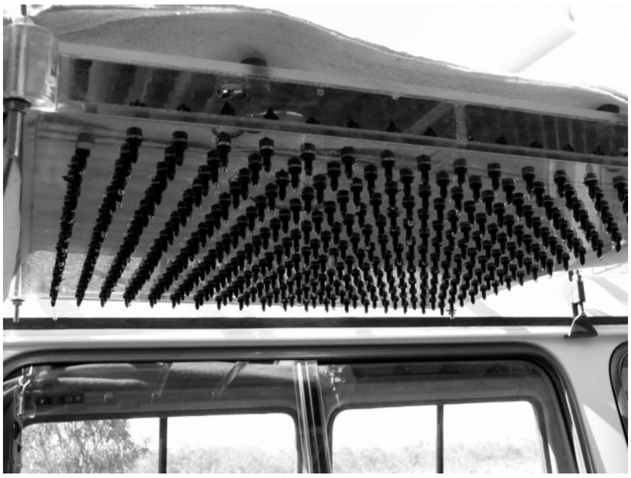

Figure 3. The dripper module. The module is shown with all drip-formers installed, and water drops can be seen in various stages of accumulation on many of these. The clear acrylic water chamber is shaded by cotton fabric to keep the apparatus and water cool. This covering also shaded the shrub and drip-tray mounted vertically below

The dripper module, shrub and tray were protected by a wind screen on two sides. Screening was kept to a minimum to allow free air circulation around the shrub during the experiments, but limited protection was required to ensure that the water drops were not swept aside when the wind was strong and gusty.

The experiments targeted the measurement of evaporation from the wet canopies during simulated rain. This required an accurate input–output water balance. The peristaltic pump delivering water to the dripper module was fed from a series of plastic reservoirs each of which was weighed before a simulated rain experiment, as well as every 5 min during the rain, to enable the volume of water delivered to the shrub to be checked independently of the nominal flow rate set on the pump. Likewise, the outflow from the tray was collected in a reservoir placed under the outlet pipe of the metal tray that caught all free and released throughfall. This reservoir was also weighed every 5 min during an experimental run, being quickly exchanged with an identical but empty container. Once input and output flows were in equilibrium, any difference between water input via the pump and output via the collector drain can only have been lost to evaporation or splash. However, no splash was detected beyond the walls of the sheet-metal trough. Consequently, water unaccounted for is taken to have evaporated. All water weights were recorded to the nearest 1 g on battery-powered digital scales, verified to have an accuracy of better than 1% in comparison with standard analytical balances in the laboratory. All experimental timing was done with a digital stopwatch.

Prior to commencing an interception experiment, the cleaned and waxed throughfall tray was wetted-up using the rainfall simulator until a steady outflow was generated. This was done to fill any static storage on the tray itself. This is quantified later. The pump was briefly stopped, immediately halting the release of water drops, the shrub quickly set in place, and the experiment started.

Air and water temperatures were recorded every 5 min during all experiments, and wind speed and relative humidity data were derived from a recording weather station located about 250 m from the experiment site. All experiments were made in the shade of a building located to the north of the experiment site. Experiments were generally continued for 60–90 min, until stability was reached in the rate of runoff from the collecting tray. Rainfall rate was held constant for the entire duration of each experiment. One experiment was run at an intensity of 5 mm $h^{-1}$, which was below the lowest speed of the digital pump. This was achieved by switching the pump on or off every 60 s, to supply a 50/50 duty cycle of the flow rate needed to deliver an intensity of 10 mm $h^{-1}$.

The wet shrub canopy was considered likely to be the main source of evaporation. However, four experiments were run with no shrub present, in order to measure the evaporative loss from the metal throughfall collecting tray. These four experiments were made at the four different intensities used in the shrub tests. The water stored on the sheet metal tray was also quantified several times during the experiments, in order to check the size of this store. An absorbent cloth was weighed dry, and then used to mop all retained water from the metal tray into a beaker. The damp cloth was then added to the beaker, allowing the total weight of retained water to be found accurately.

At the end of each 60–90 min experiment, the shrub was weighed with its retained water. This was done with care, to minimize the loss of water by shaking. The difference between wet and dry weights was used as a measure of the sCSC, though determining this parameter was not a key objective of the present work. Following weighing, the shrub was photographed from above, a 10 cm scale bar being included in the image. Subsequently, canopy area and canopy gaps were quantified from the digital photographs using standard computer software.

In data processing, the input–output analysis included appropriate adjustments for the area of the metal throughfall tray not covered by the shrub canopy. The equilibrium input and output rates used in the calculation of shrub canopy evaporation rates were the means of the last 20–30 min of each test (see Figure 4). Slight fluctuations around the steady input and output rates were related to changing water supply reservoirs (input) and wind gusts dislodging intercepted water (output). Some small fluctuations in output were also the result of streams of water trickling across the throughfall tray as sufficient water had accumulated on the waxed surface to run off.

The low intensities used in the experiments were based on the local rainfall recorded already described. The recording rain-gauge from which the record was taken was located about 400 m from the experiment site.

The diameter of the water drops delivered at each intensity was assessed by collecting 50 drips and determining their mean diameter from the aggregate weight. The interval between the release of successive water drops from a drop-forming module was also recorded for each rain intensity by timing the release of 50 drops and finding the mean interval between them.

It is important to emphasize that the estimates of the rate of evaporation from the wet shrub canopies reported here did not require the sCSC or the water retention on the metal tray to be known. Rather, the evaporation rate is taken as the difference in the flux of water being applied by the dripper system and that running off from the metal tray, once a steady rate of runoff has been established. Evaporation from the tray itself was subtracted from the final estimate of the evaporation rate. The input and output water fluxes were recorded accurately every 5 min using the weighing protocol outlined earlier. Experimental runs of 60–90 min duration were found to be sufficient to demonstrate sustained equilibrium conditions on the shrub canopy.

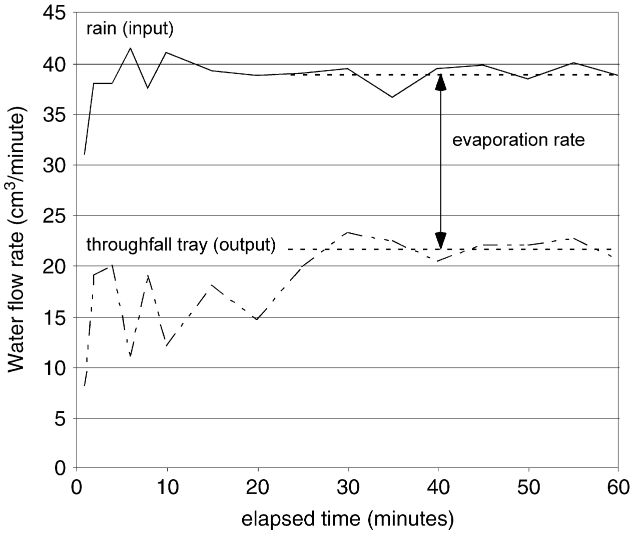

Figure 4. Plot of the experimental data from test 3, on bluebush specimen no. 2. The horizontal dashed lines through the latter part of the test indicate the mean rain rate and throughfall rates. The difference between these rates, in this case about 17 ml $\text{min}^{-1}$, represents the gross evaporation rate. The evaporative loss from the throughfall tray is then deducted to yield the net rate from the shrub canopy. See text for details

There would inevitably have been some evaporation of very small impact droplets thrown up when drops fell directly onto wet areas of the metal tray and, to a lesser extent, onto the shrub foliage. The side walls of the tray caught any large drops, and the soil outside the walls remained completely dry even after many hours of simulated rain. However, mist droplets thrown up by impacts on the metal tray may well have evaporated during their trajectory through the air. This is taken into account in the loss tests made on the tray with no shrub present, when the splash would undoubtedly have been more extensive than with most drops striking shrub foliage rather than metal. Nevertheless, the total evaporation rate recorded in these tests was always very much smaller than the rates exhibited from wet shrub canopies. Detailed results are presented later, but it can be noted here that the evaporation rate from the empty tray subject to the same simulated rain was always less than 10% of the shrub evaporation rate, and generally <6%. These are maximum estimates because, in addition to the elevated splash losses probably present during the empty tray tests (because the water drops struck the tray from their full fall height), without a shrub present the tray was more exposed to free air exchange and, thus, to enhanced potential evaporative losses.

## RESULTS

The properties of the five test shrubs are noted in Table I and the drop size characteristics for each experimental rainfall intensity are presented in Table II.

Summed across all experiments, the five shrub specimens and the empty sheet-metal tray were exposed to >24 h of low-intensity simulated rain. Data from the nearby weather station confirmed reasonably consistent

Table I. Properties of the five shrub specimens used in the interception experiments

| Specimen no. | Height (cm) | Canopy area ($\text{cm}^2$) | Dry weight (g) | sCSC (mm; g) |
|---|---|---|---|---|
| 1 | 63 | 1562 | 800 | 1·6; 250 |
| 2 | 71 | 3527 | 1400 | 0·56; 200 |
| 3 | 61 | 2911 | 1500 | 1·0;300 |
| 4 | 55 | 1460 | 1100 | 1·0;150 |
| 5 | 40 | 1583 | 750 | 0·95; 150 |

Table II. Properties of the simulated rain used in the interception experiments

| Rainfall intensity ($\text{mm h}^{-1}$) | Interval between drips (s) | Mean drop diameter (mm) | Drop impact frequency ($\text{s}^{-1}\ \text{m}^{-2}$) |
|---|---|---|---|
| 10 | 14·9 | 2·35 | 56 |
| 15 | 10·9 | 2·38 | 75 |
| 20 | 7·9 | 2·36 | 104 |

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conditions during the week of experiments. Work began in the morning, when temperatures were 18–20 C and relative humidities about 20–25%. By mid afternoon, temperatures had risen to 25–27 C and relative humidities were 15–17%. Most days were moderately windy, with average speeds of 8–12 km $h^{-1}$. There was no rain during the period of experimentation.

### *Performance of the experimental apparatus*

As described earlier, the rate of water flow to the dripper system was checked by monitoring the weight loss of the supply reservoir. The flow rate was found to depart slightly from the nominal output of the digital peristaltic pump, presumably because of wear on the Tygon tubing altering the internal tubing diameter. However, the maximum departure from the nominal rate was small (low by 1·15% at 10 mm $h^{-1}$, by 1·07% at 15 mm $h^{-1}$, and by 0·63% at 20 mm $h^{-1}$).

The waxed sheet-metal collecting tray functioned as an efficient collector of throughfall. In a typical experiment, 2–3 l of water was delivered by the dripper system. Measurements of water retained on the tray showed that a mean of 188 g water was retained. However, this storage does not affect the determination of evaporation rates from the shrub canopies, which were determined from the difference of the rain input and throughfall output fluxes at equilibrium. The water on the metal tray was mostly held in large beads with small ratios of surface area to volume, which would tend to diminish evaporation rates in comparison with a thin film over the whole tray.

It was noted earlier that experiments were run with no shrub present to quantify the evaporation rate from the tray itself. The results showed that the mean evaporation rate was 0·20 mm $h^{-1}$ (standard deviation 0·137 mm $h^{-1}$), with no clear relationship to intensity. However, the maximum evaporation rate from the bare tray was 0·36 mm $h^{-1}$, and this was recorded at the highest rainfall intensity (20 mm $h^{-1}$) when the formation and evaporative loss of small splash droplets seems likely to have been most intense.

### *The water drops*

The measurement of drop diameters generated by the drip-formers showed a mean drop diameter of 2·36 mm. This diameter varied only very slightly with rainfall intensity (Table II). Drops of this diameter have a terminal velocity of 7·1 m $s^{-1}$ (Dingle and Lee, 1972). However, given the drop fall height of only about 2 m, the water drops would only have reached about 78% of their terminal velocity (Laws, 1941).

The rate of drop release per drop-former increased systematically with rain intensity (Table II), from one drip per 14·9 s at 10 mm $h^{-1}$ to one drip per 7·9 s at 20 mm $h^{-1}$. This yields areal drop impact frequencies of about 56 $s^{-1}$ $m^{-2}$ at 10 mm $h^{-1}$, increasing to about 104 $s^{-1}$ $m^{-2}$ at 20 mm $h^{-1}$. There appear to be no published data on drop impact frequencies from drylands against which these results can be compared. They are, however, somewhat lower than the frequencies for more intense rain at Miami, Florida, reported by Foley and Silburn (2002). No other studies using simulated rain appear to have reported data on the drop impact frequencies that were involved. Nevertheless, this is an important aspect of rain viewed as a point-process at small spatial scales (Uijlenhoet and Sempere Torres, 2006) that deserves wider attention, especially when simulated rain is used in erosion experiments. Blackburn *et al.* (1974) used a drip-formers density of about 1494 $m^{-2}$ in their mobile infiltrometer, but the rate at which each drip-former released a water drop was not reported, so that the drop impact frequency cannot be estimated.

### *Evaporation rates from the shrub canopies*

From the 18 shrub interception tests, the mean rate of evaporation from the canopies at equilibrium was 3·6 mm $h^{-1}$ (standard deviation 1·14 mm $h^{-1}$), after correction for the loss from the sheet-metal throughfall collecting tray. In half of the tests, the evaporation rate was >4 mm $h^{-1}$. The highest rate was 5·76 mm $h^{-1}$, from shrub No. 1 at 10 mm $h^{-1}$ rain intensity. The lowest evaporation rate was 2·06 mm $h^{-1}$, from shrub No. 3 at 10 mm $h^{-1}$ rain intensity. This low result was obtained from an early morning experiment when the air temperature was <18 C. The course of rain input and throughfall output in a typical experimental run is shown in Figure 4.

The five shrub specimens had canopies that differed somewhat in their density. Shrub No. 2 had the least dense canopy, and exhibited the lowest evaporation rate (the mean from all tests on this plant was 2·86 mm $h^{-1}$). Shrub No. 1 appeared to have the densest canopy and exhibited the highest mean evaporation rate, of 5·57 mm $h^{-1}$ (Table III).

The evaporation data were pooled according to the intensity of simulated rain and for each shrub specimen. Differences were examined using small-sample *t*-tests (Freund, 1974). The results show no statistically significant differences among the five shrubs, though shrub No. 2 (with a low-density canopy) nevertheless has the lowest rate of evaporation. Likewise, *t*-tests showed no significant differences between mean intra-storm evaporation rates measured at 10, 15 or 20 mm $h^{-1}$.

### *Canopy storage capacities and interception losses*

Though the determination of sCSC values was not a primary objective of this study, estimates were made by noting the weight gain after equilibrium conditions had been established between rainfall and throughfall tray runoff. The mean value of sCSC for each shrub, expressed both as millimetres depth over the projected canopy area and in millilitres of water held on the plant, is included in the shrub data in Table I.

The sCSC values are quite small. The mean for the five shrubs was only 1·02 mm depth (standard deviation 0·37 mm). The largest value, for shrub No. 1, was 1·6 mm. This was a large shrub with a dense canopy.

Table III. Summary of interception test results. Data for all five shrub specimens are shown, together with the tests run using the empty throughfall tray

| Test no. | Shrub no. | Evaporation rate ($\text{mm h}^{-1}$) | Mean air temperature during test ( C) | Rainfall intensity ($\text{mm h}^{-1}$) |
|---|---|---|---|---|
| 5 | 1 | 5·76 | 22 | 10 |
| 22 | 1 | 5·38 | 25 | 10 |
| Mean (SD) | | 5·57 (0·19) | 23·50 | |
| 3 | 2 | 2·22 | 22 | 10 |
| 13 | 2 | 2·86 | 22 | 20 |
| 11 | 2 | 3·75 | 24 | 10 |
| 12 | 2 | 2·60 | 23 | 15 |
| Mean (SD) | | 2·86 (0·65) | 22·75 | |
| 14 | 3 | 2·14 | 22 | 5 |
| 7 | 3 | 2·06 | 18 | 10 |
| 8 | 3 | 2·88 | 23 | 15 |
| 9 | 3 | 3·09 | 24 | 20 |
| 1 | 3 | 4·76 | 18 | 10 |
| Mean (SD) | | 2·99 (1·09) | 21·00 | |
| 4 | 4 | 4·52 | 22·5 | 10 |
| 15 | 4 | 4·11 | 24·5 | 10 |
| 16 | 4 | 4·44 | 26 | 15 |
| 17 | 4 | 4·93 | 25·5 | 20 |
| Mean (SD) | | 4·50 (0·34) | 24·63 | |
| 18 | 5 | 4·17 | 25 | 10 |
| 19 | 5 | 3·79 | 24 | 15 |
| 6 | 5 | 4·55 | 22 | 10 |
| Mean (SD) | | 4·17 (0·31) | 23·67 | |
| 10 | Empty tray | 0·36 | 24 | 20 |
| 20 | Empty tray | 0·18 | 18 | 15 |
| 21 | Empty tray | 0·24 | 22 | 10 |
| 2 | Empty tray | 0·03 | 19 | 10 |
| Mean (SD) | | 0·20 (0·14) | 20·75 | |

The smallest was 0·56 mm, for shrub No. 2, the shrub with the least dense canopy. In terms of retained water volume, these values equate to 150–300 ml held on the canopy (Table I).

The volumes of water that were lost though interception processes during the experiments were commonly about 1 l (average: 1·03 l in the 18 shrub tests). This excludes the water that was used to wet-up the throughfall tray prior to starting each new experiment and, thus, represents only the abstraction into sCSC plus the evaporative losses. Hence, it is clear that the intra-storm evaporative losses greatly exceed the abstraction of water into sCSC. The latter only held 150–300 ml (and averaged 210 ml; see above), so that evaporation amounted to the remaining 700–850 ml, or three to four times the volume represented in the sCSC. This finding is clearly relevant to interpretations of the relative contributions made to interception losses by static storage followed by post-storm evaporation and by evaporation during rain.

## DISCUSSION

It was noted earlier that the simulated rain was composed of drops that reached <80% of their terminal velocity. To this extent, the simulations lack full similarity with natural rain. Moreover, unlike natural rain, the drops were of nearly uniform size. Therefore, it is possible that the interception rates reported above somewhat underestimate the natural rates. However, in view of the general physical reality of the low rain intensities used, the use of a dripper system was considered preferable to methods such as full immersion in a water reservoir that have been used in other studies of interception in dryland plants (e.g. Wood *et al.*, 1998). Moreover, the low rain intensities used in the current experiments, corresponding to the natural rain intensities of the field area, arguably yield more meaningful results than the unrealistically high intensities often mandated by high-pressure, spray-nozzle systems. For example, Schlesinger *et al.* (1999) used simulated rain at 140 $\text{mm h}^{-1}$ for 30 min, an intensity that they note is not representative of rain in their New Mexico study area, having not been reached even by the 1 min intensity of natural rain events. Schlesinger *et al.* (1999) note that they adopted a very high rainfall intensity in order to differentiate shrub and non-shrub plots. However, it is unclear what relevance this differentiation has, if it is not manifested during the kinds of rain intensities actually experienced in the area. Others have also used very high rain intensities, extending to 420 $\text{mm h}^{-1}$ (Keim *et al.*, 2006; other examples are cited in Dunkerley (2007)). As noted earlier, in many drylands, intensities in rain events are often only 1–5 $\text{mm h}^{-1}$. Thus, the use of more physically realistic rainfall intensities is an area where a shift in the measurement protocols used in interception experiments seems desirable. The use of very high rainfall intensities would diminish the relative significance of evaporation from wet shrub canopies, and this may have contributed to the historical focus on evaluating sCSC noted earlier. Correspondingly, this may have diverted attention from a focus on intra-storm evaporation, which may be of particular relevance to dryland shrubs.

The mean drop diameter generated by the dripper modules was 2·36 mm (standard deviation among the three intensities was 0·015 mm). Drops of this diameter are common in natural rain of the intensities simulated here (e.g. see Marshall and Palmer (1948)) and, though far less abundant numerically than smaller drops, they make up a larger fraction of the total water volume delivered per millimetre of rain depth. Larger drops are almost certainly also more important in the generation of impact droplets on wet foliage, and this is thought to be a key component of the evaporation that drives interception loss (e.g. see Murakami (2006)). Ideally, however, a wider range of drop sizes should be present in simulated rain.

There are other aspects of the experimental protocol that limit the extent to which conditions during natural rain have been captured. The experiments did not correctly recreate the near-surface conditions during thunderstorm rain, which often involve full cloud cover, gusty airflow driven by downdrafts, and elevated relative humidity. Indeed, this would only be possible within a controlled-environment chamber. An experiment under controlled environment conditions could be very informative, but to the author's knowledge has never been adopted in interception studies. As noted earlier, the dripper module that was suspended above the test shrubs generally shaded both the test plants and the throughfall tray, so that only diffuse incident radiation reached the test shrubs, akin to what would occur beneath cumulonimbus clouds. The wind screening likewise reduced ventilation around the plant foliage and the throughfall tray, with the benefit that humidity levels around the wet plant would have been increased toward those expected during rain. There are few existing data upon which to base an analysis of relative humidity at shrub height during rain in drylands. However, virga is common in the field area owing to the persistent warmth and dryness of the lower atmosphere when rain is falling from a high cloud base. Conditions at the ground frequently remain quite warm during rain, and field experience of many rain days has shown that post-rain evaporation, and evaporation during gaps in the rain event, can be very rapid. Sensible heat advected from the heated soil surface undoubtedly contributes to such evaporation, and this contributes to cumulative storm-period and annual interception loss. Data on near-surface atmospheric conditions during rain would shed light on the conditions for evaporation and could be employed to quantify and correct for any overestimation of evaporation rates contained in data derived using experiments of the kind reported here.

The results presented above show that the largest evaporation rates from the wet shrub canopies came from the largest and densest canopies, rather than from those with smaller or more open canopies. This suggests that the ventilation of the shrub canopy is less important to intra-storm evaporation than is the area of canopy that can retain water. However, more detailed measurements of the shrub canopies than were collected here would be required to investigate this more fully. In particular, observation of the shrub canopies during and after rain suggested that the leaf surfaces were not fully wetted. This presumably relates to the cover of fine hairs visible in Figure 1. Instead, it appeared that much of the water held by the shrub was in droplets rather than as a more extensive film of water covering the whole surface of the foliage.

It is clear from the results that ongoing evaporation during the simulated rain, even for the limited duration of the tests (60–90 min), exceeded the post-rain evaporation of water held in the static interception stores. This contradicts the claim made by Wood *et al.* (1998: 92) that most evaporation occurs after rain has ceased. Longer rain events, with correspondingly lower mean rainfall intensities, would increase the relative importance of evaporation during a rain event and diminish the significance of post-rain evaporation. Likewise, summer storms would almost certainly exhibit higher rates of intra-storm evaporation. The mean rate of intra-storm evaporation found in the present experiments (3·6 mm $h^{-1}$) is significant given the low intensities of many storms in this area. Additional evaporation would occur on the litter that is often found in abundance beneath these shrubs. Therefore, little water could be expected to reach the ground beneath these shrubs in rain events of low intensity. The presence of preferred drip-points beneath the canopy was not noted during the present experiments; but, if present, these might provide a means by which some water could reach the ground in larger amounts than the mean intra-storm evaporation rates would suggest.

There are various potential sources of error in the calculation of evaporation rates from the wet shrub canopies. Evaporation from the metal throughfall tray was quantified and shown to be small in relation to the overall evaporative loss. Some loss from the evaporation of very small impact droplets was almost certainly involved, but was not possible to quantify. Finally, it is likely that there was some evaporation from the growing drops suspended from the drop-formers, given that each drop took 5–10 s to develop to full size and then fall. However, these drops were large and had a small surface area-to-volume ratio, so that evaporation rates from these would not have been great. Furthermore, these evaporative losses were included in the aggregate loss determined in the tests when no shrub was present. Total evaporation losses in these tests averaged just 0·2 mm $h^{-1}$, and this is small in relation to the rates when a shrub was present. Given that the evaporation rate in the shrub tests was corrected for this non-shrub evaporation, the final rates as reported above can be considered free of major sources of error.

### *The importance of intra-storm evaporation*

It is important to understand the nature of water interception processes on dryland shrubs for a number of reasons. In dryland ecology, much attention has been paid to the role of shrubs in modifying land-surface responses to rain and runoff, and in modifying soil and nutrient losses in runoff. Quite commonly, runoff and soil loss from small experimental plots containing shrubs have been compared with plots lacking shrubs. Infiltration has been estimated from the difference between the rates of applied rainfall and runoff. Therefore, part of what was claimed to be enhanced infiltration on the shrub plots might in fact have been interception loss from the shrub canopies. This approach has been used by Tromble *et al.* (1974), Wood and Blackburn (1981), Elkins *et al.* (1986), Andreu *et al.* (1998) and Schlesinger *et al.* (1999). Though these studies have typically used very high rainfall intensities, and so minimized the significance of intra-storm evaporation from the shrub canopies, these test conditions do not accord with the natural rain intensities in the study areas concerned. The relative contributions to the apparent enhanced infiltration rates on shrub plots made by soil properties and by interception losses cannot be evaluated from these studies.

There are few dryland studies where seasonal or other longer-term interception losses have been measured. One such study was carried out in China to examine the water-balance outcome of shrub plantings designed to stabilize mobile dunes (Wang *et al*., 2005). That study employed nine throughfall collectors under the canopy of each of two shrub taxa used in land rehabilitation. Interception was estimated as the difference between open-field rainfall and throughfall (no stemflow being evident). By regressing throughfall against gross rainfall, sCSC was estimated from the regression intercept. Values for the two shrub taxa were 0·71 and 0·75 mm. This method differs from the standard method of Leyton *et al*. (1967). The Leyton method relies not on a least-squares regression of net precipitation against open-field rainfall, but rather the fitting of an envelope fitted through the points of maximum net precipitation for each rainfall. This is to avoid the tendency for intra-storm rain gaps (and evaporative losses) to diminish the net precipitation when compared with shorter storms of the same depth. This effect is not allowed for in the method used by Wang *et al*. (2005), though the scatter in their data is smaller than is usual with data derived from forest vegetation. Also, the aggregate throughfall data collected do not provide estimates of the disaggregation of interception losses into the components caused by static interception storage versus intra-storm evaporation during the monitored rain events.

A final implication of the high rates of intra-storm evaporation reported here relates to the nature of the shrub microenvironment. It is known that the soil beneath dryland shrubs exhibits higher infiltrability than nearby interspace soils (Dunkerley, 2000). This is advantageous for the capturing of stemflow, throughfall, and run-on from upslope. However, in small rain events, little or no stemflow may be generated (e.g. Cecchi *et al*., 2006), though for *Flourensia cernua*, a Chihuahuan desert shrub, more stemflow was found at low rain intensities than at high rain intensities (Mauchamp and Janeau, 1993). From shrubs such as those tested here, there would be little or no throughfall in small rain events. Consequently, in small events the shrub canopy may actually cost the plant a significant reduction in available water. Thus, the enhanced soil moisture supply in the subcanopy microenvironment may be related to the capture of run-on water and to reduced evaporative losses from the shaded soil surface (e.g. Pariente, 2002). The water loss to interception may more than offset other tendencies for trees and shrubs to facilitate the survival of ephemerals beneath the canopy (Robinson, 2004), with more extensive biomass in intershrub areas. There may be a need for shrub roots to extract water from intershrub areas where interception losses are greatly diminished, and the spread of roots may contribute to the extension of the zone of elevated soil infiltrability beyond the canopy limits (Dunkerley, 2000). Thus, depending on the shrub canopy and the local rain event properties, it is possible to envisage that the mosaic of bare water-source areas and vegetated water sinks that is often identified in drylands (e.g. Puigdefábregas, 2005) may be sustained primarily in larger rain events, and that the properties of the two landscape zones might be reversed in small events. Clearly, there are ecological aspects of canopy and litter interception at low rainfall intensities that warrant further exploration. These matters warrant attention not least because, in coming years, changes in both temperature and rainfall regimes associated with global environmental change may result in interception losses contributing to growing water stress in dryland ecosystems.

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## REFERENCES

Andreu V, Rubio JL, Gimeno-García E, Llinares JV. 1998. Testing three Mediterranean shrub species in runoff reduction and sediment transport. *Soil and Tillage Research* **45**: 441–454.

Belmonte Serrato F, Diaz AR. 1998. A simple technique for measuring rainfall interception by small shrub: "interception flow collection box". *Hydrological Processes* **12**: 471–481.

Blackburn WH, Meeuwig RO, Skau CM. 1974. A mobile infiltrometer for use on rangeland. *Journal of Range Management* **27**: 322–323.

Cecchi GA, Kröpfl AI, Villasuso NM, Distel RA. 2006. Stemflow and soil water redistribution in intact and disturbed plants of *Larrea divaricata* in southern Argentina. *Arid Land Research and Management* **20**: 209–217.

Cheng X, An S, Li B, Chen J, Lin G, Liu Y, Luo Y, Liu S. 2006. Summer rain pulse size and rainwater uptake by three dominant desert plants in a desertified grassland ecosystem in northwestern China. *Plant Ecology* **184**: 1–12.

Dingle AN, Lee Y. 1972. Terminal fallspeeds of raindrops. *Journal of Applied Meteorology* **11**: 877–879.

Domingo F, Sánchez G, Moro MJ, Brenner AJ, Puigdefábregas J. 1998. Measurement and modelling of rainfall interception by three semi-arid canopies. *Agricultural and Forest Meteorology* **91**: 275–292.

Dunkerley DL. 2000. Hydrologic effects of dryland shrubs: defining the spatial extent of modified soil water uptake rates at an Australian desert site. *Journal of Arid Environments* **45**: 159–172.

Dunkerley DL. 2007. Water interception on vegetation and elsewhere in the environment: significance, mechanisms, and research needs. *Earth-Science Reviews* submitted for publication.

Dunkerley DL, Booth TL. 1999. Plant canopy interception of rainfall and its significance in a banded landscape, arid western New South Wales, Australia. *Water Resources Research* **35**: 1581–1586.

Elkins NZ, Sabol GV, Ward TJ, Whitford WG. 1986. The influence of subterranean termites on the hydrological characteristics of a Chihuahuan desert ecosystem. *Oecologia* **68**: 521–528.

Foley JL, Silburn DM. 2002. Hydraulic properties of rain impact surface seals on three clay soils—influence of raindrop impact frequency and rainfall intensity during steady state. *Australian Journal of Soil Research* **40**: 1069–1083.

Freund JE. 1974. *Modern Elementary Statistics*. Prentice-Hall: London.

Gash JHC. 1979. An analytical model of rainfall interception by forests. *Quarterly Journal of the Royal Meteorological Society* **105**: 43–55.

Gash JHC, Lloyd CR, Lachaud G. 1995. Estimating sparse forest rainfall interception with an analytical model. *Journal of Hydrology* **170**: 79–86.

Keim RF, Skaugset AE, Weiler M. 2006. Storage of water on vegetation under simulated rainfall of varying intensity. *Advances in Water Resources* **29**: 974–986.

Klaassen W. 2001. Evaporation from rain-wetted forest in relation to canopy wetness, canopy cover, and net radiation. *Water Resources Research* **37**: 3227–3236.

Klaassen W, Bosveld F, de Water E. 1998. Water storage and evaporation as constituents of rainfall interception. *Journal of Hydrology* **212–213**: 36–50.

Laws JO. 1941. Measurements of the fall-velocity of water-drops and raindrops. *Transactions, American Geophysical Union* **22**: 709–721.

DOI: 10.1002/hyp

Leyton L, Reynolds ERC, Thompson FB. 1967. Rainfall interception in forest and moorland. In *Forest Hydrology*, Sopper WE, Lull HW (eds). Pergamon: Oxford; 163–177.

Marshall JS, Palmer WMcK. 1948. The distribution of raindrops with size. *Journal of Meteorology* **5**: 165–166.

Mauchamp A, Janeau JL. 1993. Water funnelling by the crown of *Flourensia cernua*, a Chihuahuan Desert shrub. *Journal of Arid Environments* **25**: 299–306.

Murakami S. 2006. A proposal for a new forest canopy interception mechanism: splash droplet evaporation. *Journal of Hydrology* **319**: 72–82.

Návar J, Bryan R. 1990. Interception loss and rainfall redistribution by three semi-arid growing shrubs in northeastern New Mexico. *Journal of Hydrology* **115**: 51–63.

Návar J, Carlyle-Moses DE, Martinez A. 1999. Interception loss from the Tamaulipan matorral thrornscrub of north-eastern Mexico: an application of the Gash analytical interception loss model. *Journal of Arid Environments* **41**: 1–10.

Owens MK, Lyons RK, Alejandro CL. 2006. Rainfall partitioning within semiarid juniper communities: effects of event size and canopy cover. *Hydrological Processes* **20**: 3179–3189.

Pariente S. 2002. Spatial patterns of soil moisture as affected by shrubs, in different climatic conditions. *Environmental Monitoring and Assessment* **73**: 237–251.

Puigdefábregas J. 2005. The role of vegetation patterns in structuring runoff and sediment fluxes in drylands. *Earth Surface Processes and Landforms* **30**: 133–147.

Robinson MD. 2004. Growth and abundance of desert annuals in an arid woodland in Oman. *Plant Ecology* **174**: 137–145.

Rutter AJ, Kershaw KA, Robins PC, Morton AJ. 1971. A predictive model of rainfall interception in forests. I. Derivation of the model from observations in a plantation of Corsican pine. *Agricultural Meteorology* **9**: 367–384.

Schlesinger WH, Abrahams AD, Parsons AJ, Wainwright J. 1999. Nutrient losses in runoff from grassland and shrubland habitats in southern New Mexico: I. Rainfall simulation experiments. *Biogeochemistry* **45**: 21–34.

Thurow TL, Blackburn WH, Warren SD, Taylor CA. 1987. Rainfall interception by midgrass, shortgrass, and live oak mottes. *Journal of Range Management* **40**: 455–460.

Tromble JM. 1983. Interception of rainfall by tarbush. *Journal of Range Management* **36**: 525–526.

Tromble JM. 1988a. Water interception by two arid land shrubs. *Journal of Arid Environments* **15**: 65–70.

Tromble JM. 1988b. Water budget for creosotebush-infested rangeland. *Journal of Arid Environments* **15**: 71–74.

Tromble JM, Renard KG, Thatcher AP. 1974. Infiltration for three rangeland soil-vegetation complexes. *Journal of Range Management* **27**: 318–321.

Uijlenhoet R, Sempere Torres D. 2006. Measurement and parameterization of rainfall microstructure. *Journal of Hydrology* **328**: 1–7.

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. *Hydrological Sciences Journal* **50**: 897–910.

West NE, Gifford GF. 1976. Rainfall interception by cool-desert shrubs. *Journal of Range Management* **29**: 171–172.

Wheater HS, Butler AP, Stewart EJ, Hamilton GS. 1991. A multivariate spatial-temporal model of rainfall in southwest Saudi Arabia. I. Spatial rainfall characteristics and model formulation. *Journal of Hydrology* **125**: 175–199.

Wildy DT, Pate JS, Barte JR. 2004. Budgets of water use by *Eucalyptus kochii* tree belts in the semi-arid wheatbelt of Western Australia. *Plant and Soil* **262**: 129–149.

Wood MK, Blackburn WH. 1981. Grazing systems: their influence on infiltration rates in the rolling plains of Texas. *Journal of Range Management* **34**: 331–335.

Wood MK, Jones TL, Vera-Cruz MT. 1998. Rainfall interception by selected plants in the Chihuahuan Desert. *Journal of Range Management* **51**: 91–96.

Xiao Q, McPherson EG. 2002. Rainfall interception by Santa Monica's municipal urban forest. *Urban Ecosystems* **6**: 291–302.

Xiao Q, McPherson EG, Simpson JR, Ustin SL. 1998. Rainfall interception by Sacramento's urban forest. *Journal of Arboriculture* **24**: 235–244.