*Journal of Arid Environments* (1987) 12, 119–126

# Soil moisture content and plant transpiration in the Chihuahuan Desert of New Mexico

William H. Schlesinger*, Paul J. Fonteyn† & Giles M. Marion‡

*Accepted 25 April 1985*

Thermocouple hygrometers were used to monitor soil water potential in control and harvested (bare) plots in the Chihuahuan Desert of New Mexico (U.S.A.) from June 1983 to June 1984. Soil water potentials were converted to water contents using the moisture tension release characteristics for each soil horizon. Comparisons of seasonal fluctuations in soil water storage on these plots suggest that 72% of incident precipitation is removed by plant transpiration in this ecosystem. Plant uptake of water from the lower soil profile is an important factor affecting the rate and depth of $CaCO_3$ deposition in desert soils.

## Introduction

In arid regions of the Southwest, most rainfall occurs in small storms of short duration. Much of the moisture may evaporate from the upper soil horizons within a short time after these rainstorms. As much as 93% of the annual incident precipitation is lost by evaporation in creosotebush desert near Tucson, Arizona (Sammis & Gay, 1979). Little is known about the percolation of moisture to the plant rooting zone and the subsequent removal of this water by plant transpiration. Such movements of soil moisture are important to soil profile development in arid regions, in which accumulations of ions and precipitated secondary minerals, such as $CaCO_3$, are common (Arkley, 1963, 1967; Stuart & Dixon, 1973; Eisenberg, Dan *et al.*, 1982; Mullins, 1981). The present paper provides an estimate of the removal of water by plant transpiration in the desert of southern New Mexico, as part of a study of the rate and process of $CaCO_3$ deposition in desert soils.

## Study area

Experimental plots were established at the desert Long Term Ecological Research (LTER) site on the New Mexico State University Ranch, 40 km north-northeast of Las Cruces, New Mexico. The plots were located on the northeast-facing piedmont of Mt Summerford in the Doña Ana Mountains. The geomorphic surface is of late Pleistocene age (Jornada II) and has a slope of 2°. Calciorthid and Typic Haplargid soil profiles of coarse loamy texture have developed in gravelly alluvium derived from weathered quartz monzonite. A calcic horizon designated $B_{2K}$ is present at 37 cm (SE 2·7). In most areas this layer is about 20 cm thick and shows stage III carbonate morphology (Gile, Peterson *et al.*, 1966). Carbonate filaments are

* Department of Botany, Duke University, Durham, North Carolina 27706, U.S.A.
† Department of Biology, Southwest Texas State University, San Marcos, Texas 78666, U.S.A.
‡ Systems Ecology Research Group, San Diego State University, San Diego, California 92182, U.S.A.

0140–1963/87/020119+08 $03.00/0

commonly found in the $B_{IK}$ horizon that extends from 2 to 37 cm in depth. In Haplargid profiles, however, the upper portion of this interval is a carbonate-free $B_t$ horizon with accumulations of illuvial clay. The vegetation is dominated by creosotebush (*Larrea tridentata*), with *Gutierrezia sarothrae, Zinnia acerosa* and *Opuntia phaeacantha* as secondary associates (Table 1). Above-ground biomass totals 327 g/m$^2$, with 66% contributed by *Larrea tridentata* (unpublished data).

## Methods

Two experimental plots for each of irrigated, harvested (bare) and control treatments were established in late May 1983. Only data from the harvested and control plots are used in this paper, and because the data from replicate plots were similar, they have been treated as replicate measurements from a single plot of each type in order to simplify the presentation. Each 10 × 10 m plot contained a 7 × 7 m area in which measurements were made, surrounded by a 1·5-m buffer zone. On 4–5 June 1983 all above-ground biomass was harvested from two plots, which were subsequently weeded of sprouts and seedlings at 2-week intervals for the remainder of the study.

Five access tubes were randomly located in each plot. Each tube contained five thermocouple hygrometer sensors (Wescor #PCT-55-30-SF) for measurements of soil water potential. Sensors at depths of 7, 21 and 35 cm monitor equal intervals of the rooting zone, sensors at 50 cm monitor soil moisture in the calcic horizon and sensors at 70 cm are below the caliche layer. Each sensor was read with a microvoltmeter (Wescor HR33T) in the dew-point mode at *c.* 2-week intervals beginning on 24 June 1983. Before being placed in the field each sensor was calibrated in 0·05, 0·5, 1·3 and 1·5 molal NaCl solutions. A linear regression relating voltage to water potential was calculated for each sensor. Field measurements were corrected for soil temperature at the time of sampling.

Although the mean values for soil water potential in replicate plots were very similar throughout the study, measurements from the soil hygrometers were highly variable. Standard errors were often greater than 10% of the mean value even when the data from both replicate plots were treated as a single sample ($n = 10$ at each depth and time). This variation compromised the level of our comparisons and interpretations, although general trends are clear. The performance of the hygrometers was checked 1 year after installation by comparison with measurements of pre-dawn water potential of the shrubs in the study plots. Mean values in the rooting zone agreed within ±0·3 MPa with the plant values which were *c.* −5 MPa at that time (see Results) (Fonteyn, Schlesinger *et al.*, 1987).

**Table 1.** *The number of shrubs and cacti in each of the 100-m$^2$ study plots*

| | Area 1 | | | Area 2 | | |
|---|---|---|---|---|---|---|
| Species | I | C | H | I | C | H |
| *Larrea tridentata** | 17 | 24 | 44 | 67 | 41 | 12 |
| *Gutierrezia sarothrae* | 50 | 51 | 48 | 18 | 69 | 148 |
| *Zinnia acerosa* | 6 | 3 | 13 | 8 | 6 | 0 |
| *Opuntia phaeacantha* | 2 | 1 | 1 | 3 | 2 | 3 |
| *Yucca elata*† | 1 | 0 | 0 | 0 | 0 | 4 |
| *Menodora scabra* | 0 | 0 | 3 | 1 | 0 | 0 |
| *Ephedra trifurca* | 1 | 0 | 0 | 0 | 0 | 0 |
| *Parthenium incanum* | 0 | 0 | 2 | 1 | 0 | 0 |
| *Opuntia leptocaulis* | 0 | 0 | 0 | 1 | 0 | 0 |

C, control; H, harvest; I, irrigated.

* Stem clusters closer than 25 cm are considered as individuals.

† Basal rosettes.

Using a volumetric corer, soil samples from five pits located adjacent to the plots were measured for bulk density and used to examine moisture tension release characteristics for each soil horizon. Sieved (<2 mm) samples were equilibrated in a pressure-plate apparatus at 0·01, 0·03, 0·1, 0·4, 0·8 and 1·5 MPa, and percentage soil moisture was calculated after the samples had been dried at 110°C. Moisture tension release curves were plotted using mean values for each horizon ($n$=5, Fig. 1). Standard errors for these means were always less than 10% of the mean value. These values allowed water potential data to be converted to percentage soil moisture at potentials greater than −1·5 MPa. Because the curves were nearly asymptotic at less than −1·5 MPa, extrapolations to estimate moisture held at lower potentials were impossible. The mean of soil water contents at −0·8 and −1·5 MPa was used as a constant value for percentage soil moisture held at less than -1·5 MPa. Changes in soil water storage were calculated for a 1-m profile. Thermocouple hygrometers at 7, 21, 35, 50 and 70 cm were assumed to monitor profile intervals of 0–14, 14–28, 28–42, 42–58 and 58–100 cm, respectively.

## Results and discussion

### *Control plots*

Except for the sensors at 7 cm, soil water potential was similar on 24 June 1983 and 17 June 1984 in the control plots (Fig. 2*a*). However, seasonal patterns in soil water potential were apparent during the year. Potentials in the surface horizon fluctuated in response to individual rainstorms, although the magnitude of the fluctuations was lower in the winter due to lower rates of evaporation from the surface (Cable, 1980; Kemp, 1983). All horizons showed increasing soil moisture in the autumn, with the increase in soil water potential

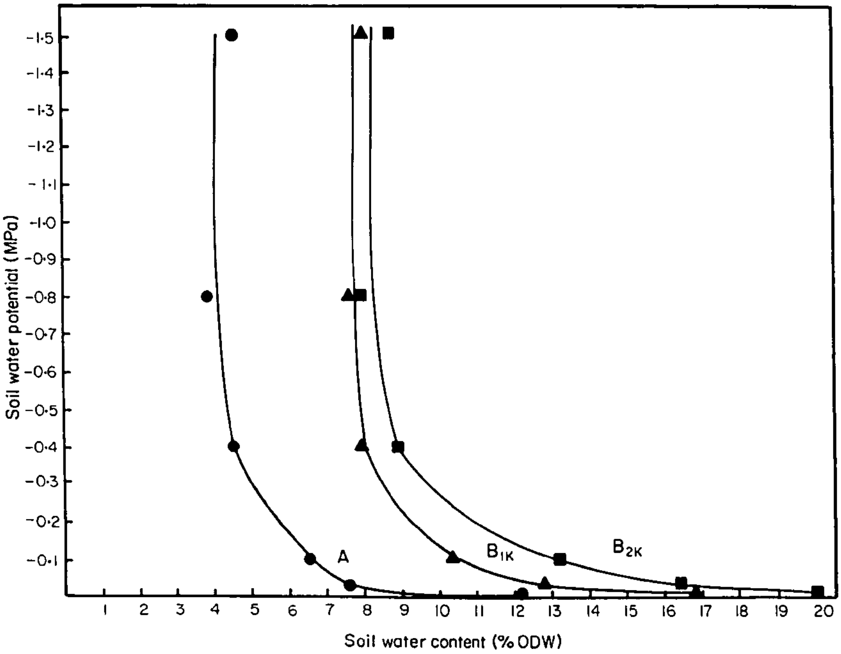

**Figure 1.** Soil water potential as a function of soil water content (percentage of oven-dry weight) for three soil horizons in the Chihuahuan Desert.

occurring sequentially from the surface downward. To simplify the diagram, only data from depths of 7, 35 and 70 cm are shown in Fig. 2. The surface horizon acts to buffer the fluctuations in the lower horizons by allowing percolation only during major precipitation events and by providing a diffusional barrier to evaporation. Nevertheless, evapotrans-

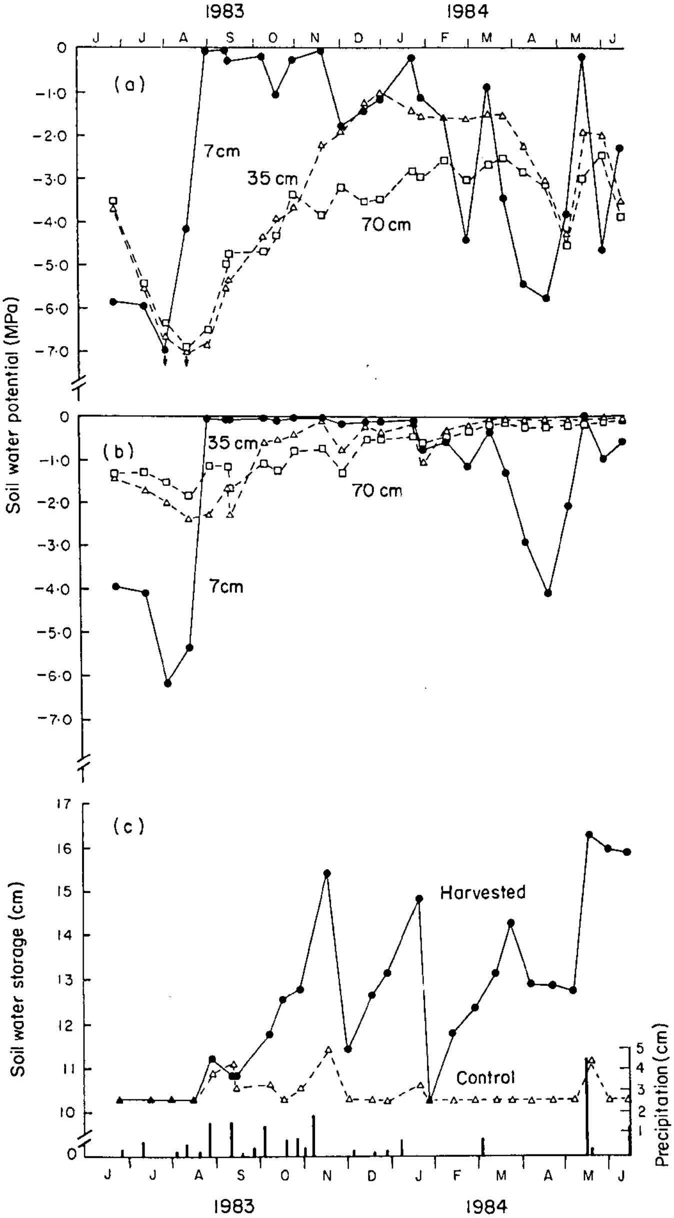

**Figure 2.** (*a*) Seasonal changes in soil water potential at three depths (●, 7 cm; △, 35 cm; □, 70 cm) in the control plots during 1983–1984. (*b*) Seasonal changes in soil water potential in harvested plots. (*c*) Seasonal changes in total moisture storage in the soil profile in control (△) and harvested (●) plots and precipitation events.

piration removes water to below −7·0 MPa in all horizons in the summer. Most of the soil water potentials (Fig. 2*a*) cannot be accurately converted to soil water content using the moisture tension release curves (Fig. 1), because potentials were usually less than −1·50 MPa, and percentage soil moisture was therefore assigned a constant value. Seasonal changes in soil water storage (Fig. 2*c*) are primarily due to short-term fluctuations in the A-horizon.

Despite the presence of a calcic horizon at 37 cm, soil water potential fluctuations at 70 cm were similar to those at 35 cm. Hennessey, Gibbens *et al.* (1983) found that little soil moisture penetrated caliche layers in field experiments in the Chihuahuan Desert. However, in our sites small amounts of water may pass through localized discontinuities or 'pipes' in the caliche, thereby increasing the water potential of the lower horizons.

Our measurements of pre-dawn water potential in *Larrea* (–5·40 MPa) and *Gutierrezia* (−5·01 MPa) on 5 July 1984 showed better agreement with the mean of sensors at 21- and 35-cm depths (−5·08 MPa) than with sensors at 70 cm (−4·69 MPa). Nevertheless, our field observations of root distribution and the changes in water potential at 70 cm indicate that some plant roots penetrate the calcic horizon and remove water from below this layer, although a small amount of water may also move upward as a vapour or unsaturated flow. Cunningham & Burk (1973) found lower plant water potentials in *Larrea tridentata* growing on soils with a caliche layer than on soils without this horizon. Their interpretations of such observations were made in the context of an impenetrable calcic horizon that restricted rooting to a small volume of soil.

Although both evaporation and transpiration remove water from the surface horizon, loss by transpiration predominates in the lower profile. Comparison of mean soil water potentials at 70 cm between sampling periods without precipitation allows a calculation of the relative rate of decline in soil water potential as a result of transpiration (Fig. 3*a*). These data form two patterns depending upon season (Cable,1980). During the winter and spring, transpiration causes a decline in soil water potential of 0·01–0·10 MPa/day, with the rate of decline increasing as soil water potential decreases. Despite high soil water potentials during this period, low ambient temperatures probably limit plant transpiration; thus the highest rates of decline in soil water potential in this interval are during warmer periods of late spring when soil water potential has fallen to *c.* −3·0 MPa. Between sampling intervals in the summer, the rate of decline in soil water potential is greatest (*c.* 0·18 MPa/day) at soil water potentials between −4·0 and −5·0 MPa, and the rate of decline slows as soil water potential decreases ($r = +0{\cdot}82$; $p < 0{\cdot}05$)

There are measurable decreases in soil water potential at potentials *c.* –6·0 MPa. In laboratory experiments, Odening, Strain *et al.* (1974) found stomatal closure (zero net photosynthesis) at *c.* −7·5 MPa for *Larrea tridentata*; however, field measurements of this species in the Sonoran Desert suggest that transpiration declines linearly and ceases between –5·0 and –6·0 MPa of plant water potential (Oechel, Strain *et al.*, 1972; Odening, Strain *et al.*, 1974; Nilsen, Sharifi *et al.*, 1984). Changes in soil water potential at 35 cm are roughly similar to those shown for 70 cm (Fig. 3*b*). The summer pattern of soil water removal is similar to that found for cold desert species in Utah, in which transpiration decreased linearly with a decline in soil water potential in the range from −3·0 to −8·0 MPa (Moore, White *et al.*, 1972).

## *Harvested plots*

During the year of study, soil water potential increased in all horizons in the harvested plots (Fig. 2*b*). The recharge of soil moisture began with autumn rains and, again, the recharge of water is seen from the surface horizons downward. Horizons at 21–70 cm showed a consistent increase in water content, reaching potentials of −0·02 to −0·09 MPa on 17 June 1984. Water potential at the 7-cm level fluctuated throughout the year in

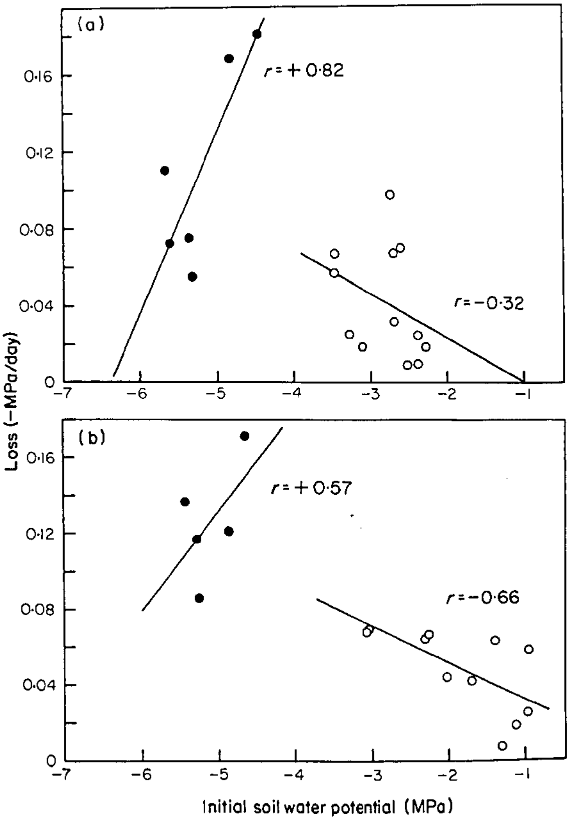

**Figure 3.** Change in soil water potential during a study interval as a function of the water potential at the beginning of the interval, for soil horizons at (*a*) 70 cm and (*b*) 35 cm. ○, Data from winter and spring; ●, data from summer. Only intervals with no precipitation are included.

response to individual rainfall events, although the magnitude of the fluctuations was reduced compared to that in the control plots, especially in the latter half of the study (Fig. 2*a*). Greater soil water storage in the lower horizons reflects an elimination of root uptake and transpiration compared to the control plots.

Since most of the soil moisture potentials were greater than −1·5 MPa in the harvested plots, soil water content can be estimated using the moisture tension release curves (Fig. 1) and changes in water storage from initial conditions can be calculated by difference. Assuming a constant soil water content at potentials less than −1·5 MPa (Fig. 1), there were no changes in water storage in the profile, *c*. 10 cm of $H_2O$, from 24 June to 16 August 1983 (Fig. 2*c*). Water storage showed periodic increases from August through January 1984, but this water was held largely in the surface horizon and was lost during periods without rainfall. In early February, increased water storage in the $B_{1k}$ and $B_{2k}$ horizons caused a large increase in total water storage in the profile, as water contents in these horizons increase rapidly at soil water potentials above −0·2 MPa (Fig. 1). Water stored in these horizons was not lost by evaporation during periods without rainfall. On 8 May 1984, all of the 2·5-cm increase in soil water storage from initial conditions was due to increases below 14-cm depth. More than half of the increase was held in the interval 58–100 cm, below the calcic horizon. After an unusually large storm on 15 May, 84·8% of the increased storage measured on 17 June (5·6 cm) was held below 14-cm depth.

Both evaporation and transpiration are operating on the control plots, while presumably evaporation is the only pathway for water loss from the harvested plots. The difference in soil water content between the harvested and control plots at each of the five peaks (27 August and 19 November 1983, and 22 January, 25 March and 17 June 1984) represents water that might otherwise have been lost by transpiration on the harvested plots. Most of this water evaporates from the harvested plots during subsequent periods of drought. An annual estimate of transpiration of 14·2 cm for this desert ecosystem is derived as the sum of the differences between each trough and the subsequent peak soil moisture on the harvested plots (17·1 cm), less the sum of the same differences on the control plots (2·9 cm), for all of the trough-to-peak cycles of the study year.

Long-term mean annual rainfall is 21 cm in this region, and 19·7 cm fell during the year of study. The sum of the periodic increases in soil water storage on the harvested plots (14·2 cm) suggests that about 72% of incident rainfall is removed by transpiration annually. For comparison, Lane, Romney *et al.* (1983) calculated that transpiration removes 27% of incident rainfall from creosotebush ecosystems in the Mojave Desert of Nevada, whereas Sammis & Gay (1979) found a 7% loss by transpiration in the Sonoran Desert of Arizona.

Harvest of above-ground biomass alters other soil properties that may have affected our measurement of transpiration, yielding a conservative estimate. Harvested plots show higher surface soil temperatures and moisture contents that may result in greater evaporative losses. Infiltration is greater under shrub canopies (Lyford & Qashu, 1969; Elkins, Sabol *et al.*, 1986) and may be reduced upon shrub removal. Soil water potential may have increased below 100-cm depth on harvested plots. All of these effects would act to decrease soil moisture changes in the harvested plots, and consequently our estimates of transpiration may be low.

## Implications for ecosystem processes

Our observations of higher soil water potentials in harvested plots are consistent with observations of higher plant water potentials in studies of desert plant competition, in which potential competitors are harvested from field plots (Fonteyn & Mahall, 1981; Robberecht, Mahall *et al.*, 1983; Ehleringer, 1984). Transpiration removes a large portion of the annual moisture received in precipitation, and transpirational losses appear to be the main pathway for the removal of moisture from the lower soil horizons. By the end of the first year after harvest, soil moisture storage had increased to 63% above initial conditions.

Movements of soil water are directly involved in the deposition of pedogenic carbonate in arid soils. Soil water moving to the lower profile is often saturated with respect to calcite (Schlesinger, 1985), which precipitates as $P\mathrm{CO}_2$ fluctuates seasonally or as plants remove water through transpiration (Stuart & Dixon, 1973). Precipitation of carbonate begins at a depth that is correlated to the mean annual wetting of the soil profile (Arkley, 1967), and proceeds upward as a carbonate-plugged horizon develops (Gile, Peterson *et al.*, 1966). As the calcic horizon develops, it impedes the downward movement of soil water and becomes impenetrable to most roots. Root water uptake is then concentrated in the horizon just above the caliche and leads to further carbonate precipitation in the profile. By controlling the amount and movement of soil water, plant roots may control the rate and depth of carbonate precipitation in arid soils.

We thank Tom DeMoulin, Joan Walker and Bret Whitford for field and laboratory assistance, Dr Walter Whitford for frequent advice and site coordination, and Leland Gile for help in characterizing and understanding soil profile development. Ken Knoerr, Paul Kramer, Bob Luxmoore and Peter Wierenga provided helpful reviews of the manuscript. These investigations were supported by NSF Grant BRS 8212466 to Duke University in cooperation with the Desert Long-Term Ecological Research Program.

## References

Arkley, R. J. (1963). Calculation of carbonate and water movement in soil from climatic data. *Soil Science*, **92**: 239–248.

Arkley, R. J. (1967). Climates of some great soil groups of the western United States. *Soil Science*, **103**: 389–400.

Cable, D. R. (1980). Seasonal patterns of soil water recharge and extraction on semidesert ranges. *Journal of Range Management*, **33**: 9–15.

Cunningham, G. L. & Burk, J.H. (1973). The effect of carbonate deposition layers ('Caliche') on the water status of *Larrea divaricata*. *American Midland Naturalist*, **90**: 474–480.

Ehleringer, J. R. (1984). Intraspecific competitive effects on water relations, growth and reproduction in *Encelia farinosa*. *Oecologia*, **63**: 153–158.

Eisenberg, J., Dan, J. & Koyumdjisky, H. (1982). Relationships between moisture penetration and salinity in soils of the northern Negev (Israel). *Geoderma*, **28**: 313–344.

Elkins, N.Z., Sabol, G. V., Ward, T. J. & Whitford, W. G. (1986). The influence of subterranean termites on the hydrological characteristics of a Chihuahuan desert ecosystem. *Oecologia*, **68**: 521–528.

Fonteyn, P. J. & Mahall, B. E. (1981). An experimental analysis of structure in a desert plant community. *Journal of Ecology*, **69**: 883–896.

Fonteyn, P. J., Schlesinger, W. H. & Marion, G. M. (1987). Accuracy of soil thermocouple hygrometer measurements in desert ecosystems. *Ecology*, **68** (in press).

Gile, L. H., Peterson, F. F. & Grossman, R. B. (1966). Morphological and genetic sequences of carbonate accumulation in desert soils. *Soil Science*, **101**: 347–360.

Hennessy, J. T., Gibbens, R. P., Tromble, J. M. & Cardernas, M. (1983). Water properties of caliche. *Journal of Range Management*, **36**: 723–726.

Kemp, P. R. (1983). Phenological patterns of Chihuahuan Desert plants in relation to the timing of water availability. *Journal of Ecology*, **71**: 427–436.

Lane, L. J., Romney, E. M. & Hakonson, T. E. (1983). Water balance calculations and net production of perennial vegetation in the Mojave Desert. *Journal of Range Management*, **37**: 12–18.

Lyford, F. P. & Qashu, H. K. (1969). Infiltration rates as affected by desert vegetation. *Water Resources Research*, **5**: 1373–1376.

Mo6re, R. T., White, R. S. & Caldwell, M. M. (1972). Transpiration of *Atriplex confertifolia* and *Eurotia lanata* in relation to soil, plant, or atmospheric moisture stresses. *Canadian Journal of Botany*, **50**: 2411–2418.

Mullins, J. A. (1981). Estimation of plant available water capacity of a soil profile. *Australian Journal of Soil Research*, **19**: 197–207.

Nilsen, E. T., Sharifi, M. R. & Rundel, P. W. (1984). Comparative water relations of phreatophytes in the Sonoran Desert of California. *Ecology*, **65**: 767–778.

Odening, W. R., Strain, B. R. & Oechel, W. C. (1974). The effect of decreasing water potential on net $CO_2$ exchange of intact desert shrubs. *Ecology*, **55**: 1086–1095.

Oechel, W. C., Strain, B. R. & Odening, W. R. (1972). Tissue water potential, photosynthesis, $^{14}C$-labeled photosynthetic utilization and growth in the desert shrub, *Larrea divaricata* Cav. *Ecological Monographs*, **42**: 127–141.

Robberecht, R., Mahall, B. E. & Nobel, P. S. (1983). Experimental removal of intraspecific competitors: effects on water relations and productivity of a desert bunchgrass, *Hilaria rigida*. *Oecologia*, **60**: 21–24.

Sammis, T. W. & Gay, L. W. (1979). Evapotranspiration from an arid zone plant community. *Journal of Arid Environments*, **2**: 313–321.

Schlesinger, W. H. (1985). The formation of caliche in soils of the Mojave Desert, California. *Geochimica et Cosmochimica Acta*, **49**: 57–66.

Stuart, D. M. & Dixon, R. M. (1973). Water movement and caliche formation in layered arid and semi-arid soils. *Soil Science Society of America, Proceedings*, **37**: 323–324.