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Stemflow contribution to the 'fertile island' effect in creosotebush, *Larrea tridentata*

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Stemflow, throughfall and bulk precipitation were collected on six creosotebushes (*Larrea tridentata*) during 18 events in the summer rainy season in the northern Chihuahuan Desert. The average stemflow was 16·8 ± 1·9%; throughfall averaged 64·7 ± 3·2%. The concentration of all ions measured were significantly higher in stemflow than in the bulk precipitation. Total nitrogen, sulfate, and calcium concentrations were more than an order of magnitude higher in the stemflow than in the bulk precipitation. Concentration of ions in the upper 10 cm of soil were generally higher in soils under shrubs than in soils between shrubs. Measured quantities of ions in dry-fall were of sufficient magnitude to account for the increased concentration in stemflow water of most ions. Increases in nitrogen in stemflow water may be due to biological activity of stem crust micro-organisms in addition to dry-fall. Dry-fall that collects on the leaves and stems of this desert shrub may contribute to the 'fertile island' effect on the soils under the canopies of creosotebushes.

Keywords: bulk precipitation; creosotebush; dryfall; *Larrea tridentata*; soil fertility; stemflow; throughfall

Introduction

In many deserts there is considerable spatial heterogeneity in soil resources. The classic 'island of fertility' that forms under shrub canopies in arid regions are among the best examples (Garcia-Moya & McKell, 1970; Charley & West, 1975, 1977; West & Klemmedson, 1978; Barth & Klemmedson, 1982; Parker *et al.*, 1982, Virginia & Jarrell, 1983). This accumulation of nutrients in the surface soil under shrubs results from complex, poorly understood interactions between the plant (e.g. nutrient uptake, litter fall, and dry fall (deposition of fine dust from the atmosphere)), soil (e.g. erosion, deposition), and soil biota (e.g. mineralization, decomposition).

Shrubs effect not only the accumulation of nutrients but also the interception,

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infiltration and storage of water (Pressland, 1973; Elkins *et al.*, 1986; Nulsen *et al.*, 1986; Joffre & Rambal, 1988). The structural properties of desert shrubs and the surface characteristics of their leaves provide the potential for deposition and accumulation of dust and dry-fall on the leaf surfaces, and the subsequent transport of those materials to the soil under the shrub by stemflow and throughfall. If the chemical composition of the dry-fall is rich in materials that are limiting plant nutrients, water moving through the canopy as throughfall and stemflow can contribute to the development of 'fertile islands' under shrub canopies and can enhance the water availability in the soil volume with the highest concentration of shrub fine roots (Martinez-Meza & Whitford, 1996).

Creosotebush, *Larrea tridentata* (Sesse & Moç. ex DC.) Cov., is a multi-stemmed, evergreen shrub that ranges in height from 50 cm to more than 200 cm. It is a dominant shrub in North American hot deserts. In the northern Chihuahuan Desert, soils under the canopies of *L. tridentata* are known to have higher concentrations of nitrogen than soils of the intershrub spaces (Parker *et al.*, 1982). In forests, stemflow water is frequently nutrient-enriched either from materials accumulated on the leaf surfaces as dry-fall or as the result of foliar leaching (Eaton *et al.*, 1973; Schlesinger, 1978; Parker, 1983; Crozier & Boerner, 1984; Herwitz, 1986). The morphology of *L. tridentata* and the elevated concentrations of nitrogen in soils under this shrub suggested that stemflow or canopy throughfall could be a significant contributor to the development of 'fertile islands' in desert creosotebush stands. Here we report a study that investigated the chemical concentration of selected nutrients in stemflow and throughfall compared to the chemistry of bulk precipitation.

Methods

The study was conducted on the Jornada Long-Term Ecological Research Program site (32° 19' N, 106° 42' W) approximately 35 km NNE of Las Cruces, New Mexico. The area is typical of the northern Chihuahuan Desert with a sparse cover of creosotebush shrubs on the piedmont slopes. The average rainfall is 235 mm with more than 60% falling between July and September as convectional storms. Stemflow, throughfall and bulk precipitation were collected for 18 rain events over a 13-month period beginning in August 1985 through September 1986. Storms smaller than 6 mm did not produce sufficient stemflow and throughfall for analysis and were not included in the analysis. During the period of study the monthly rainfall exceeded the 100-year mean by between 5·4 and 1·75 times for the months sampled, except for July and September of 1986 which were close to or below the average.

Six creosotebush shrubs were selected for study; two branches on each shrub were selected at random for collection of stemflow. A hole was cut into a polyethylene funnel which was fitted around the base of each selected stem and sealed with silicone sealant. The funnel emptied into a sealed 2 l plastic bottle via a plastic tube. The collection bottles were set in holes in the soil and fastened in place with a wooden stake. Throughfall was collected in two bottles fitted with funnels placed on opposite sides of the mid-point of the canopy of each shrub. Bulk precipitation was collected in three bottles fitted with funnels placed in the open spaces between shrubs.

All collection bottles, tubes and funnel surfaces were acid washed three times with 1·0 N HCl and rinsed five times in distilled, deionized water before being used for sample collection. The collection bottles were retrieved from the field as soon after a rain event as possible. After each event, all funnels and tubes were acid washed and rinsed with distilled, deionized water and the collection bottles replaced with clean bottles. In the laboratory after the volume measurements were made, subsamples to which 100 μl of phenylmecuricacetate was added, were stored in a refrigerator for later chemical analysis.

Each sample was filtered through a 0·45 μm millipore filter. The filtered sample was analysed for NH_4-N, NO_3-N and PO_4-P on a Traacs 800 Autoanalyzer using standard techniques. Total N and P were measured in a separate aliquot which was then digested with potassium persulfate (D'Elia *et al.*, 1977), and the digest was analysed for NO_3 and PO_4 on the autoanalyser. The difference between total N (as NO_3) after digestion and the sum of the NH_4 and NO_3 before digestion was taken as the concentration of soluble organic N. A similar approach was followed for soluble P. The filtered sample was analysed for Cl and SO_4 on a Dionex 2010i ion chromatograph, and for Ca and Mg on a Perkin Elmer 3100 atomic absorption spectrophotometer. Appropriate amounts of $LaCl_3$ were used to suppress interferences during the analysis of Ca and Mg; Na and K were measured by flame emission on the same instrument.

The canopy area of each of the stems selected for measurement was estimated by summing the canopy areas of all of the sub-branches of the sample stem. Canopy areas were calculated as triangles or ellipses that included leaf areas and the interleaf spaces. The shape chosen was that which was most appropriate for the shape of a component sub-branch. Stemflow volume per unit canopy area was estimated by averaging the stemflow volumes and canopy areas for the two sample stems per plant. Throughfall and bulk precipitation were estimated on the basis of the area of the collection funnel. Percentage of intercepted rainfall as stemflow and throughfall was calculated on the basis of the proportion of the total shrub canopy sampled by the collection apparatus.

Dry-fall samples were collected monthly using an Aerochem Metrics wet/dry precipitation collector located 300 m upslope from the study site. The collector bucket was 1·0 m above the soil surface in an area where average shrub height is less than 1 m. Dry-fall samples were removed from the bucket by addition of 0·5 l of distilled, deionized water. The solution was transferred to an acid washed bottle for transport to the laboratory. Chemical analyses were the same as used on the stemflow, throughfall, and bulk precipitation samples.

Soil samples (upper 10 cm and 10–20 cm of soil) were collected with a 10-cm diameter corer at mid canopy, and at mid-distance between canopies of six shrubs. Soil samples were air-dried and ground to pass a 2 mm sieve. Subsamples for total N and total P were digested by a Kjeldahl technique in a block digestor (Bremner & Mulvaney, 1982). Inorganic N was extracted with 2 M KCl (Keeney & Nelson, 1982). Ammonium N in the extracts was analysed colorimetrically (indophenol blue) in an automated procedure and NO_3-N was analysed colorimetrically in an automated procedure (Technicon Industrial Method No. 100-70W). Available P was analysed as $NaHCO_3$-extractable (PO_4)P (Olsen & Sommers, 1982). Soluble cations were extracted using saturation extract methods (Richards, 1954; Rhoades, 1982) and analysed using inductively coupled plasma atomic emission spectrophotometry.

Data were analysed by one-way analysis of variance.

Results

The average fraction of intercepted rainfall coverted to stemflow was 16·8 ± 1·9% with a range of 5·9% to 26·9% for the rainfall events for which measurements were obtained. The average throughfall fraction was 64·7 ± 3·2% with a range between 44·2% and 78·3%. Stemflow water had concentrations of most of the ions measured that ranged between 2 and 10 times the concentrations in the bulk precipitation (Table 1). The concentration of ions in the throughfall was slightly elevated but not significantly except for SO_4, K and total nitrogen (Table 1).

There was considerable variation in the concentration of ions in dry-fall during the year of study with the largest variation during the months of the growing season (Table

Table 1. *Concentrations of ions (p.p.m.) in bulk precipitation, throughfall, and stemflow in creosotebush,* Larrea tridentata, *in the northern Chihuahuan Desert*

Ion	Bulk precipitation	Throughfall	Stemflow
NO_3	0·10 a	0·16 a	0·87 b
NH_4	0·12 a	0·13 a	0·31 a
SO_4	0·80 a	1·86 b	10·47 c
K	0·80 a	1·12 b	9·42 c
Na	0·08 a	0·09 a	0·25 b
Mg	0·02 a	0·12 a	0·95 b
Ca	0·37 a	0·74 a	3·60 b
Total N	0·23 a	0·78 b	3·77 c
Total P	0·03 a	0·07 a	0·27 b

Numbers followed by different letters are significantly different at $p < 0{\cdot}05$.

2). Sulfate and calcium accounted for most of the ions in dry-fall but concentrations of these ions were not the most variable temporally (Table 2).

There were significantly higher concentrations of nutrients in soils under the shrub canopies when compared with soil from the intershrub spaces. There were no significant differences in the concentrations of measured nutrients under and between shrub canopies at soil depths greater than 10 cm (Table 3). Some of the ions that were significantly enriched in soils under the shrub canopies were in low concentration in the dry-fall, e.g. K, Mg and P (Tables 2 and 3). However concentrations of these ions were significantly higher in stemflow than in throughfall and bulk precipitation.

Discussion

The fractional percentage of intercepted rainfall that reaches the soil as stemflow in *L. tridentata* is within the range of values recorded in forests (Parker, 1983) and is also within the range reported for small trees in arid regions (Pressland, 1973; Nulsen *et al.*, 1986; Navar & Bryan, 1990). The throughfall values are also within the range of values reported for a variety of tree species (Parker, 1983). A significant fraction of the bulk

Table 2. *Average monthly concentration of ions (p.p.m.) (±standard deviation) in dry-fall collected at study site during the year of study. Dry-fall averages calculated on the basis of the full year and for the growing season (June–September) which corresponds to the summer monsoon season in the northern Chihuahuan Desert*

Ion	Annual	Growing season
NO_3-	0·68±0·43	1·1±0·7
NH^{4+}	0·22±0·13	0·3±0·2
SO_4	3·71±2·97	7·1±3·6
K	0·47±0·58	1·0±1·0
Na	0·41±0·22	0·5±0·3
Mg	0·15±0·1	0·3±0·1
Ca	2·67±1·81	4·4±2·7
Total N	1·37±0·95	2·2±1·4
Total P	0·19±0·2	0·4±0·3

Table 3. *Comparison of nutrient concentrations (mean±standard deviation) in soil collected from under the mid-point of the canopy of* L. tridentata *shrubs and in soils from the mid-point between shrub canopies.* NO_3*-N,* NH_4*-N, and* PO_4*-P in mg* kg^{-1} *of soil; total N in g* kg^{-1} *of soil;* Na^+*,* K^+*,* Mg^{++}*, and* Ca^{++} *concentrations in meq* l^{-1}

	Under		Between	
Ion	0–10 cm	10–20 cm	0–10 cm	10–20 cm
NO_3-N	2·4±0·6	1·4±0·1	2·4±1·0	1·2±0·07
NH_4-N	2·3±0·2	1·9±0·1	2·1±0·3	1·8±2·6
Total-N	0·5±0·04	0·4±0·01	0·4±0·03	0·4±0·01
PO_4-P	4·6±0·5*	3·1±0·4*	2·9±0·5	2·2±0·4
Na^+	0·3±0·04	0·4±0·03	0·4±0·05	0·3±0·05
K^+	1·0±0·1*	0·3±0·1*	0·6±0·1	0·1±0·02
Mg^{++}	0·8±0·08	0·4±0·07*	0·6±0·08	0·3±0·05
Ca^{++}	4·7±0·5	3·2±0·2	4·1±0·6	2·9±0·1

*Differences in concentrations under and between canopies that were significant at $p<0·05$.

precipitation is channelled to the soil via the stems and this volume of water is markedly enriched in nutrients.

The enrichment by ions in the surface soil under the canopies of *L. tridentata* demonstrates that these shrubs exhibit the classic 'fertile island' phenomenon of desert shrubs (Garcia-Moya & McKell, 1970; Parker *et al.*, 1982; Virginia & Jarrell, 1983). Data from this study suggest that some of this enrichment may be the consequence of nutrients entering the soil at the base of the shrub by stemflow and by nutrients in throughfall water. It has been suggested that stemflow and throughfall nutrients primarily originate as dry-fall or result from leaching of nutrients from the leaves (Parker, 1983). In creosotebush communities, intershrub spaces are regularly subjected to overland flow which probably depletes dry-fall nutrients from those sites. If we assume that as little as 10% of the dry-fall adheres to creosotebush leaf surfaces, and is entrained in throughfall and stemflow water, dry-fall could account for nearly all the enrichment of stemflow and throughfall by certain ions. The high concentrations of sulfate and calcium in throughfall and stemflow probably originate as dry-fall that collects on leaf and stem surfaces. The higher concentrations of K and Mg may originate as ions leached from the leaves by the rainwater but could also be from dry-fall.

The pattern of nutrient enrichment of stemflow water from creosotebushes appears to be more than simple washing of dry-fall accumulation on leaf surfaces. The stems of *L. tridentata* in the northern Chihuahuan Desert are covered with a black, crustose, microbial layer. Water flowing down the stems passes over this layer picking up particulates and soluble organics resulting in a reddish-brown colour of the stem flow water. The microbial layer is dominated by fungi, *Coleophoma* spp., but also may contain algae, bacteria, and cyanobacteria (John Zak, pers. comm.). The high concentrations of NO_3, Mg, Ca, total N and total P in the stemflow could be washed from this microbial crust. If dry-fall were the only contributor to the concentrations of stemflow ions, there should be little difference in the concentrations in throughfall and stemflow. The small differences in soil chemistry of under-canopy soils when compared to intershrub spaces are probably the result of the random selection of shrubs. In other studies, we found that the morphology of the shrub has a significant effect on the 'fertile island' effect. Shrubs with a distinct inverted cone shape had little nutrient enrichment in the under-canopy soil but did have higher nutrient content in soils adjacent to the stem (Whitford *et al.*, 1996). The data from that study suggests that the 'island of fertility' effect is primarily due to under-litter accumulation below the canopy of shrubs with low exterior stem angles. However shrubs in which most of all stem angles (with reference to the horizontal) are large, stemflow is enhanced and stemflow nutrients would be transported to the deep root zone by channelized flow (Martinez-Meza & Whitford, 1996). Thus, while the nutrient enrichment in stemflow may contribute to the nutrient requirements of the shrub, enriched throughfall appears not to be significant in the development of 'fertile island' under creosotebush.

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