

Groundwater controls on episodic soil erosion and dust emissions in a desert ecosystem

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ABSTRACT

Feedbacks between vegetation, soils, and sediment transport processes maintain arid landscapes in geomorphically active degraded states or in more biologically productive and geomorphically stable states. Landscape evolution models and resource management strategies require a detailed understanding of thresholds that limit sediment transport in deserts, but it can be difficult to quantify geomorphic responses to abrupt environmental change. Here we use measurements of fallout radionuclides and salt content in soils, horizontal sediment fluxes, vegetation cover, and saturated zone depth in Owens Valley, California (USA), to quantify the geomorphic response of a desert landscape to changes in groundwater availability. Owens Valley has a well-documented history of surface-water diversions and pumping during the A.D. 1987–1992 drought, and we studied 11 sites having a gradient of ~0.5 m to 8 m of groundwater decline during this time. We show that short-length-scale (<50 m) sediment redistribution is active in areas with a range of environmental histories, but centimeter-scale net soil loss occurred when photosynthetic vegetation cover declined to <20% where local groundwater remained shallow enough to produce evaporite salts. Erosion and dust emissions are most severe in central Owens Valley when groundwater falls below the 2 m effective rooting depth of native meadow vegetation but remains shallow enough (<6 m) so that capillary action maintains loose erodible sediment at the surface.

INTRODUCTION

Arid and semiarid regions represent over 40% of Earth's land surface, and broad-scale land degradation (i.e., desertification) could potentially impact the 2.5 billion people who live in these regions (Reynolds et al., 2007a). In arid environments, localized regions of shallow groundwater create friable salt crusts through capillary action that can make the soil more erodible and make it a potential dust source (Reynolds et al., 2007b). Sediment transport and soil loss can lead to changes in desert ecosystem structure that are difficult to reverse due to internal feedback processes (Schlesinger et al., 1990), and dust generation has far-reaching consequences for human health (Prospero et al., 2008), terrestrial and marine ecosystem productivity (Okin et al., 2011), and global climate (Tegen et al., 1996). An understanding of the hydrological and biological thresholds that limit mass transport on arid landscapes is needed to inform sustainable land-use management strategies in these sensitive regions.

Owens Valley (California, USA) is a high-elevation basin ~300 km northeast of Los Angeles, supplying that city with one-third of its water supply. The Owens (dry) Lake is a 280 km² salt-encrusted playa that became North America's largest source of atmospheric particulate matter

(<10 μm) after much of the Owens River was diverted to the Los Angeles Aqueduct (Gillette et al., 2004). Although the dry lake playa is the best documented source of dust, a 180 km² expanse of the Owens River valley north of the lake has shallow groundwater, saline surface crusts, and alkali meadow vegetation adapted to these conditions (Fig. 1). Alkali meadows have high vegetation cover dominated by the grasses *Distichlis spicata*, *Sporobolus airoides*, and co-occurring species, creating a unique biodiversity hotspot that stabilizes soil from wind erosion (Vest et al., 2013). During periods of low snowmelt, groundwater underlying meadows in central Owens Valley has been pumped to supplement surface-water diversions. Intense pumping during a drought in A.D. 1987–1992 caused a 1–10 m lowering of the local groundwater table that, in turn, led to decreased grass cover and higher encroachment of shrubs and non-native annuals (Elmore et al., 2003). Within these degraded areas, exposed shrub and grass root pedestals indicating erosion are widespread, but the link between groundwater, vegetation decline, and soil loss has not been described in Owens Valley. Given that groundwater-dependent vegetation cover decreases with depth to groundwater (Elmore et al., 2006), we hypothesize that soil erosion in central Owens Valley is

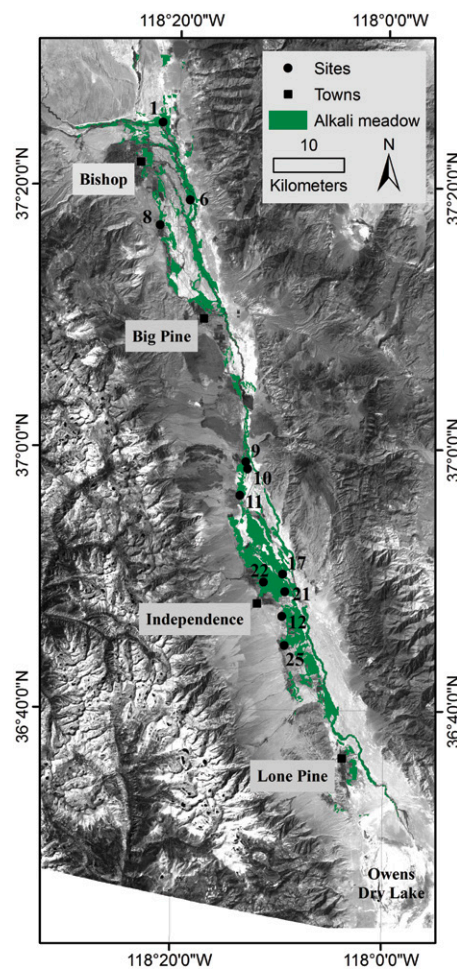


Figure 1. Owens Valley (California, USA) study region with sampling site locations. Sites 6 and 8 are reference sites.

greatest in areas impacted by the largest groundwater declines.

Short-lived radionuclides that are delivered to landscapes primarily via rainfall (e.g., “fallout radionuclides”) and adhere to soil particles are used to quantify and trace sediment transport (Wallbrink and Murray, 1996). Naturally occurring cosmogenic ⁷Be (half-life, $t_{1/2}$ = 53 d) and radon-derived ²¹⁰Pb ($t_{1/2}$ = 22 yr) are introduced to the uppermost 1–2 cm of topsoil with rainfall

at a relatively constant rate each year, and weapons-testing product ^{137}Cs ($t_{1/2} = 30$ yr) was introduced in a pulse primarily during 1956–1968. In dry climates, limited leaching causes the nuclides to be concentrated in the upper decimeter of soil, making them ideal tracers of topsoil erosion (Kaste et al., 2011; Pelletier et al., 2005). Points on the landscape with low radionuclide inventories compared with levels supported by atmospheric deposition are caused by soil loss, and relatively high radionuclide inventories are caused by local soil accumulation.

METHODS

We identified two reference sites where depth to groundwater and vegetation cover remained relatively constant between 1985 and 2010 to compare with impacted sites where groundwater and/or vegetation resources dropped significantly during this time (Fig. 1; Table 1). Impacted sites had groundwater declines spanning a gradient of >1–8 m. At most of these sites, 3 yr average photosynthetic vegetation cover dropped to <10% as the water table declined below the ~2 m rooting depth of native vegetation during 1987–1992 because of pumping and low precipitation (Elmore et al., 2006). Site 10 was unique in that photosynthetic vegetation cover remained stable from 1985 to 2010 but was consistently very low (<10%). Each sampling unit is a 2500 m² site within 100 m of a groundwater monitoring well, so depth to water (DTW) is constrained. Annual sediment fluxes at each site were quantified with four Big Spring Number Eight (BSNE) sediment traps mounted on a 1 m pole (Vest et al., 2013). At each site we sampled two soil profiles at 1 cm resolution to measure the detailed vertical distribution of fallout radionuclides, and we collected bulk soil cores (0–12 cm) every 5 m on transects going north outward from the BSNE traps to at least 25 m. Sites 6, 12, and 21 were selected for more intensive sampling with four soil core transects going radially outward from the BSNE traps. Soil samples were homogenized in the laboratory and measured for radionuclide content (Bq kg⁻¹) via low-background gamma spectrometry (Kaste et al., 2011). Radionuclide inventories (Bq m⁻²) for each sampling point were calculated using the bulk density of the core samples or integrating the soil profile samples from the surface to 12 cm, and all points were averaged together within each site to calculate a mean inventory.

RESULTS

Local Soil Redistribution

We expected that sites with low vegetation cover, and particularly bare areas between vegetation patches, would be most prone to dust emissions due to high connectivity, while isolated shrubs might trap locally eroded material (Okin et al., 2009). Three years of direct

TABLE 1. SAMPLING SITE CHARACTERISTICS IN OWENS VALLEY, CALIFORNIA, USA

Site	Vegetation decline	Groundwater decline (m)	Mean depth to water, A.D. 1987–1994 (m)	Site median ^{137}Cs (Bq m ⁻²)
1	Yes*	3.7	4.9	610
6	No	0.4	2.5	733
8	No*	1	1.9	777
9	Yes	5.4	6.4	440
10	No	3	4.8	250 [†]
11	Yes	4.7	6.0	690
12	Yes	7.7	7.9	625
17	Yes	1.3	2.4	280 [†]
21	Yes	0.6	2.4	185 [†]
22	Yes*	1.9	2.6	570
25	Yes	3.6	5.0	110 [†]

Note: Sites in bold are reference sites. Vegetation decline is quantified with remote sensing (Elmore et al., 2006), and maximum three-year average groundwater decline is given for 1985–2010.

*Three-year average photosynthetic vegetation cover remained >20%.

[†]Site mean ^{137}Cs soil inventory is statistically distinguishable from atmospheric ^{137}Cs flux ($p < 0.05$ for sites 17, 21, and 25; $p < 0.1$ for site 10).

measurements with BSNE traps indicates that annual horizontal sediment fluxes are typically ~0.1 kg m⁻¹ in areas with nearly complete vegetation cover (<10% bare soil) to ~20 kg m⁻¹ in areas with >50% bare soil (Vest et al., 2013). While these measurements indicate that horizontal transport rates are relatively high where cover is reduced, alone they reveal little about the net sediment budget at each site or the longer-time-scale erosional history. We use fallout radionuclides to trace sediment transport in Owens Valley across a range of spatial scales, with different nuclides narrating processes covering time scales on the order of their respective half-lives (Walling et al., 1999).

Soil radionuclide inventories (Bq m⁻²) supported by atmospheric fluxes are calculated using depositional data or undisturbed “reference” sites that are assumed to be geomorphically stable over the relevant time scale, and we used both methods to calculate ^{137}Cs fallout to our study region (see the Methods section in the GSA Data Repository¹). If the site mean radionuclide inventory is statistically indistinguishable from the amount supported by atmospheric deposition, there are no detectable net sediment gains or losses at the scale of the site. However, if the site mean radionuclide inventory matches the atmospheric flux but wide variability occurs between the 5 m sampling points, this indicates short-length-scale sediment transport consistent with grain saltation where the mass losses and gains are balanced over the scale of the site.

We found that mean soil ^{7}Be inventories across our sites in central Owens Valley could be described by a slight precipitation gradient (Kaste et al., 2011), indicating that sediment

¹GSA Data Repository item 2016251, methods, table with soil loss estimates, radionuclide profiles, and climate record, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.

transport at the kilometer length scale was undetectable with this radionuclide. Within reference and disturbed sites, soil ^{7}Be inventories were narrowly constrained, having coefficients of variation (CV) <28% (Fig. 2A). Because of its half-life, ^{7}Be traces transport processes operating over the last 6 mo, and soil inventories appear to reflect the spatial heterogeneity of the fallout depositional processes, especially small-scale rain shadowing by patchy vegetation (Kaste et al., 2011). In contrast, the CVs for ^{137}Cs and ^{210}Pb at reference and impacted sites were significantly higher (Fig. 2A). Given that ^{137}Cs inventory variability was approximately three-fold higher compared to ^{7}Be , we conclude that transport processes beyond those related to its initial atmospheric deposition are controlling ^{137}Cs distribution on the landscape within sites. Further supporting this was a relationship between ^{137}Cs inventory variation within sites with shallow groundwater (DTW <6 m) and median annual horizontal sediment fluxes that we quantified using the BSNE stems ($r^2 = 0.86$; Fig. 2B). While within-site ^{137}Cs inventory variability is best explained by short-length-scale sediment movement by saltation, significant differences that we observe at the kilometer scale from site to site are best explained by net erosion from degraded sites and longer-distance transport.

Net Soil Erosion from Soils with Shallow Groundwater Declines

We measured a wide range of ^{137}Cs inventories across 11 field sites in central Owens Valley (0–2500 Bq m⁻², $n = 150$). Using an analysis of variance (ANOVA) test on log-normalized ^{137}Cs inventory data comparing each individual impacted site with the reference inventories, we found that four of the nine impacted sites had significantly low ^{137}Cs inventories (Table 1), and the results can be summarized by groundwater conditions (Fig. 3). Mean soil ^{137}Cs inventories

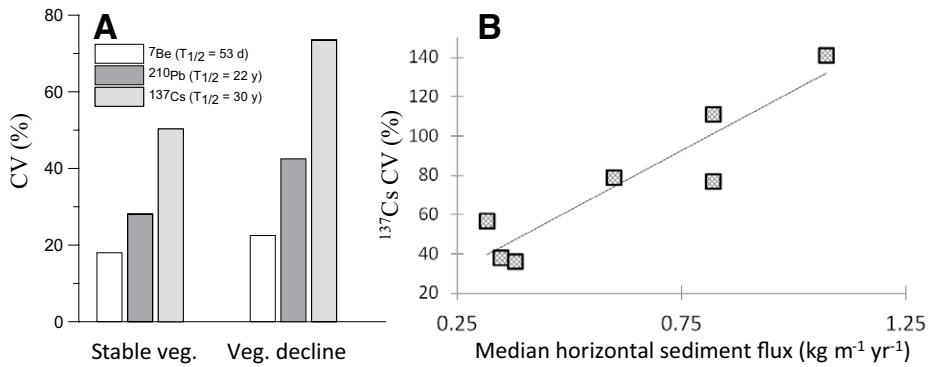


Figure 2. A: Coefficient of variation (CV) associated with atmospheric fallout radionuclide mean soil inventories at reference sites, and those associated with significant vegetation (veg.) decline, Owens Valley (California, USA). B: Relationship between soil ¹³⁷Cs CV and measured horizontal sediment fluxes at sites where depth to water <6 m.

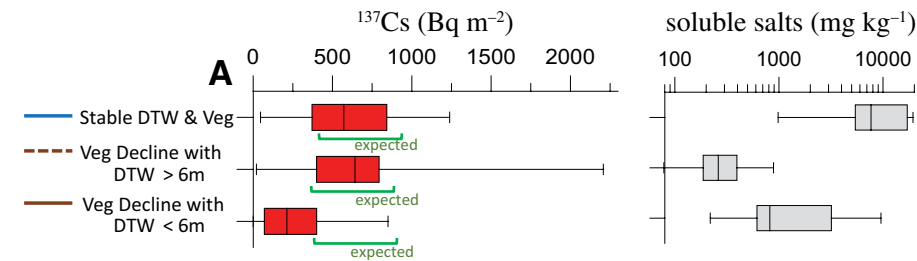


Figure 3. A: Soil ¹³⁷Cs inventories (box gives middle 50%, whiskers show 5th and 95th percentiles), ¹³⁷Cs inventory ranges expected from atmospheric deposition (green bracket), and water-extractable salts, at sampling points in reference (stable) sites and those with vegetation decline under two groundwater conditions (Veg—vegetation; DTW—depth to groundwater). B: Vegetation cover record. C: Depth to groundwater, with upper and lower bounds given for sites with largest groundwater declines and for sites with more shallow groundwater declines.

at reference sites are indistinguishable from the total projected atmospheric flux (651 ± 228 Bq m⁻²), indicating no net soil loss at the site scale since the atmospheric weapons-testing era. However, at impacted sites with vegetation declines, ¹³⁷Cs inventories varied much more widely, with values below and above the levels predicted from atmospheric deposition.

Surprisingly, sites with the largest groundwater declines with mean DTW >6 m during the drought period had ¹³⁷Cs inventories that were statistically indistinguishable from those at the reference sites (Table 1). These areas had significant collapses in photosynthetic vegetation cover, and soils here were low in soluble salts

(Fig. 3). The ¹³⁷Cs inventory variability measured here is much higher than at reference sites, and higher than for ⁷Be as noted previously, so soil losses and gains are balanced locally by small-length-scale (<50 m) transport processes with no off-site soil losses. We conclude that dust emissions have been low at these deeper-groundwater sites since 1965. While regional dust deposition could potentially inflate soil ¹³⁷Cs inventories and make areas appear more geomorphically stable, direct measurements of ¹³⁷Cs in dust made here combined with measurements of dust deposition fluxes of ~20 mg m⁻² d⁻¹ quantified in our study region by others (Reheis, 1997) indicate that this process would

have only a small (<5%) effect on the soil ¹³⁷Cs inventories.

In contrast to sites with very deep groundwater drawdowns, soil ¹³⁷Cs inventories were significantly depleted where groundwater levels remained more shallow during the period of vegetation collapse (Figs. 3A–3C). The four sites with the most significant ¹³⁷Cs losses were sites that had three-year average photosynthetic vegetation cover <20% and the mean DTW remained ≤5m during the drought (Table 1). Net loss of ¹³⁷Cs from a wide area is mostly likely dominated by dust emissions because of the strong preferential partitioning of this radionuclide to fine grains, which can be transported hundreds of kilometers away from Owens Valley (Reheis, 1997). Centimeter-scale erosion magnitudes (post-1965) were calculated at shallow-groundwater sites (Table DR1 in the Data Repository) using a model that accounts for the vertical migration of ¹³⁷Cs into the soil since deposition and for the preferential removal of fine-grained material by wind (see the Data Repository). These sites appear to have remained connected to the groundwater via capillary action, as evidenced by the relatively high soil salt content (Fig. 3). Salt mineral growth physically disrupts the soil through dilation and plays a critical role in generating loose sediment that can be transported by wind (Reynolds et al., 2007b).

Multiple Data Sets Indicate Episodic Erosion in Owens Valley during the 1987–1992 Drought

By tracing sediment transport using techniques that are sensitive to different time scales, we find that geomorphic processes in central Owens Valley have not been steady over the past half-century. Highest erosion rates are determined by the ¹³⁷Cs method which would be impacted by any event since ca. A.D. 1965, compared with ⁷Be measurements and the BSNE traps which captured only more recent years (Table DR1). Enriched atmospheric ²¹⁰Pb in the upper soil profile and logarithmic declines consistent with steady advection-diffusion (Fig. DR1 in the Data Repository) indicate that soils have been steadily accumulating fallout and reequilibrating with the supply of ²¹⁰Pb from the atmosphere in recent years, a process that can only happen if erosion is low (Aalto et al., 2003). In contrast, the vertical distribution of ¹³⁷Cs is more mixed with a smaller concentration gradient with depth in the upper ~5 cm at degraded sites (Figs. DR1B–DR1D). Integrated ²¹⁰Pb/¹³⁷Cs inventory (Bq m⁻²) values also indicate that, at impacted sites showing evidence of erosion, soils have been more geomorphically stable for the past one to two decades (Fig. DR1). If soil eroded from the landscape after 1965 during a discrete event, then ¹³⁷Cs would have been permanently lost, but landforms can regain ²¹⁰Pb from atmospheric deposition if the soils stabilize. We find

that soil $^{210}\text{Pb}/^{137}\text{Cs}$ (Bq m^{-2}) values at reference sites range from 1.7 to 3.5, with a median value of 2.6, which is consistent with other measurements made in the region (Monaghan, 1989). However, at eroded sites $^{210}\text{Pb}/^{137}\text{Cs}$ values typically ranged from 5 to 10. Highest erosion during the most recent years would have preferentially removed ^{210}Pb over ^{137}Cs , which is the opposite of what we observe.

The inventory variability (Fig. 2) and profiles (Fig. DR1) indicate a period of disturbance that caused redistribution, apparent soil mixing, and mass loss from soils sometime in the past, followed by years during which off-site losses were reduced. Episodic periods of higher erosion likely occurred during 1987–1992, when vegetation cover dropped the largest amount (Fig. 3B), precipitation was below normal for several years, and temperature was 2° higher than normal. Strong winds capable of generating dust storms also coincided with the early part of the drought (Fig. DR2), and episodes of high particulate matter (PM_{10}) were documented in Owens Valley during this time (Watson et al., 1997). While we hypothesized that sites with the largest groundwater declines in Owens Valley would be more eroded because of the direct control that DTW has on vegetation cover in meadows, we found that the most eroded locations are where photosynthetic vegetation cover declined to $<20\%$ and DTW remained within 6 m of the surface. We conclude that local sediment redistribution in central Owens Valley is active across a range of vegetation and groundwater conditions, but that net erosion is limited by a sensitive DTW threshold. Our findings indicate that desert landscapes can be significantly altered by just one to a few meters of groundwater change.

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Methods: Atmospheric ¹³⁷Cs flux determination & Erosion Model

To calculate total ¹³⁷Cs atmospheric fluxes to each site we used direct measurements of atmospheric fallout collected by the Department of Energy during 1956-1972 (US ERDA, 1977) and monthly precipitation at each site calculated by the PRISM Climate Group, Oregon State University. Detailed records of weapons-derived ⁹⁰Sr wet deposition fluxes (Bq m⁻²) per cm of rainfall were collected in Alabama, U.S.A. during the weapons testing era which we use to extrapolate total fluxes for each site's monthly rainfall records in Owens Valley. Total amounts of ¹³⁷Cs deposition to each site was calculated using conversion factor of 1.6 Bq ¹³⁷Cs/Bq ⁹⁰Sr, and accounting for radioactive decay of ¹³⁷Cs since deposition (to 2010, thus all measurements are corrected to this date). The magnitude of meter-scale spatial variations in fallout deposition from rainshadowing in this landscape was evaluated using measurements of ⁷Be (T_{1/2} = 53 d). Because of its short half-life, heterogeneities in soil ⁷Be at a single site will reflect differences in atmospheric deposition patterns from small-scale rainshadowing effects and sediment redistribution from wind in the months prior to the soil collection. We use two relative standard deviations (1 σ = 17.5%) of ⁷Be inventories¹⁷ to generate a 95% interval that accounts for the maximum amount spatial variability that we would expect for soil ¹³⁷Cs and at our sites in Owens Valley that is solely from atmospheric depositional processes. We were able to directly evaluate these ¹³⁷Cs deposition projections and spatial heterogeneity by measuring ¹³⁷Cs in at reference sites with stable groundwater and vegetation cover since the late 1980s. The reference region had 654 \pm 275 Bq ¹³⁷Cs m⁻², equivalent inventories to the projected ¹³⁷Cs deposition of 651 \pm 228. Given that our calculated atmospheric ¹³⁷Cs flux based on Owens Valley precipitation data and ⁹⁰Sr measurements and our reference site inventories are equivalent, and these values are consistent with other regional depositional models (e.g., Simon et al., 2004) we feel very confident in our calculated ¹³⁷Cs fluxes across central Owens Valley

We apply an erosion model (Walling et al., 1997) that relates ¹³⁷Cs inventories to soil loss by comparing ¹³⁷Cs at different points on the landscape to levels supported by atmospheric deposition. The

model accounts for the vertical migration of ^{137}Cs into the soil since the 1960s and for the preferential removal of fine-grained material, which tends to have higher ^{137}Cs concentrations than coarser materials (Walling et al., 1997). Mobilized sediment collected in the BNSE stems was used for the grain-size correction, and the advection-diffusion parameters of the model were calibrated using vertical profiles from the reference sites similar to the one in Figure 3A. While this model gives a first-order measure of the magnitude of soil erosion at our sites in Owens Valley (Table DR1), these values should be considered minimum erosion rates because of three model assumptions: i) erosion rates have been steady since ^{137}Cs deposition, ii) a zero value of ^{137}Cs can return a magnitude of erosion that is limited by the total depth penetration for ^{137}Cs , and iii) the model cannot account for the possibility that a location on the landscape was eroded but subsequently had deposition of soil with ^{137}Cs . Excess ^{210}Pb is calculated by subtracting the ^{210}Pb which is supported by soil ^{222}Rn from the total ^{210}Pb activity. This method uses the deficiency of ^{210}Pb to ^{226}Ra measured at depth to estimate the fraction of ^{222}Rn which escapes the soil (Kaste et al., 2011). Soluble salts (Figure 3) were determined by equilibrating 10 g dry soil with 50 mL of distilled de-ionized water for 30 minutes, and using a conductivity meter calibrated with KCl to measure and calculate mg salt/liter in the solution (Poage et al., 2008). We filtered and gamma-counted a subset of these solutions and found no detectable ^{210}Pb or ^{137}Cs activity, indicating that the radionuclides were not significantly soluble in water.

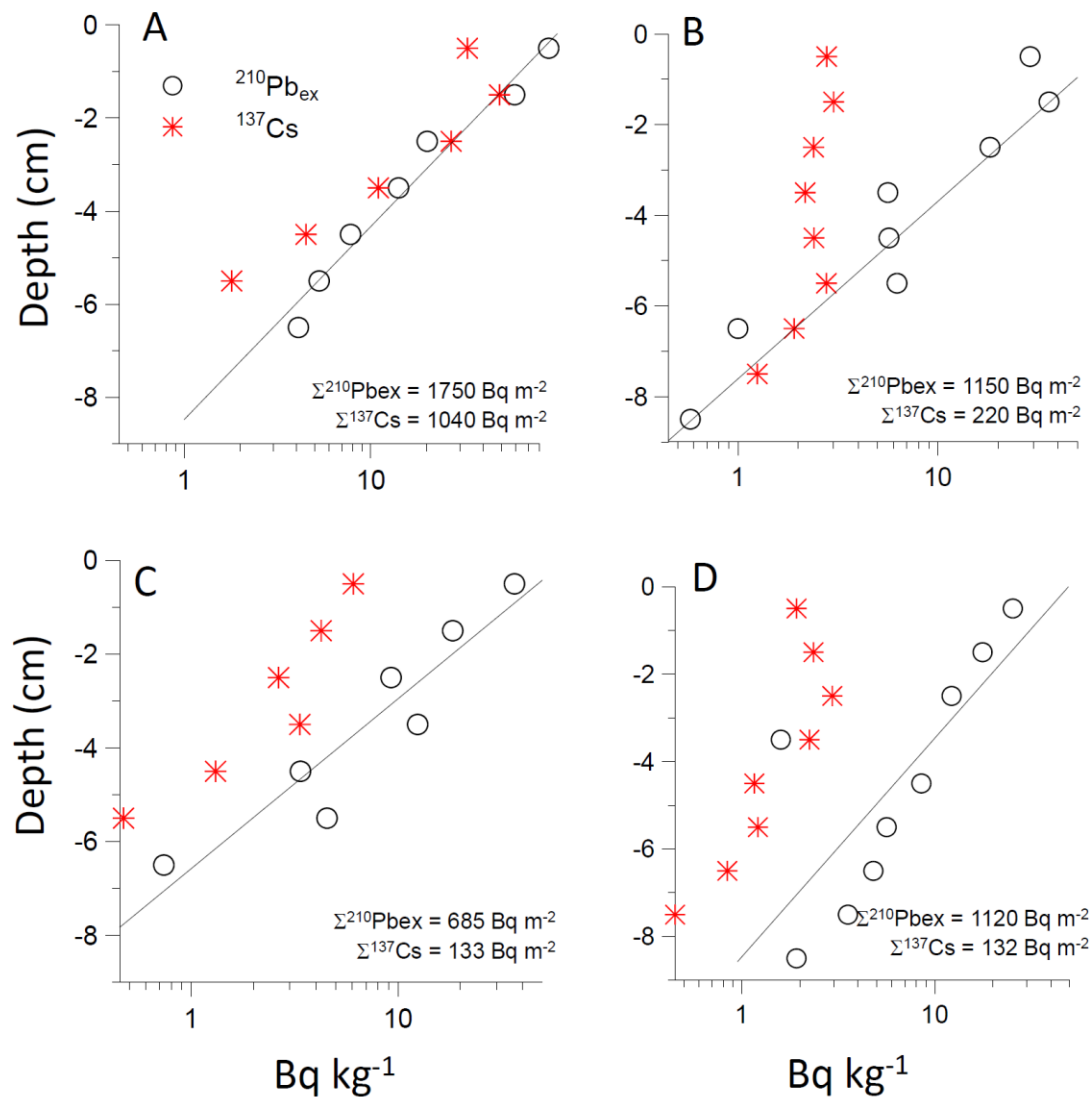


Figure DR1. Vertical profiles of excess ^{210}Pb ($^{210}\text{Pb}_{\text{ex}}$, ^{210}Pb in excess of that supported by in-situ decay of ^{222}Rn) and ^{137}Cs in soils at a reference (A) and sites with vegetation decline (B-D). $^{210}\text{Pb}_{\text{ex}}$ has significant logarithmic decline (line) with depth at each site, but ^{137}Cs is more mixed in the upper soil at impacted sites with shallow groundwater (B-D). Integrated inventories given for each profile in Bq m^{-2} .

	BSNE Sediment Traps	¹³⁷ Cs 1965-2010	p value
<u>Reference</u> Vegetation Cover >50%	3-28 (4) ^a	0-60 (0)† ^A	0.85
<u>Vegetation decline</u> DTW >6m	28-193 (30) ^b	0-60 (0)† ^A	0.064
<u>Vegetation decline</u> DTW <6m	10-49 (22) ^a	80-133 (115) ^B	0.001

Table DR1. Annual vertical fluxes ($\text{g m}^{-2} \text{y}^{-1}$) calculated using BSNE sediment collectors and annual soil losses ($\text{g m}^{-2} \text{y}^{-1}$) measured from 1960 using ¹³⁷Cs distributions in soil under different groundwater decline conditions. Vertical fluxes were determined using the relationship between soil texture, horizontal fluxes captured by the BSNE stems, and dust emissions (Marticorena and Bergametti, 1995). Interquartile ranges given with median values in parentheses. †Net soil losses not detectable because ¹³⁷Cs inventories were not significantly different than atmospheric depositional fluxes at the site scale. P values are given for a Mann-Whitney U test of differences between samples within a row, and different letters (a, b, etc.) show significant differences detected ($p < 0.05$) within a column.

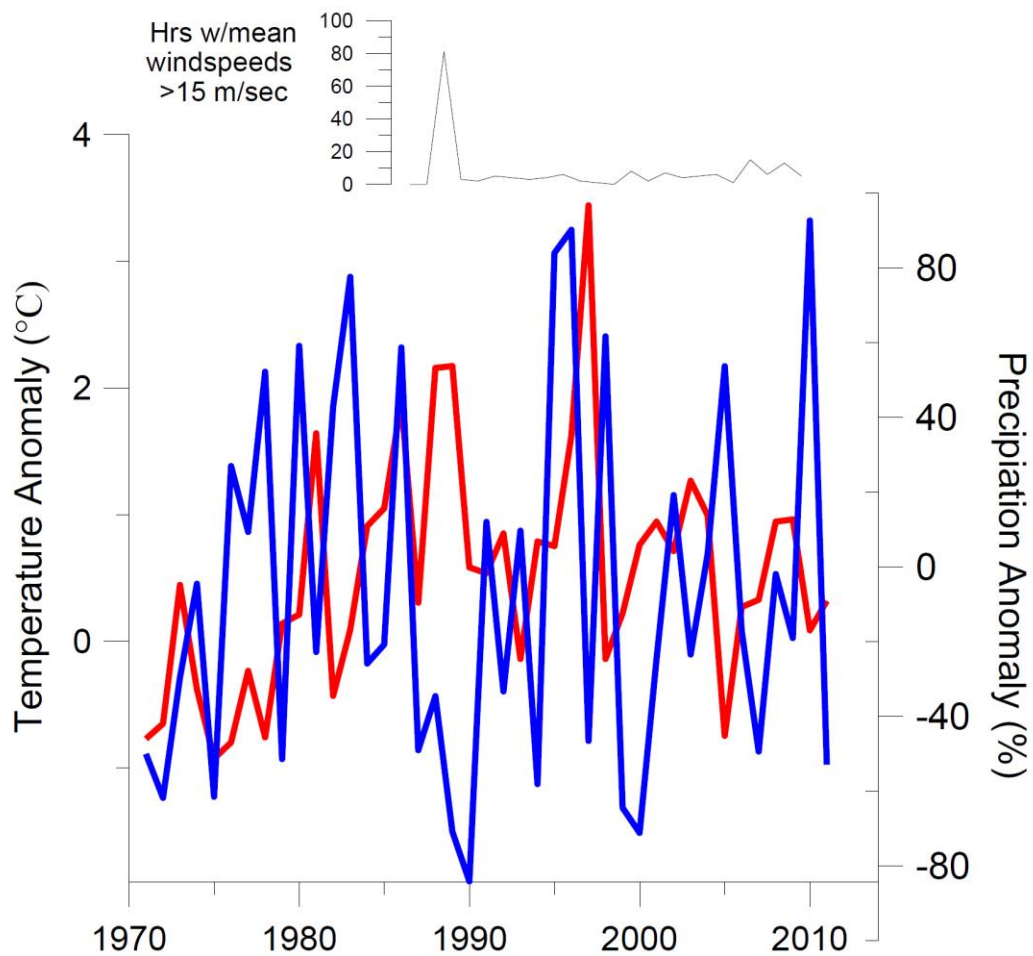


Figure DR2. Temperature (red), precipitation (blue), and wind data for the study area. Temperature and precipitation data are from Independence, CA (Western Regional Climate Center), and are plotted relative to the National Climate Data Center’s annual normal for that station. The upper inset shows the number of hours that the Great Basin Air Pollution Control District Lone Pine monitoring station recorded average hourly windspeeds >15 m/s (record began in 1986)

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