Water funnelling by the crown of *Flourensia cernua*, a Chihuahuan Desert shrub

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In arid climates, plant growth and survival depend primarily upon the amount of soil water available at the roots. Variation in soil water content at the individual plant level must then be taken into account to analyse the production and dynamics of vegetation cover. The plant itself modifies local water availability through rainfall interception and stemflow. Rainfall interception and stemflow was studied for a shrub, *Flourensia cernua*, a dominant species of vegetation stripes in the Chihuahuan Desert, Mexico, in order to determine to what extent it could influence soil water recharge.

Simulated rainfalls were applied at two intensities on six 1 m^2 plots centered around each shrub. Shrub cover was determined from vertical photographs. Experimental clipping from three shrubs allowed observations on the decrease in stemflow according to cover and measurement of the dry biomass of leaves and twigs. An experimental design enabled measurements to be made on throughfall, runoff from the base of the shrub, and to deduce stemflow and infiltration.

Stemflow accounted for 4–45 per cent of the rainfall in our study plots and was significantly correlated with shrub cover. It was higher for the lower rainfall intensity. Stemflow, together with a high soil permeability, resulted in a greater soil water recharge under the shrub.

Introduction

Water availability in arid climates is low and extremely variable in space and time. The spatial availability of water depends upon the location of rainfall and redistribution by runoff, at both the landscape and plant level (Schlesinger & Jones, 1984; Cornet *et al.*, 1988).

The distribution and dynamics of vegetation is indirectly related through numerous interactions to the redistribution of water (MacMahon & Schimpf, 1981). Edaphic parameters such as macroporosity, surface permeability or soil water retention influence the rates of runoff, soil water storage and therefore plant recruitment, growth and survival. The formation of soil surface crusts by the 'splash' effect of raindrops, which lowers soil permeability (Casenave & Valentin, 1989; Valentin, 1991) is prevented by vegetation cover. Moreover, the cover improves soil water retention by increasing the organic matter content and the macroporosity due to roots and faunal activity (Tiedemann & Klemmendson, 1973; Joffre & Rambal, 1988). Generally, these parameters are related through positive feedbacks (Schlesinger *et al.*, 1990).

A direct influence of vegetation on the spatial distribution of water is through mechanical effects such as rainfall interception and stemflow (Zinke, 1967). Interception and storage by the crown lead to direct losses through evaporation into the atmosphere. If interception is followed by stemflow, it leads to patterns of soil water content which are variable according to the size of the plant (Specht, 1957; Eschner, 1967). We hypothesized that the inverted cone shape of *Flourensia cernua* a Chihuahuan Desert shrub, channelled significant quantities of water to its base, thus strongly affecting the local water availability. Since rainfall simulation was shown to be a suitable method for studying infiltration processes (Bach *et al.*, 1986; Valentin, 1991), this experimental approach was used on $1 m^2$ plots centered around each shrub to analyse rainfall partitioning and infiltration under the crown.

Materials and methods

The study site was located in the Mapimi Biosphere Reserve, in the Chihuahuan Desert, Mexico (26°N, 103°W). Mean annual rainfall, from 13 years of observation at the Reserve station, is 283 mm with an interannual coefficient of variation of 23%. More than 70 per cent of the rainfall occurs in summer, from June to September. The soil of the area is a clay to sandy-clay loam, with structural surface crusts of low permeability where the vegetation cover is low (Delhoume, 1988; Janeau, 1990).

Flourensia cernua DC. (Tarbush, *Asteraceae*), is a characteristic shrub of the Chihuahuan Desert (Dillon, 1984). It is multi-stemmed, and looks like an inverted cone. The average height is 1·50 m and the diameter ranges from 1 to 1·50 m (Ludwig *et al.*, 1975). A typical shrub (Fig. 1) has no trunk and the branches run obliquely from the base. Leaf average size is 20×6 mm, orientated upwards in an oblique to sub-vertical position. In the Mapimi Reserve, it is abundant in vegetation stripes where it occurs together with *Hilaria mutica* (Buckl.) Benth. (tobosa grass) and *Prosopis glandulosa* Torr. var. *torreyana* (Benson) M.C. Johnst. (honey mesquite) (Cornet *et al.*, 1988).

In a vegetation stripe, we randomly selected six isolated shrubs to apply simulated rains. We used the rainfall simulator conceived by Asseline & Valentin (1978), modified by Bernard (1987). It consists of a sprinkling device at the top of a 4 m-high telescopic tower. A large canvas cover encloses the experimental area to exclude wind. The sprinkling device is a calibrated nozzle fed by a constant waterflow, oscillated by an electric motor. Rainfall intensity can be controlled within a range of 10–150 mm/h by modifying the angle of oscillation, thus adjusting the frequency with which the sprinkler passes over the plot. Simulated rainfall is slightly different from natural precipitation because the size and energy of raindrops is not regulated.

The simulated rainfalls applied in the experiment were chosen after an analysis of the 1987–90 rainfall intensity data (Delhoume, unpubl. data). Various authors showed that water storage in the branches was about 1 mm (Zinke, 1967; Pressland, 1973; Tromble, 1988). In order that all the simulations began with the same wet condition, we first applied a 5 min rain at 20 mm/h. Two rains of constant intensity were then applied, the first rain at 20 mm/h for 45 min (amount 15 mm), the second at 50 mm/h for 15 min (amount 12·5 mm). A dripping time of 10 min was allowed between two rains.

Around each shrub, we laid out a $1 m^2$ steel frame inserted to a depth of approximately 5 cm into the soil. The interior surface was covered with impermeable cement, forming an inclined surface, except for a $0·1 m^2$ central area around the shrub base. The water running from this central area was collected in a metallic tube. The downslope limit of the frame bore holes at ground level and was surrounded by a plastic gutter designed to collect the runoff from the cemented surface, i.e. throughfall. This design allowed us to determine how rainfall was partitioned between throughfall, runoff from the central area, and
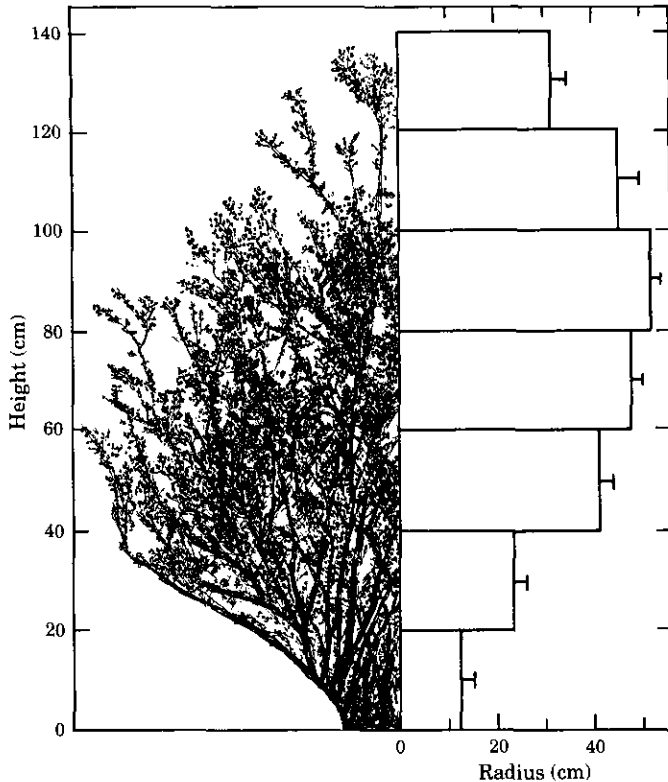
Figure 1. A representative *Flourensia cernua* shrub used for rainfall simulations to determine rainfall partitioning and infiltration. The average radius (and S.E.) at seven height levels for the six shrubs used are shown.

infiltration at the base, calculated as the difference between total rainfall and throughfall plus central runoff. The infiltration at the base is composed of direct rain proportional to the central area (10 per cent of the rain) and the intercepted rainfall brought by stemflow. Since it was not possible to determine whether the direct rain on the central area was intercepted, and that it reached the central area even without shrub, it was excluded from the calculation of stemflow. The stemflow was then calculated as the fraction of the rain collected from the cemented surface without shrub ($0.9 \times$ rain) and brought down to the shrub base by interception and stemflow: stemflow = (infiltration $- 0.1 \times$ rain)/ $0.9 \times$ rain, expressed as a percentage.

Rains were applied to each shrub, and after partial defoliation of three of them. There were two successive clippings corresponding to a 10 and 25 per cent decrease in cover respectively. The diameter of each individual was measured and its cover determined from a vertical photograph. For the three clipped individuals, we measured, after each clipping, the leaf and branch biomass following a 72-h drying period at 80°C. The total biomass was separated into four groups: leaves, twigs of less than 2 mm diameter, twigs between 2–10 mm, and twigs of more than 10 mm diameter. The area and dry biomass of 10 samples of 10 leaves per plant were measured (Delta T. Devices leaf area meter) to determine the leaf weight per unit area and to estimate the total leaf surface per shrub.

Results

Biomass/cover

The average radius of the six shrubs studied are presented in Fig. 1. The inter-individual variation in cover before clipping was high, cover ranged from 14 to 50% (Table 1). The two clipping levels corresponded to a clear decrease in cover within the same range: 16 per cent average decrease for the first clipping and 32 per cent for the second.

The average dry biomass for the three shrubs before clipping was 2480 g (S.E. 290, $n = 3$). The distribution of dry biomass is shown in Fig. 2. The proportion of leaves was 8·1% (S.E. 1·2, $n = 3$) and changed to 3·3% (S.E. 0·4, $n = 3$) after the second clipping. Clipping induced both a decrease in total biomass and a change in biomass distribution at the expense of leaves and thin twigs, benefiting the thick branches (Fig. 2). No significant correlation was found between cover and biomass of the large diameter branches. Conversely, significant linear correlations ($p < 0·01$) were obtained between the cover and the leaf biomass ($r^2 = 0·83$), thin twig biomass ($r^2 = 0·54$), and medium twig

Table 1. *Covers of the shrubs used for rainfall simulations (as a percentage of the plot surface). Two successive clippings were applied to the first three plants*

| Plant number	1	2	3	4	5	6
No clipping (%)	29	40	50	14	29	43
First clipping (%)	27	36	37	—	—	—
Second clipping (%)	21	30	30	—	—	—
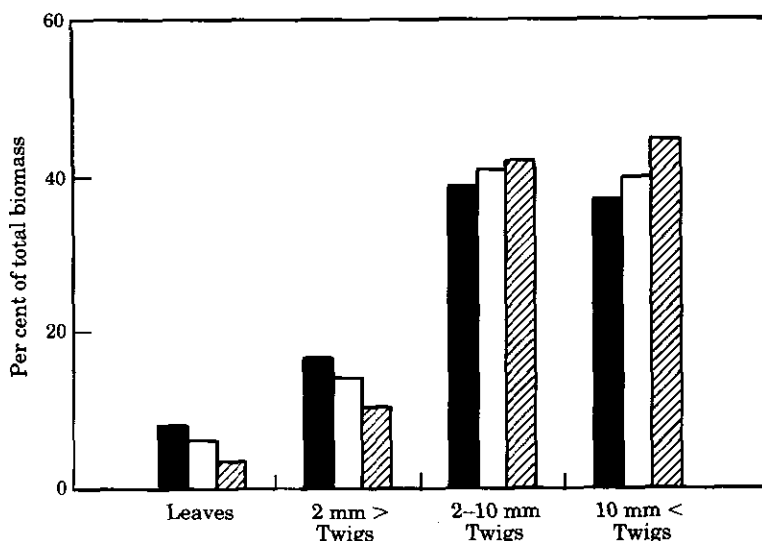
Figure 2. Dry biomass distribution of a Chihuahuan Desert shrub. The three clipping levels are shown as three successive bars: ■, before clipping; □, 85 per cent of initial cover; ▨, 70 per cent of initial cover. Data are percentages of the total biomass in each group (average of three plants). The differences between clipping levels are only significant ($p < 0·01$) for the first two groups.

biomass ($r^2 = 0.81$). The leaf biomass per unit area was $96.7 \, g/m^2$ (S.E. 1.7, $n = 30$) with no significant difference between plants. Total leaf area was 1.2, 2.1 and $2.6 \, m^2$ for plants 1, 2, and 3 respectively.

Stemflow and infiltration

During the experiment, runoff from the central circle was only observed once in plot 1, accounting for 5·5 per cent of the rain at low intensity and 16 per cent at high intensity. This plot was characterized by a more compact soil surface at the shrub base. Only a few small puddles were observed 3–10 min after the beginning of the high intensity rains on plot 3, infiltrating very rapidly after the end of the rain. Except for plot 1, all the water reaching the shrub base infiltrated at the base. For the three clipped shrubs, the total experiment lasted for 4 h and the infiltration was 36, 44·5 and 37·5 l (plots 1, 2, and 3 respectively) on a $0.1 \, m^2$ surface.

Stemflow ranged from 4 to 45 per cent of the rain in the experiment. The average increase in water input at the shrub base was three (low cover – high intensity) to five-fold (high cover – low intensity) (Fig. 3). In this latter case, more than half of the total amount
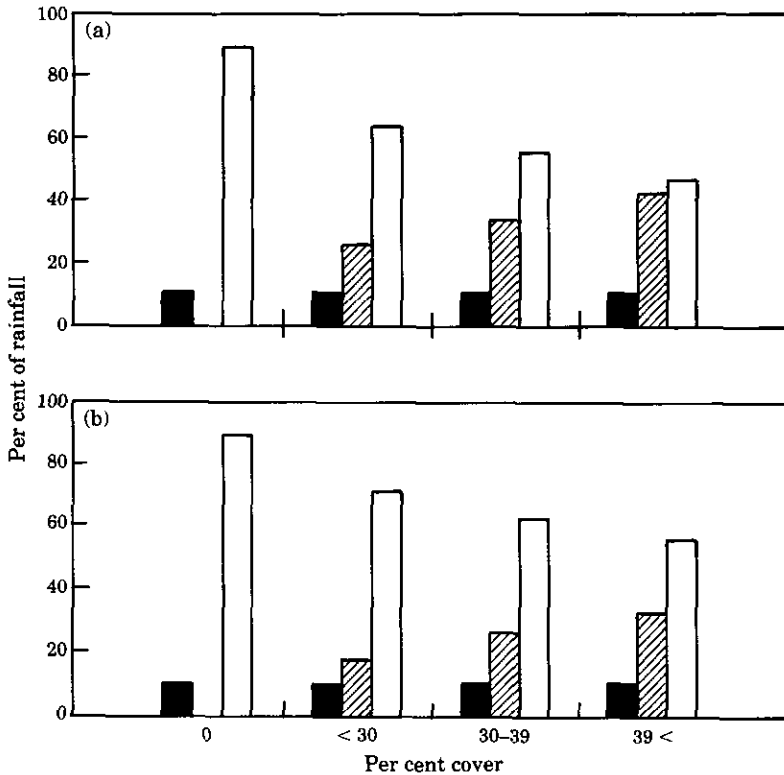
Figure 3. Rainfall partitioning as percentages of total rain by the crown of a Chihuahuan Desert shrub at two simulated rainfall intensities: (a) low, 20 mm/h and (b) high, 50 mm/h, intensities. The data for three classes of shrub cover are shown: $<30\%$ ($n = 5$), 30–39% ($n = 4$) and $>39\%$ ($n = 3$). The zero cover gives a partition of rainfall proportional to the areas. ■, Direct rain at the shrub base ($0.1 \, m^2$); ▨, stemflow, the differences are significant between cover classes and intensities ($p < 0.001$) with no interaction; □, throughfall.

of rain reached the shrub base, accounting for only one-tenth of the plot surface. Stemflow was significantly different between the two rainfall intensities ($p < 0.001$, F test), with an average of 24·6 per cent of the rain (S.E. 2·5, $n = 12$) for the higher, and 32·6 per cent (S.E. 2·7, $n = 12$) for the lower (Fig. 3). Significant linear regressions ($p < 0.001$) were observed between stemflow and cover for both intensities (slope 0·87 and $r^2 = 0.83$ for low intensity; slope 0·78 and $r^2 = 0.76$ for high intensity). We could not obtain better correlations with the biomass parameters, and no significant correlation was observed between stemflow and the biomass of twigs more than 10 mm diameter.

Discussion

In arid climates, rainfall variability and unpredictability makes it difficult to obtain sequences of natural precipitations of comparable intensities. Simulated rainfall is repeatable with great accuracy and enables the researcher to analyse rainfall partitioning at the plant level.

Our results show that stemflow, after interception by the crown, is an important component of rainfall and can channel nearly one half of the total rainfall to the shrub base. Stemflow is higher for low intensity rainfall.

It should be stressed that, in our experiment, there were no differences in the size and kinetic energy of raindrops for the two rainfall intensities (which may not be true for real precipitations). Therefore, the differences in stemflow were due to saturation of the leaf and branch surfaces, increasing dripping at high intensity. The positive correlations we obtained between stemflow and cover show that the total surface of interception, measured by vertical projection, is an important determinant of stemflow. Moreover, it is easy to measure.

Previous rainfall partitioning studies on trees and shrubs have shown that stemflow was very variable between species. Zinke (1967), reviewing data on North American forests, demonstrated that stemflow was generally less than 5 per cent for trees but gave examples of two shrubs channelling 14·6 and 30 per cent of the total rainfall. Some of these differences are probably due to plant size and architecture. Pressland (1973) obtained an average stemflow of 18% for *Acacia aneura* F. Muell. trees ranging from 4 to 12 m high, whereas Slatyer (1965) measured a stemflow of 40% for trees less than 6 m high of the same species. Slatyer (1965) described the studied trees as having an architecture particularly favourable for stemflow. The importance of architectural parameters such as position of ramifications, branch and leaf slope, makes it difficult to obtain a good relationship between stemflow and simple plant descriptors. Glover & Gwynne (1962) noted that leaf drip increased when maize leaves were curved downwards. It can explain the low correlations obtained by Pressland (1973) using the tree basal area or the horizontal projection of the crown area. The orientation of both leaves and stems of *F. cernua* (Fig. 1) allows the intercepted water to run off down the petiole, onto the stem and to the shrub base without dripping to the soil. Good positive correlations between stemflow and plant cover can be expected mainly for this type of shrub.

In this experiment, soil surface porosity and physical characteristics at the shrub base did not limit water infiltration. The total quantity of water which infiltrated the 1000 cm^2 central surface reached 45 l during the 4 h of the experiment. This high rate of infiltration is related to faunal activity, the presence of roots and the abundance of litter (especially important are the presence of dead roots and termite activity). Moreover, the base of the biggest individuals often show a depression due to axis splitting, as described by Vasek (1980) for *Larrea tridentata* Cov., where infiltration is very rapid. Therefore, stemflow allows a very efficient soil water recharge under the shrubs. This effect was clearly shown by Specht (1957). Obtaining soil profiles after a rain, he showed that soil moisture was 10% at a depth of 90 cm under *Banksia ornata* F. Muell. Only 50 cm away from the crown, soil moisture was only 1%. This shows that high infiltration drives water to deep layers before

the saturation of superficial layers. This effect is probably important for the survival of an individual shrub since it creates a water reserve excluded from soil evaporation and which might not be available to other shallow rooted species. It may be the start of a positive-feedback effect when the biomass of the shrub increases or decreases. Moreover, stemflow may have consequences on the interactions between species. Walker & Noy Meir (1982) proposed that the relative dominance of trees and grasses in savannas depended on the use of different soil layers by these bioforms; stemflow may influence the result of such a relation. This local water concentration may also facilitate seedling and young plant survival at the shrub base and promote a 'nurse effect'.

An important consequence of rainfall interception and stemflow is that the kinetic energy of raindrops is lowered and that it brings an indirect precipitation of low energy to the soil. The main mechanisms for the formation of surface crusts (colloidal dispersion, aggregate fractioning, and splash effect), depend on raindrop impact (McIntyre, 1958; Rose, 1960; Hudson, 1971) and were shown to be positively related to raindrop energy. The intercepted rainfall cannot, therefore, contribute to the formation of such impervious crusts. Since they are important factors in the water balance of landscapes in tropical semi-arid areas (Casenave & Valentin, 1989; Valentin, 1991), rainfall interception and stemflow lead to an overall improvement of water use at the landscape scale. Moreover, this phenomenon may be the basis for a positive feedback in vegetation development.

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