Soil Moisture Attributes of Three Inland Sand Dunes in the Mojave Desert

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Abstract: Soil moisture attributes were investigated in three active sand dunes in the Mojave Desert of southern Nevada and California. Soil water content increased significantly with increasing soil depth, and decreased when moving toward dune habitats. Path analysis revealed direct causal effects of soil depth and habitat type (dune and nondune) on soil water content. Among soil moisture variables, significant interaction was detected between habitat type and geomorphic surface (terrace and slope) for area of water spread (surface water runoff). When examining habitat type or geomorphic surface alone, significant differences were detected in all measured moisture variables. Significant differences were also found in site for water infiltration and depth of water penetration. The Kelso, Ash Meadows, and Death Valley dunes had different soil moisture attributes compared with adjacent *Larrea-Ambrosia* shrublands.

Introduction

Active sand dunes cover less than 1 percent of the North American deserts (Sharp 1966). Desert sand dunes are edaphically distinct from surrounding habitats in terms of extremely high percentage of sand, instability of sand substrates, and rate of sand movement. Long and dry seasons, low soil nutrient levels, high air and soil temperatures, as well as mobile and abrasive sand with coarse texture are characteristics of inland desert dunes (Bowers 1986; Pavlik 1985). Low soil moisture, low organic litter, and matter are also typical of dune environments (Barbour and others 1999; Bowers 1982). However, soil moisture increases with depth in the inland dunes (Bowers 1982; Prill 1968; Sharp 1966).

Although sand dune ecosystems appear simple, they are actually complex and delicately balanced (Bowers 1986). Sand dunes are unique continental islands isolated by their physical and biological properties or by factors related to the evolution of the landscape through geological time (Brown 1972). Because of low economic and agricultural values, dunes are one of the least studied ecosystems in the Southwestern United States. There have been a number of studies pertaining to the edaphic characteristics of eolian deposits in arid environments of the Southwest (Holiday 1990; Lancaster 1993, 1998; Lei 1998; McFadden and others 1987; Sharp 1966; Wells and others 1990). Yet, little attention has been focused on the soil surface and moisture characteristics of inland dunes in the Mojave Desert.

Despite limited economic and agricultural values, sand dunes are an important component of the Mojave Desert landscape, and are ecologically and edaphically interesting (Lei 1998). Two hypotheses were made prior to data collection: (1) soil moisture attributes would differ among the three dune sites, between dune and nondune habitats, and between two geomorphic surfaces (terrace and slope) within a habitat, and (2) gravimetric soil moisture would be partially influenced by habitat type and soil depth. These two hypotheses were tested by a combination of field and laboratory measurements of soil moisture attributes in the Kelso, Ash Meadows, and Death Valley dunes with their adjacent *Larrea tridentata-Ambrosia dumosa* (creosote bush-white bursage) shrublands (nondunes) in the Mojave Desert of southern Nevada and California.

Methods and Materials

Study Site

Field studies were conducted at three dune systems in southern Nevada and California (fig. 1) during the summer of 2001. The Kelso and Death Valley dunes are in southern California, and the Ash Meadows dunes are in southern Nevada (fig. 1). Elevations varied considerably, ranging from 85 m below sea level in Death Valley to 670 m above sea level in Kelso and Ash Meadows (table 1). Among the three active dunes, Death Valley has the highest mean monthly air temperature (fig. 2) and the lowest mean monthly precipitation (fig. 3).

The substrates were deep, unstable, and coarse grained on all three dunes. Within each dune system, variations in sand particles were observed. Sand particles, ranging from coarse to fine in texture, can be distinguished according to their particle size distribution and mean grain size (Lancaster 1993). Different sand occupies distinct areas of the dune field, suggesting that dunes represent a stacked sequence of sand deposition events (Lei 1998).

Atriplex spp. (saltbush) and *Larrea tridentata* commonly occur in dune and marginal dune habitats in the Kelso, Ash Meadows, and Death Valley dunes. Marginal dunes were located between active dunes and adjacent nondune areas, with sand more or less stabilized. Abundant vegetation may eventually cause soil to develop. *Larrea* plants are typically larger and taller in dune fields compared to its nondune

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Figure 1—Location of three inland sand dunes in southern Nevada and California. Dune systems are numbered as follows: 1 = Ash Meadows, 2 = Death Valley, and 3 = Kelso.

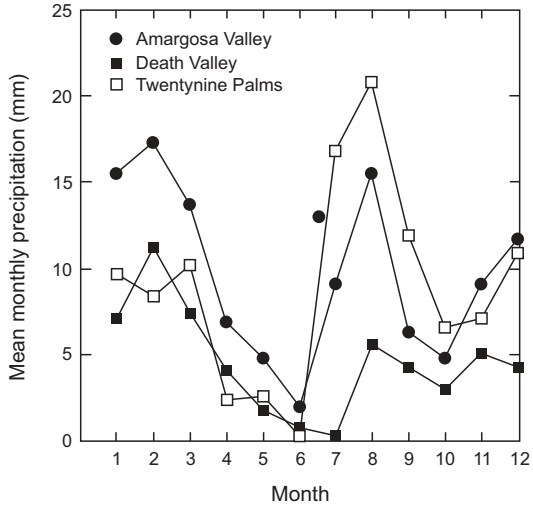

Figure 2—Mean monthly precipitation in Twentynine Palms, Amargosa Valley, and Death Valley (local climatological data, NOAA). Ash Meadows lies within the Amargosa Valley, while Kelso Dunes lies approximately 20 km northeast of Twentynine Palms. Weather data are not available in Kelso Dunes.

counterpart (Lei 1999). *Larrea* and *Ambrosia* are codominant shrub species occurring in the adjacent nondune habitats of the Kelso Dunes and Ash Meadows, while *Larrea-Atriplex* spp. form a common shrub association in Death Valley. *Hymenoclea salsola* (cheesebush) and *Salsola* spp. (Russian-thistle) are frequently found in dune habitats of Ash Meadows. *Achnatherum hymenoides* (Indian ricegrass) and *Astragalus lentiginosus* (locoweed) are herbaceous plants occurring in Kelso Dunes (Lei 1999).

Field and Laboratory Measurements

For each sand dune, 14 transects were established with each transect containing dune habitats, ecotone (marginal dune), and adjacent nondune shrublands. These 14 transects were randomly distributed around the entire dune area. Dune plots, with an area of 100 m^2, were located at least 200 m into the dune environments, whereas nondune plots were located 200 m from the nearest marginal dunes.

At the center of each adjacent nondune plot, one soil sample was extracted to depths of 5 cm and 20 cm only due to the presence of caliche layers near the surface. However, at the center of each dune plot, one soil sample was extracted at multiple depths—5, 20, 40, 90, and 130 cm. Soils were

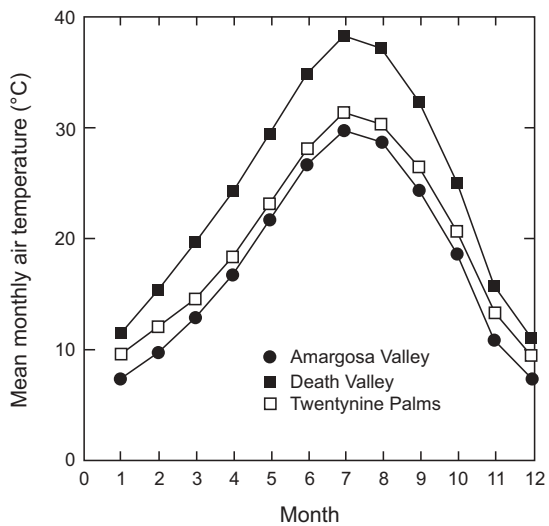

Figure 3—Mean monthly air temperature in Twentynine Palms, Amargosa Valley, and Death Valley (local climatological data, NOAA). Ash Meadows lies within the Amargosa Valley, while Kelso Dunes lies approximately 20 km northeast of Twentynine Palms. Weather data are not available in Kelso Dunes.

Table 1—Geographic characteristics of three inland sand dunes in the Mojave Desert.

Dune system	County, State	Latitude	Longitude	Elevation
		- - *N* - -	- - *W* - -	- *m* -
Ash Meadows	Nye, NV	36°20'	116°15'	670
Death Valley	Inyo, CA	36°35'	116°00'	< 85
Kelso	San Bernadino, CA	34°55'	115°40'	670

passed through a 2-mm sieve to remove large rocks and plant roots. A soil sieve also separated sand, silt, and clay from material larger than 2 mm such as gravels and cobbles. Soil samples were measured for gravimetric moisture. Soils were oven dried at 105 °C for 72 hours. Gravimetric soil moisture (soil water content) was determined by calculating the differences between fresh and oven-dried mass divided by dry mass. To ensure compatibility, air temperatures in the field were recorded concurrently when soil samples were collected.

Water infiltration rates were measured using a PVC pipe (cylinder), 5.5 cm in diameter and 9.5 cm tall. This cylinder was open at both ends, and was gently tamped into the dune and nondune soils to a depth of 2 cm to avoid leakage, and then 50 ml of water was ponded above the core inside of the cylinder (Brotherson and Rushforth 1983). Infiltration into the core was measured with a stopwatch as the number of seconds needed for the ponded water to disappear into the core (Brotherson and Rushforth 1983).

Approximately 1.5 L of water, serving as artificial rain, was manually poured through a perforated 13-cm disk, with perforations evenly spaced on a 0.1-cm grid. The disk was placed 1.0 m above ground. The total delivery time for the water to be dispensed on the dune or nondune soil was 60 seconds to create precipitation at a cloudburst level (Brotherson and Rushforth 1983). A sudden, heavy precipitation is significant due to its impacts on surface-water runoff and fluvial erosion. Depth of water penetration was immediately measured and recorded once the water had soaked into the soil.

Surface-water runoff was measured by recording the downslope and across-slope spread of water that was artificially rained onto study sites (Brotherson and Rushforth 1983). The area of water spread from these two slope measurements was computed using the formula for the area of an ellipse using the following equation: (πab), where a and b are radii of an ellipse (Larson and others 1994). Since surface water runoff did not form a perfect elliptical shape, measured areas were likely to be overestimates.

Soil movement was assessed by visually quantifying the amount of soil loss via fluvial erosion during a measured cloudburst. The following index was used at the spot of this cloudburst: 1 = no appreciable movement; 2 = moderate movement—up to 10 percent of soil particles being displaced, and 3 = heavy movement—between 10 and 20 percent of soil particles being displaced (Brotherson and Rushforth 1983).

Statistical Analyses

One-way Analysis of Variance (ANOVA; Analytical Software 1994) was used to detect significant effects of site (three dunes), habitat type (dune, marginal dune, and adjacent shrublands), and soil depth on soil water content. Tukey and Scheffe's multiple comparison tests (Analytical Software 1994) were used to compare site means when significant effects of habitat type and soil depth were detected. Pearson's Correlation (Analytical Software 1994) was conducted to correlate soil water content with site, habitat type, and geomorphic surface (terrace and slope). Path analysis includes a path diagram (fig. 4) with direct causal pathways whose strengths were indicated by partial regression coefficients (path coefficients), with arrows indicating the direction of causal connection from predictor (site, habitat type, and soil depth) to response (soil moisture) variables. A short, unlabeled (residual) arrow appeared in the path diagram, indicating that other abiotic factors would have some influence on the overall gravimetric soil moisture.

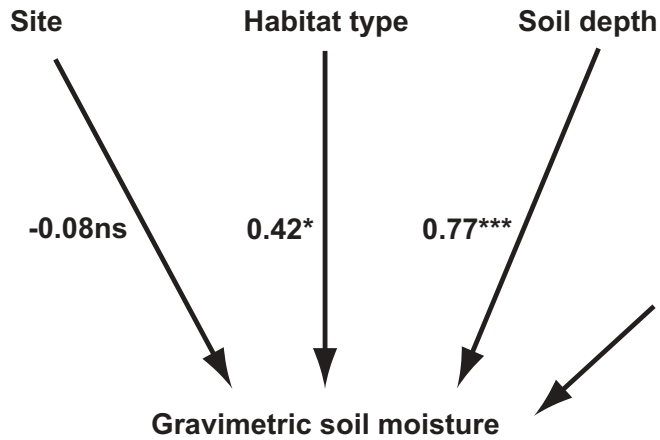

Figure 4—Path diagram depicting proposed causal influences of site, habitat type, and soil depth (environmental attributes) on gravemtrica soil moisture. The direct causal effect of each attribute (straight, one-headed arrow) on soil moisture is the standardized partial regression coefficient (path coefficient). A short, unlabeled (residual) arrow is shown to indicate that additional climatic, edaphic, and geomorphic factors may play a role in determining the overall soil moisture content.

Multivariate Analysis of Variance (MANOVA; Analytical Software 1994) was performed on soil moisture attributes with site, habitat type, and geomorphic surface as main effects. P-values equal to or less than 0.05 are reported as statistically significant.

Results

Gravimetric soil moisture were significantly different in site, habitat type, and soil depth ($P \leq 0.01$). Dune substrates had a significantly lower ($P \leq 0.001$) water content at the upper 20 cm than nondune substrates. Soil water content reached as high as 1.48 percent at 130 cm beneath the surface in the Ash Meadows dunes during midsummer.

Among the three dune fields, Death Valley dunes consistently exhibited the lowest soil water content at all depths (table 2). Mean summer precipitation fell below 5 mm (fig. 2), while mean summer air temperature exceeded 30 °C in Death Valley (fig. 3). In all three dunes, soil water content increased significantly as soil depth increased ($P \leq 0.001$; table 2). Path analysis revealed significant direct causal effects of soil depth and habitat type on soil water content (fig. 4). Despite more extreme monthly and annual weather conditions found in Death Valley, dune site had little direct effect on soil water content (table 3). According to path analysis, soil water content was significantly directly influenced by soil depth and

Table 2—Soil water content (percentages) at various depths in dune and adjacent nondune (*Larrea-Ambrosia*) habitats during July 2001 in the Mojave Desert (n = 14 per habitat in each dune system). Due to the presence of caliche layers near the soil surface, soil moisture was not examined beyond 20 cm in nondune habitats[a].

	Ash Meadows		Death Valley		Kelso	
Soil depth	Dune	Nondune	Dune	Nondune	Dune	Nondune
- - cm - -						
5	0.12aA	0.26aB	0.07aA	0.18aB	0.15aA	0.33aB
20	.34bA	.79bB	.15bA	.46bB	.39bA	.84bB
40	.64c	—	.41c	—	.59c	—
90	.98d	—	.74d	—	.92d	—
130	1.48e	—	1.08e	—	1.37e	—

[a]Mean values within each dune system (in rows) followed by different upper case letters are significantly different at P ≤ 0.05. Mean values within each habitat (in columns) followed by different lower case letters are also statistically significant at P ≤ 0.05.

Table 3—Relationship between three environmental variables and soil water content. The direct causal effect of each variable is the standardized partial regression coefficient (path coefficient). Total causal influence (Pearson's r-value) sums all direct and indirect pathways.

Variable	Direct causal	Indirect causal	Total causal
Site	–0.08[a]	–0.09[a]	–0.17[a]
Habitat type	.42[b]	.23[a]	.65[c]
Soil depth	.70[c]	.16[a]	.94[c]

[a]Nonsignificant
[b]Significance levels P ≤ 0.05.
[c]Significance levels P ≤ 0.001.

habitat type. Soil water content was subject to additional biotic and abiotic influences, representing by a residual arrow (fig. 4). Although not quantitatively examined in this study, other direct and indirect causal effects on soil water content may include absorption of water by plants, gravity, slope exposure, topography, macropore, soil compaction, soil particle size, air temperature, precipitation, evaporation, relative humidity, and amount of cloud cover.

Moreover, time for water infiltration and depth of water penetration increased significantly (P ≤ 0.001; table 4) from the surrounding *Larrea-Ambrosia* shrublands to dune fields. Among the three dunes, Death Valley had a significantly shorter time for water infiltration and greater depth of water penetration. Downslope, across slope, and area of water spread were significantly smaller (P ≤ 0.001; table 4) in dune than in nondune substrates. Water-born soil movement (fluvial erosion) was significantly greater at slope than at terrace sites (P ≤ 0.01; table 4) regardless of habitat types.

Among the soil moisture regimes, significant interaction (P ≤ 0.001; table 5) was detected between habitat type and geomorphic surface for area of water spread (surface water runoff) only. When examining habitat type or geomorphic surface alone, significant differences (P ≤ 0.05; table 5) were found in all measured moisture variables. There were also significant differences (P ≤ 0.05; table 5) in site for water infiltration and water movement into the soil.

Discussion

The Kelso, Ash Meadows, and Death Valley dunes in the Mojave Desert of southern Nevada and California were edaphically distinct in terms of soil moisture status from the surrounding *Larrea-Ambrosia* shrublands. In all dunes, soil water content increased with depth, and decreased from the surrounding *Larrea-Ambrosia* shrublands to dune fields.

Because of larger pore size, coarser particles, extremely high percent sand, and less organic matter, dune soils provide less moisture retention than nondune soils. In this study, soil moisture in the top 20 cm was less than 1 percent, but soil moisture increased significantly as depth increased in all three dunes during the midsummer season. Death Valley had significantly lower soil water content than Kelso Dunes and Ash Meadows, primarily due to a combination of higher evaporation and summer air temperature, lower summer precipitation, relative humidity, cloud cover, and lower elevation. Low moisture availability, usually less than 1 percent at or near the soil surface, is a common characteristic of inland sand dunes in Western America, including the Eureka, Mojave Desert dunes, and northeastern Colorado dunes (Bowers 1986; Lei 1998). Water does not store well in shallow soils, mainly due to rapid evaporation. Conversely, water is stored well in deep soils and can support perennial plants with deep roots. The loss of water in deep soils is primarily by percolation into groundwater, absorption of plant roots, and transpiration from plant leaves (Prill 1968). Moisture in dune sand comes from precipitation (Bowers

Table 4—Moisture characteristics of dune and adjacent nondune (*Larrea-Ambrosia* shrubland) soils in southern Nevada and California of the Mojave Desert (*n* = 14 per habitat in each dune system).

Moisture parameter	Ash Meadows		Death Valley		Kelso	
	Dune	Nondune	Dune	Nondune	Dune	Nondune
Infiltration rate	*seconds*					
Terrace	138.7	214.3	121.3	189.4	132.4	218.6
Slope	212.3	241.1	201.8	229.7	229.5	256.9
Depth of water penetration	*cm*					
Terrace	3.6	3.2	3.7	3.4	3.8	3.5
Slope	3.2	2.9	3.4	3.1	3.3	2.9
Downslope spread	*cm*					
Terrace	51.7	67.4	45.1	70.8	48.7	75.4
Slope	62.1	85.7	53.2	86.4	59.8	89.7
Across slope spread	*cm*					
Terrace	36.1	61.2	33.6	59.4	34.4	62.7
Slope	44.0	74.2	39.9	68.5	41.9	70.2
Area of spread	cm^2					
Terrace	933.2	2,062.4	757.7	2,012.8	837.6	2,363.8
Slope	1366.2	3,179.5	1,061.3	2,959.2	1,252.8	3,148.5
Soil movement	*fluvial erosion*					
Terrace	1.4	1.2	1.4	1.2	1.4	1.
Slope	1.6	1.4	1.7	1.4	1.7	1.3

Table 5—MANOVA results (P-values) of the effects of habitat type, geomorphic surface, site, and their interactions on six soil moisture attributes: water infiltration, depth of water penetration, downslope and across-slope water spread, area of water spread, and water-borne soil movement.

Source	Infiltration	Depth	Downslope	Across slope	Area	Soil
Habitat type (A)	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001
Geomorphic surface (B)	.0005	.0000	.0137	.0001	.0000	.0006
Site (C)	.0005	.0295	.7024	.2750	.1663	.7065
A, B	.1497	.1372	.5041	.3752	.0028	.2562
A, C	.7301	.6726	.5942	.9868	.6100	.3743
B, C	.7118	.6014	.9770	.6710	.8228	.7065
A, B, C	.9153	.2372	.9689	.7804	.9396	.3641

1982). Shortly after a rain, moisture at the soil surface may be as high as 3 percent (Ramaley 1939). Sandy soils have large pores, which drain water downward by gravity after soils are moistened at the surface. Abundant water may be available in inland sand dunes below the surface layers, with the top 20 cm of dry sand insulating moister sand below from air exchange (Bowers 1982; Sharp 1966).

In this study, dune sand had considerably more available water than its sandy texture would suggest. For instance, percolating water can reach depths such that it is immune to evaporation but available to plant roots. Another process is vapor-phase addition of water to sand. This mechanism occurs as dew and mist that condense during the night on cold sand particles. As heating occurs during the day, some of this water evaporates into the atmosphere. A significant portion of water vapor, however, moves downward by diffusion to the cooler sand. The addition of moisture to sandy desert soils via this mechanism is essential. The hardpan restricts rooting in nondune sites. Because there are no root restriction zones in dunes, plants can root to much deeper depths so moisture stored at depth can be extracted.

Water percolated into dune soils significantly faster than into nondune soils in this study. The infiltration rate of South African soils is influenced by many factors, including organic matter, soil texture, and slope (Dean and Yeaton 1993). Significant interaction was found between habitat type and geomorphic surface for surface water runoff. Substantially higher water infiltration and greater depth of water penetration are expected on extremely sandy dune soils with terrace surface compared to adjacent nondune soils with slope surface, presumably due to a larger pore size, higher moisture leaching rate, and lower compaction.

Additionally, soil can be removed by the action of heavy rains or flash floods. In this study, dune soils exhibited a significantly lower surface-water runoff compared to nondune soils because dune soils absorbed more water during and shortly after a simulated cloudburst. With increased infiltration and reduced surface-water runoff, deeper penetration of water into the soil occurred at terrace than at slope

sites. Nevertheless, a significantly greater fluvial erosion was detected at slope than at terrace sites in both dune and nondune soils. Although a short cloudburst did not create extensive fluvial erosion, some movement of soil particles occurred at the surfaces of slope sites when water traveled rapidly downslope by gravity. However, substantially more surface-water runoff and soil loss via fluvial erosion are likely to occur in both dune and nondune substrates if cloudbursts have longer duration, higher frequency, and/or greater intensity.

Active inland sand dunes occupy only a tiny fraction of the North America desert landscape. The Kelso, Ash Meadows, and Death Valley dunes of the Mojave Desert are different from the surrounding *Larrea-Ambrosia* shrublands in terms of soil moisture attributes. Compared to adjacent shrublands, sand dunes are edaphic islands that have water available at depth and that are important in shaping unique biogeographic patterns through time. Future research is required to investigate additional soil attributes, such as chemical nutrients and biological properties, in inland dunes of North America and on other continents.

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