Ecological controls on water-cycle response to climate variability in deserts

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The impact of climate variability on the water cycle in desert ecosystems is controlled by biospheric feedback at interannual to millennial timescales. This paper describes a unique field dataset from weighing lysimeters beneath nonvegetated and vegetated systems that unequivocally demonstrates the role of vegetation dynamics in controlling water cycle response to interannual climate variability related to El Niño southern oscillation in the Mojave Desert. Extreme El Niño winter precipitation (2.3–2.5 times normal) typical of the U.S. Southwest would be expected to increase groundwater recharge, which is critical for water resources in semiarid and arid regions. However, lysimeter data indicate that rapid increases in vegetation productivity in response to elevated winter precipitation reduced soil water storage to half of that in a nonvegetated lysimeter, thereby precluding deep drainage below the root zone that would otherwise result in groundwater recharge. Vegetation dynamics have been controlling the water cycle in interdrainage desert areas throughout the U.S. Southwest, maintaining dry soil conditions and upward soil water flow since the last glacial period (10,000–15,000 yr ago), as shown by soil water chloride accumulations. Although measurements are specific to the U.S. Southwest, correlations between satellite-based vegetation productivity and elevated precipitation related to El Niño southern oscillation indicate this model may be applicable to desert basins globally. Understanding the two-way coupling between vegetation dynamics and the water cycle is critical for predicting how climate variability influences hydrology and water resources in water-limited landscapes.

climate change | ecohydrology | El Niño

Evaluating potential impacts of climate variability on subsurface components of the water cycle, particularly percolation below the root zone (equated with groundwater recharge), is essential for water resources and waste disposal. Currently, an estimated 1.1 billion people of the world's population of 6 billion lack access to sources of clean drinking water (1). Water scarcity is greatest in semiarid and arid regions because of limited supplies and increasing demand due to greater population growth relative to more humid regions (2). Semiarid ecosystems are expanding and currently represent ≈30% of global terrestrial surface area (3). Approximately 40% of the U.S. population growth between 1960 and 2000 occurred in semiarid and arid states in the U.S. Southwest (U.S. Census Bureau). Contaminant transport is similarly important because deserts are considered favorable sites for waste disposal (4). For example, the proposed U.S. repository to isolate highly radioactive waste for 10,000 yr is located in Yucca Mountain, within the Mojave Desert, Nevada (5). Many studies indicate that vegetation responds dynamically to climate variability and feeds back to significantly impact land atmosphere interactions and climate predictions (6–8). Vegetation dynamics may be equally important in regulating the impact of climate variability on subsurface water flow and recharge, which are critical for water resources and waste disposal in deserts.

Desert environments are particularly vulnerable to climate variability because low soil water contents provide little buffer against climate extremes. Key questions are how climate variability will impact subsurface components of the water cycle (e.g., recharge) and whether vegetation dynamics will regulate this response. This paper interprets the results of field-monitoring data from weighing lysimeters installed beneath nonvegetated and vegetated systems to demonstrate the role of vegetation on the water cycle response to climate variability at the Nevada Test Site (NTS) in the Mojave Desert (Fig. 1). Interannual climate variability on a global scale is determined primarily by El Niño southern oscillation (ENSO), which results in highly elevated winter precipitation in the U.S. Southwest. The 8-yr monitoring record provides an ideal opportunity to evaluate the impact of climate variability because it includes the largest El Niño during the last century (1997–1998) that would be expected to result in episodic recharge. Understanding interactions between vegetation dynamics and the water cycle developed from this site was extended to millennial timescales by evaluating archival records provided by soil water chloride and water potential (pressure) profiles in thick unsaturated zones in desert systems.

Materials and Methods

System response to interannual climate variability was evaluated by using point monitoring data (1994–2002) from weighing lysimeters. The role of vegetation was isolated by comparing results from nonvegetated and vegetated lysimeters. The vegetation response was regionalized by using satellite data. Water cycle response to climate variability was extended to regional scales by using soil water potential monitoring at several locations throughout the U.S. Southwest. The process understanding of system response to current climate variability was extended to millennial timescales by using soil water chloride and water potential profiles.

Two weighing lysimeters, one vegetated and the other nonvegetated, were installed in a closed alluvial basin within the NTS (36°51′ 9.13′′ N, 115°56′ 56.06′′ W; elevation, 976 m) by the Nevada Site Office (Waste Management Division) within the U.S. National Security Administration (9, 10) (Fig. 1). The lysimeters are soil-filled concrete containers (2 × 4-m area, 2 m deep) that measure changes in soil water storage; they are open at the surface and hydrologically isolated from surrounding soil (Fig. 7, which is published as supporting information on the PNAS web site). Lysimeters are used to monitor the water balance at the land surface (11–13):

$$\Delta S = P - E(T) - D, \quad [1]$$

where ΔS is change in soil water storage, P is precipitation, E is evaporation from nonvegetated lysimeters, ET is evapotranspiration from vegetated lysimeters, and D is drainage. An elevated

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Abbreviations: ENSO, El Niño southern oscillation; ET, evapotranspiration; NDVI, Normalized Difference Vegetation Index; NTS, Nevada Test Site.

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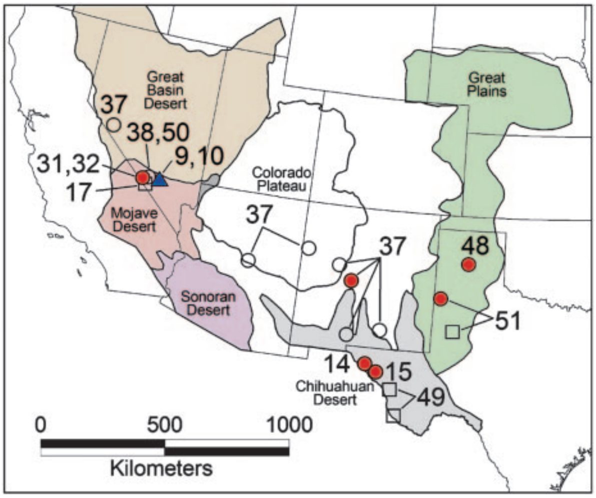

Fig. 1. Measurement locations relative to geographic and desert provinces in the Western U.S. The paired vegetated and nonvegetated lysimeters (solid triangle) are located in the NTS within the Mojave Desert and have time series of soil water storage data. Other monitored sites (solid circles) have field-monitored water potential time-series data and one-time borehole chloride sampling. Remaining locations have either one-time sampling for both water potential and chloride (open squares) or for chloride only (open circles). Numbers indicate referenced studies (9, 10, 14, 15, 17, 31, 32, 37, 38, 48–51).

rim around the edge of the lysimeters precludes runon and runoff. Precision balances at the base of the lysimeters measure weight changes to within ± 200 g, which corresponds to water-storage changes of ±0.025 mm. Increases in soil water storage occur in response to inputs (precipitation), and decreases occur in response to outputs (evaporation, transpiration, and drainage). The lysimeters were filled with soil that consisted of 20% gravel, 70% sand, and 10% silt-loam, which is classified as gravelly loamy sand. The soil was compacted to a bulk density of 1.5 kg/m^3 that corresponds to a porosity of 37%.

The vegetated lysimeter was planted in February 1994 with greenhouse-grown seedlings for three species of perennial shrubs: *Larrea tridentata* (creosote bush), *Lycium andersonii* (desert thorn), and *Atriplex canescens* (four-wing saltbush). Annual grasses also grew on the lysimeter. Use of nonvegetated and vegetated lysimeters allows evapotranspiration (ET) to be subdivided into estimates of evaporation and transpiration (*Supporting Text*, which is published as supporting information on the PNAS web site). Time domain reflectometry probes were installed to monitor soil water content at depths ranging from 0.1 to 1.7 m in both lysimeters. However, reliable soil water content data could be obtained only from the vegetated lysimeter because probes in the nonvegetated lysimeter generally malfunctioned. The lower physical boundary of the lysimeter is open to the atmosphere, which prevents drainage except when the sediments at the lysimeter base are saturated with water. Modeling analysis was used to simulate unimpeded (free) drainage from the lysimeter, which would occur in the natural system (*Supporting Text*).

Vegetation response to climate variability was extended to regional scales by using satellite data. Normalized Difference Vegetation Index (NDVI) anomalies were derived from advanced very high resolution radar satellite data in a 2,450-km^2 area surrounding the lysimeters. NDVI data from the National Center for Earth Resources Observation and Science Data Center (U.S. Geological Survey) consisted of composited bimonthly values (spatial resolution 1 pixel = 1 km), corrected for atmospheric water vapor. NDVI departure-from-average maps for a given 2-week period were developed by comparing each pixel with its average value based on a 14-yr record (1989–2003), omitting data from 1994 because of poor quality. NDVI anomaly maps were developed for May 1995, May 1996, and May 1998.

Water cycle response to climate variability was extended from point lysimeter data to regional scales by using time-series soil water potential (pressure) monitoring at locations throughout the U.S. Southwest (Fig. 1). In the unsaturated zone, water potentials are negative (less than atmospheric pressure) and decrease (become more negative) as the soil dries. A time series of soil water potentials was used to evaluate penetration depths of wetting fronts related to precipitation and drying fronts related to ET.

The process understanding of the subsurface water cycle response to current climate variability was extended to millennial timescales by using measured soil water potential and chloride profiles in thick unsaturated zones. The profiles provide information on both the direction and magnitude of water movement over millennial timescales and have been measured for up to 50 borehole locations throughout the U.S. Southwest (Fig. 1). Water potential profiles based on laboratory measurements on soil cores collected in the field provide information on the direction of water movement because water moves from regions of high to low potential (14–17). Chloride, which is derived from atmospheric precipitation and dry fallout at the land surface, moves into the soil with infiltrating water. Subsurface sources and sinks of chloride are negligible because chloride is conservative (nonreactive) (18) and precipitates from solution only at high concentrations (220,000 mg/liter) (19). Furthermore, chloride is nonvolatile, and plant uptake of chloride is negligible. Chloride in unsaturated-zone pore water can be used to infer the subsurface water cycle response to long-term climate variability. Low chloride concentrations indicate high water fluxes that flush chloride through the unsaturated zone and may be related to subhumid and humid climates. In contrast, high chloride concentrations indicate low or upward water fluxes that allow chloride to build up in the unsaturated zone because water is removed by plants through ET, leaving chloride behind. Estimates of the long-term annual chloride deposition rate allow the age of the water at a given depth to be estimated.

The methods applied in this study allowed evaluation of the role of biospheric feedbacks in controlling water cycle response to climate variability at point (lysimeter) to regional (water potential monitoring sites) scales at interannual (ENSO, lysimeter, and water potential monitoring) to millennial (glacial/interglacial, soil water potential, and chloride data) timescales in semiarid and arid regions in the U.S. Southwest.

Results and Discussion

Water cycle response to interannual climate variability was shown by the 8-yr lysimeter monitoring record, which includes moderate (1994–1995) and strong (1997–1998) El Niños followed by weak (1995–1996) and moderate (1998–1999) La Niñas (Fig. 2 and Fig. 8, which is published as supporting information on the PNAS web site; see also *Supporting Text*). In the U.S. Southwest, El Niños are characterized by cool, wet winters and La Niñas, by warm, dry winters. The regional impact of ENSO on precipitation in the U.S. Southwest can be seen in precipitation maps for winter 1994–1995 (El Niño), winter 1995–1996 (La Niña), and winter 1997–1998 (El Niño) (Fig. 3). Annual precipitation during the monitoring period was representative of the 1963–2001 record (Fig. 9, which is published as supporting information on the PNAS web site).

The dominant role of vegetation in controlling the subsurface components of the water cycle is shown by comparison of soil water storage in the vegetated lysimeter with that in the nonvegetated lysimeter. Soil water storage increases (up to 50%) were similar in both lysimeters in response to 2.3–2.5 times normal winter precipitation (December–February) related to

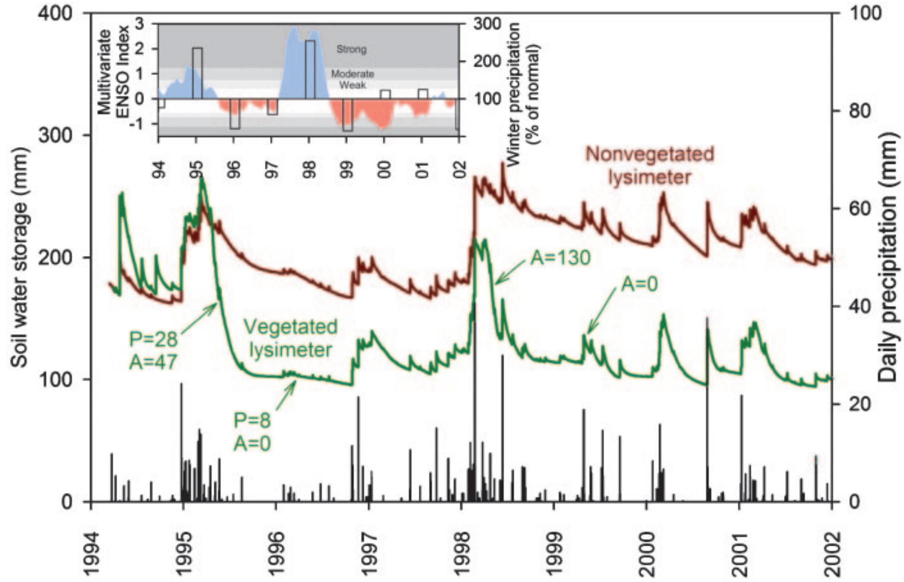

Fig. 2. Measured soil water storage to a depth of 2 m in both vegetated and nonvegetated lysimeters and daily precipitation depths at the NTS location. The initial water storage increase in 1994 in the vegetated lysimeter represents irrigation applied to establish vegetation. Above-ground biomass productivity (g/m^2) is shown for measurements in May 1995 and May 1996 for annual and perennial vegetation at the nearby Yucca Mountain site (25) and May 1998 and May 1999 for annual vegetation at the nearby free air CO_2 experiment site (26) (Fig. 5*b*). (*Inset*) Relationship between the multivariate ENSO index (blue shading; El Niño, red shading; La Niña) and percent of normal 1971–2000 winter precipitation (normal, 46 mm, December–February; columns) at the NTS location.

1994–1995 and 1997–1998 El Niño events, respectively (Fig. 2). However, soil water storage decreases were much greater in the vegetated lysimeter in the months immediately after El Niño events, and total soil water storage in the vegetated lysimeter was half that of the nonvegetated lysimeter at the end of the measurement period. Soil water storage decreased to values recorded before the 1994–1995 infiltration in 2 months in the vegetated lysimeter vs. 22 months in the nonvegetated lysimeter, indicating an order-of-magnitude higher rate of soil water storage decrease in the vegetated vs. nonvegetated lysimeter. Large differences (factor of 5) in the rate of soil water storage decreases were also recorded after the 1997–1998 El Niño.

Differences in soil water storage responses of vegetated and nonvegetated lysimeters to ENSO can be explained by the inability of evaporation to remove water that penetrated to greater depths during and after elevated El Niño winter precip-

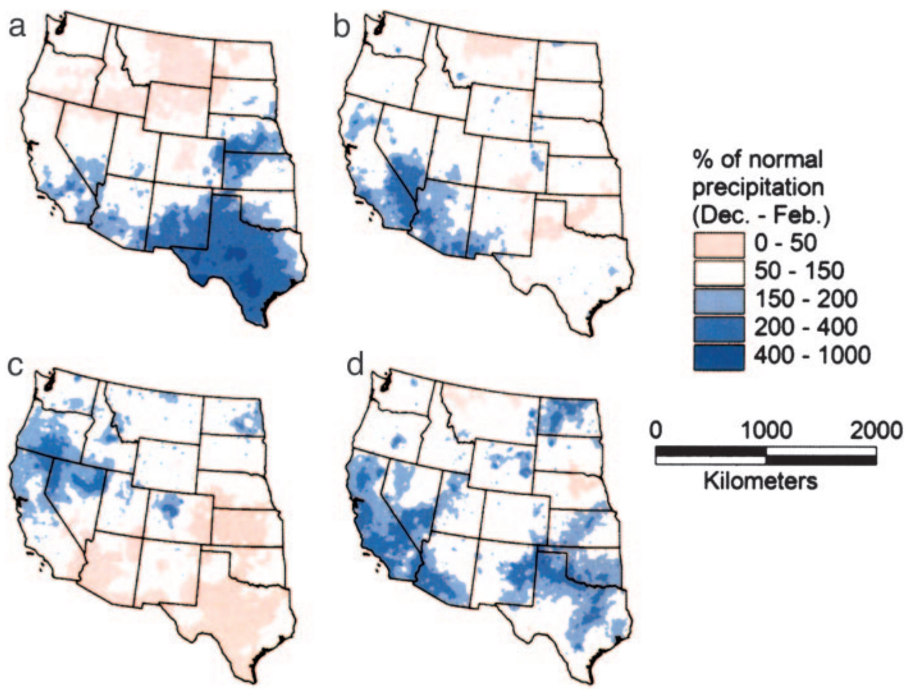

Fig. 3. Percent of normal 1971–2000 winter (December–February) precipitation during 1991–1992, normal (*a*); 1994–1995, El Niño (*b*); 1995–1996, La Niña (*c*); and 1997–1998, El Niño in the Western U.S. (*d*). Data were obtained for ≈3,750 rain gauge locations from the U.S. National Oceanic and Atmospheric Administration National Climate Data Center database.

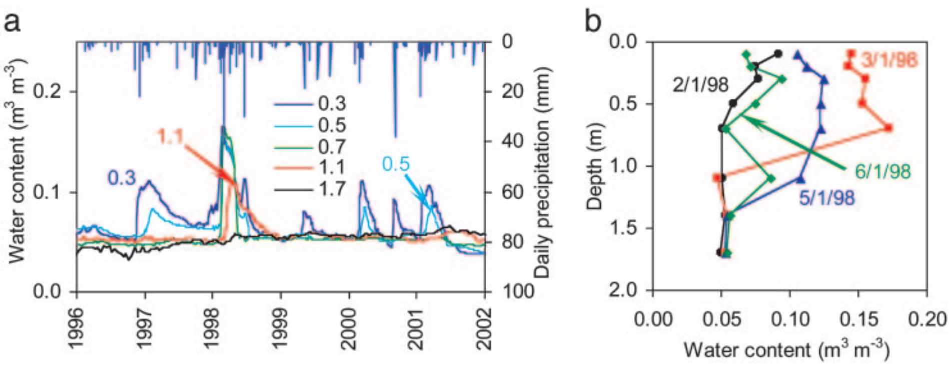

Fig. 4. Daily soil water content time series (*a*) and soil water content profiles (*b*) for selected dates in the vegetated lysimeter at the NTS location.

itation (Fig. 2). Water that penetrated to shallow depths (0.3–0.5 m) during non-El Niño periods (2000, 2001) was rapidly removed from both lysimeters, as shown by the rapid decrease in soil water content (Fig. 4) and similarity in decreases of soil water storage (Fig. 2 and Fig. 10, which is published as supporting information on the PNAS web site). In contrast, water penetrated to depths between 1.1 and 1.7 m during and after El Niño periods (Fig. 4). Soil water recession was subsequently much more gradual in the nonvegetated lysimeter than in the vegetated lysimeter and results in long-term memory of previous El Niños. Soil water storage in the nonvegetated lysimeter remained elevated throughout the rest of the monitoring period after the 1997–1998 El Niño because water had infiltrated to depths greater than could be readily removed by evaporation. Although information on rooting depths was not available, temporal variations in soil water content at different depths in the vegetated lysimeter provide information on root activity. More deeply rooted shrubs rapidly removed water down to 1.1–1.7 m depth, whereas shallow-rooted grasses readily dried out the near-surface zone (Fig. 4). Soil water storage changes in the vegetated lysimeter are similar to soil water content measurements in surrounding areas of the Mojave Desert, which suggest that the vegetated lysimeter results are representative of the natural system (20).

Elevated El Niño winter precipitation should result in deep drainage and ultimately groundwater recharge in nonvegetated systems, as shown by modeling analysis of the nonvegetated lysimeter. The simulations resulted in 40 mm of drainage from the nonvegetated lysimeter during the monitoring period (Fig. 11, which is published as supporting information on the PNAS web site; see also *Supporting Text*). Although the nonvegetated lysimeter in this study was not designed to provide an analog of natural systems because most natural systems are vegetated, it may represent nonvegetated conditions associated with salinization and agricultural fallow crop rotations. Simulated drainage beneath the nonvegetated lysimeter is consistent with increased recharge related to fallow periods in the U.S. and Australia (21–23).

Use of nonvegetated and vegetated lysimeters allows ET to be subdivided into estimates of evaporation and transpiration (Fig. 5*a*; see also *Supporting Text*). Rapid water storage decreases after El Niño winter precipitation correspond to increased transpiration rates that peaked in May 1995 and May 1998 and were much less in May of the following years. High transpiration was associated with increased vegetation biomass productivity. Measured above-ground biomass productivity, particularly annuals, was much greater after El Niño winters than after La Niña winters when annuals did not germinate at nearby locations in Nevada (Fig. 2) (24, 25). The correlation between annual ET and precipitation at the lysimeter location ($r = 0.93$; Table 1, which is published as supporting information on the PNAS web site) is similar to the correlation between annual biomass productivity and precipitation at other southern Nevada locations ($r = 0.90$) (26). In these water-limited ecosystems, elevated precipitation results in large increases in vegetation productivity, which is referred to as the "greening of the desert."

Measured variations in above-ground biomass productivity can be extended to regional scales based on correlations with NDVI anomalies from satellite data (Fig. 5*b*; see also *Supporting Text*). Spatial NDVI anomalies ($-15\% \leq$ normal $\leq 15\%$) are shown for May 1995 and May 1998, which represent periods of peak biomass

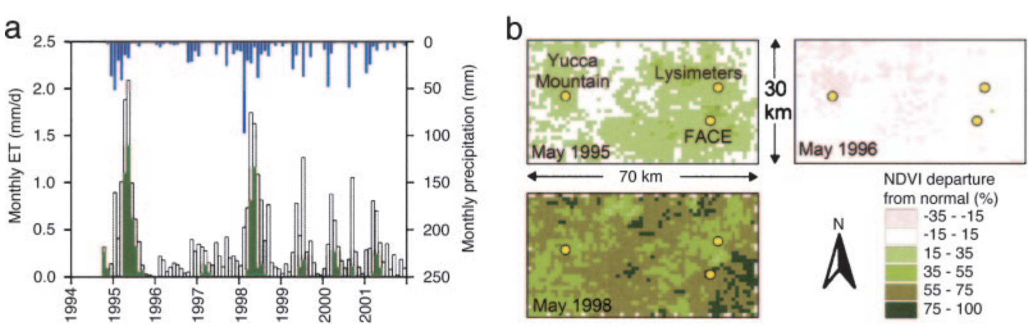

Fig. 5. Variability of precipitation (*a*), ET (*a*), and NDVI anomalies (*b*). (*a*) Monthly total precipitation (upper solid columns) and average monthly ET rates (lower columns, total height). ET is separated into evaporation (E, lower open columns) and transpiration (T, lower solid columns). Calculated T rates provide a lower bounding estimate of T because E in the nonvegetated lysimeter is greater than E in the vegetated lysimeter as a result of higher soil water content and the lack of shade provided by vegetation (see *Supporting Text*). (*b*) NDVI anomalies for the region surrounding the NTS lysimeter location in response to El Niño (May 1995 and May 1998) and La Niña (May 1996) precipitation. Ground-based biomass productivity (Fig. 2) was measured at nearby Yucca Mountain and free air CO_2 experiment sites (25, 26).

productivity with NDVI anomalies of up to +80–100% of normal after elevated El Niño winter precipitation. Negative NDVI anomalies were found in May 1996, when biomass productivity was at a minimum and corresponds to a La Niña period. NDVI anomalies correlate with variations in soil water storage and can be used as an indicator of soil water storage at interannual timescales. Temporal variability in vegetation productivity is readily observed from the land surface and may provide an important indicator of subsurface hydrology. Although the lysimeter and above-ground biomass productivity measurements represent point data, El Niño climate forcing and satellite vegetation response show that the processes are operating at a regional scale. Strong correlations between NDVI and interannual precipitation variability related to ENSO in deserts in Australia, South America, and Africa (27, 28) indicate that the processes described in the U.S. Southwest may apply to deserts globally. The strength of the NDVI–precipitation relationships has resulted in the proposed use of NDVI as a proxy for precipitation variability (27, 29).

Vegetation controls on subsurface water cycle response to interannual climate variability can be extended from point (lysimeter) to regional scales based on soil water potential measurements in areas between stream channels (interdrainage) in basin-floor settings in other deserts (Amargosa and Chihuahuan Deserts) in the U.S. Southwest (Fig. 1; see also Fig. 12, which is published as supporting information on the PNAS web site). Water potential monitoring indicates that wetting from infiltration is restricted to the upper meter of the soil profile (30–33). For example, a 12-yr monitoring record from a vegetated sandy site in the Chihuahuan Desert shows that the wetting front (zero water potential) penetrated to a maximum depth of 0.8 m in response to elevated (three times normal) winter precipitation in 1991–1992 (Figs. 3 and 12; see also Fig. 13, which is published as supporting information on the PNAS web site). However, vegetation removed all infiltrated water the next spring, as shown by the sharp decrease in water potentials indicating rapid drying (Fig. 12).

Lysimeter results demonstrate two-way coupling between soil water storage and vegetation. As discussed by Rodriguez-Iturbe (34), soil water storage or soil moisture is both the cause and consequence of vegetation dynamics and has led to the emergence of the field of ecohydrology. The importance of the biosphere in controlling the soil water balance within the context of climate variability has been shown in previous studies (35, 36). Elevated El Niño winter precipitation results in large increases in soil water storage that enhance vegetation biomass productivity, which then feeds back to rapidly reduce soil water storage (Fig. 14, which is published as supporting information on the PNAS web site). Vegetation dynamics provide a negative feedback by reducing the impact of El Niño precipitation perturbations on the subsurface water cycle. Rapid removal of excess infiltrated water in the vegetated lysimeter resets soil water storage within months and results in no long-term memory of previous El Niños. The net result is that elevated El Niño winter precipitation does not result in deep drainage below the root zone or ultimately in groundwater recharge in interdrainage desert areas because of the coupling between soil water storage and dynamic vegetation that removes all excess infiltrated water through ET. Even small amounts of recharge in interdrainage areas would otherwise significantly impact water resources because interdrainage basin-floor settings represent ≥75% of the desert area.

The observed coupling between biospheric processes and the subsurface water cycle currently occurring in the U.S. Southwest can be extended to millennial timescales. Evidence of drying of soil profiles in the U.S. Southwest is provided by upward decreases in soil water potential, indicating upward water movement, and by large chloride accumulations below the root zone (bulge shape concentration profiles) (37–39) (Fig. 6; see also Fig. 15, which is published as supporting information on the PNAS web site). Paleohydrologic evidence indicates drier conditions during the Holocene (reduced lake levels and lower water tables) preceded by wetter conditions during the Pleistocene (overflowing lakes, higher water tables, and groundwater discharge) (40) (*Supporting Text*). Modeling analysis of profiles throughout the U.S. Southwest using high water potential and low chloride concentrations as initial conditions indicates that 10,000–15,000 yr of upward water movement (fluxes ≤0.1 mm/yr) is required to reproduce the currently observed upward water potential and chloride bulge profiles (33, 41). This time is consistent with the Pleistocene (glacial) to Holocene (interglacial) climate change. Paleobotanical and palynologic data indicate that the climate change was associated with a change from mesic (Pleistocene) to xeric (Holocene) vegetation (42, 43). Thus, xeric vegetation has maintained dry conditions in the root zone throughout the interglacial period, and the drying front initiated by the mesic to xeric vegetation transition has steadily migrated deeper into the profile (Fig. 15). Chloride concentrations at depths below the chloride bulge represent Pleistocene conditions that are out of equilibrium with current climate forcing (Fig. 6). Similarity in soil water potential and chloride profiles in interdrainage settings with different soils and climate throughout the U.S. Southwest has been attributed to the overriding control of vegetation on the water balance of these systems (37).

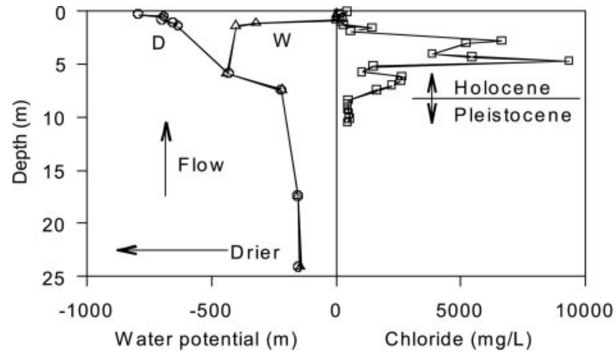

Fig. 6. Soil water potential and chloride concentration depth profiles in the Chihuahuan Desert, Texas. The profiles are typical of interdrainage settings in semiarid/arid areas of the U.S. Southwest. Zero water potential indicates water-saturated soil, and more negative water potentials indicate drier soil. Water flows from regions of high (less-negative) to low (more-negative) water potentials, as indicated by the upward-pointing arrow that represents drying during the Holocene. Two water potential profiles from the 12-yr monitoring record (Fig. 12) are shown, with one depicting the wettest period (W, April 30, 1992) during the monitoring record (1990–2002) and one depicting conditions typical of dry periods (D, April 30, 2000). Wetting is restricted to the shallow subsurface (≤0.8 m, Fig. 12). High water potentials at depth are consistent with wetter conditions during the Pleistocene. Higher chloride concentrations near the root zone reflect upward (evapotranspirative) water movement and drying of the profile during the Holocene interglacial period, whereas low chloride concentrations at greater depths indicate downward water movement during the Pleistocene glacial period.

This study has important implications for waste disposal and water resources in arid to semiarid regions. The results favor the suitability of interdrainage basin-floor settings for waste disposal and indicate that vegetation prevents recharge over millennial timescales. The concept of using vegetation and associated ET to minimize water movement into buried waste has been used in the design of evapotranspirative covers for waste containment (44). In contrast, biospheric feedbacks attenuate the impact of current climate variability (El Niño or La Niña), precluding episodic groundwater recharge; moreover, these processes have been ongoing since the last glacial period.

The ability of vegetation to regulate subsurface flow indicates that changes in vegetation, either natural or anthropogenic, are

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likely to impact groundwater recharge. Natural vegetation changes, such as a shift from native perennial shrubs to invasive annual grasses, as seen after wet El Niños in the U.S. Southwest (25) (Fig. 2), may result in increased recharge. Changes in recharge would result from a shallower rooting depth of grasses vs. shrubs and vegetation removal associated with increased vulnerability of grasses to wildfires because of a greater amount and continuity of fine fuels (45, 46) in the U.S. Southwest. Anthropogenic changes in vegetation related to agriculture inadvertently increased groundwater recharge rates in the early 19th century, e.g., up to 2 orders of magnitude in Australia (47). A detailed understanding of ecological controls on the water cycle will be required to predict the impact of managed changes in ecosystems on recharge.

Measurements of fundamental physical and ecological processes in this study provide unequivocal field evidence of the importance of vegetation dynamics in controlling the subsurface water cycle response to climate variability in semiarid and arid regions. The results indicate that episodic recharge is unlikely and that xeric vegetation can maintain dry conditions in the subsurface for millennial timescales. Although the study focused on the U.S. Southwest, satellite data suggest that the findings may apply to desert basins globally.

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