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Modifying landscape connectivity by reducing wind driven sediment redistribution, Northern Chihuahuan Desert, USA

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ABSTRACT

Shrub encroachment into perennial grasslands is occurring in many arid parts of the world. As shrubs displace perennial grasslands, bare patches can coalesce creating sediment transport pathways that further enhance sediment fluxes by wind transport. Reducing the connectedness of these pathways could slow or stop grassland loss by limiting sediment redistribution. To test this hypothesis, sediment retention structures, hereafter called “Connectivity Modifiers” (Con-Mods), were placed in bare gaps of existing shrublands to block sediment movement by wind transport on two sites: the basin floor and a bajada (i.e. piedmont slope) at the Jornada Basin LTER in southern New Mexico. Wind blown sediment collectors and short-lived radionuclides ($^{210}Pb_{ex}$, ^{137}Cs, and ^{7}Be) were used to determine if these structures are affecting seasonal aeolian sediment transport within bare gaps. Net sediment flux rates at 10 cm height indicate a loss of 2.5–14.2 g m^{-2} d^{-1} for both sites for the monsoon season (Jul–Nov), while the basin floor site was the most responsive in reducing sediment transport by collecting 16.5 g m^{-2} d^{-1} over the windy season (Dec–May). Con-Mods contained 30–50% higher surface radionuclide activities than the control plots for both transport seasons on the basin floor. However, there was no detectible difference between surface concentrations for the structures and controls seasonally on the bajada site. This study demonstrates that changes in connectivity can influence sediment movement. Altering sediment transport through bare gaps could influence ecosystem state changes in arid systems; thereby increasing the likelihood of recruitment of native plants.

1. Introduction

As a result of desertification, semi-arid grasslands in many parts of the world have been displaced by woody vegetation (Eldridge et al., 2011). The expansion of shrubs into these ecosystems affects many rangeland properties, such as decreased forage production (Oba et al., 2000), increased soil redistribution rates (Schlesinger et al., 1990), alteration of spatial patterns of nutrients (Schlesinger and Pilmanis, 1998; Li et al., 2008), and loss of biodiversity (Ratajczak et al., 2012). The changes in these biological and physical factors directly affect the socioeconomic value of the landscape, which impacts 38% of the global population that resides in arid to semi-arid regions (Reynolds et al., 2007).

As shrubs invade perennial grasslands in the northern Chihuahuan Desert, the length, number and arrangement of connected bare patches coalesce to create transport corridors (Okin et al., 2001, 2009). These corridors enhance the redistribution and loss of soil resources by wind and water erosion (Parsons et al., 2003; Gillette et al., 2006), which accelerates the effects of desertification (Schlesinger et al., 1990). The expansion of bare patches, associated with shrub encroachment, can dramatically affect how the ecosystem functions. For example, alteration of land surface processes, such as albedo (Beltran-Przekurat et al., 2008), microclimate (D’Odorico et al., 2010), and soil moisture availability (Peters et al., 2010) can reduce the re-establishment of native grasses.

Sediment transport by wind and water is a key component of desertification (e.g. Schlesinger et al., 1990). Changes in connectivity that influence sediment movement are strongly related to ecosystem state change in arid and semi-arid systems (Bestelmeyer et al., 2011). It has been hypothesized that changes in the connectivity of bare erodible surfaces over time cause desertification in arid and semi-arid regions (Okin et al., 2009).

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Therefore, we hypothesize that altering the trajectory of a landscape away from desertification may be achieved by changing the connectivity of these landscapes (Okin et al., 2009).

Sediment retention structures, called “Con-Mods” (Okin et al., 2015), were designed to modify the connectedness of wind and water transport corridors. Con-Mods are intended to interact with sediment transport within bare gaps to block sediment movement and increase sediment deposition/retention; thereby reducing the connectedness of transport corridors. Quantifying the effects of altering sediment transport will provide more insight on the feedbacks that exist between the length of transport corridors, sediment movement, nutrient loss, plant establishment, growth and mortality associated with desertification.

Field monitoring of sediment transport on two landforms (basin floor and bajada) was conducted on a seasonal basis, in two shrub-dominated plant communities in southern, New Mexico. Our study used a short-lived radionuclide multi-tracer approach using $^{210}Pb_{ex}$ ($t_{1/2}$ = 22.3 years), ^{137}Cs ($t_{1/2}$ = 30.3 years) and ^{7}Be ($t_{1/2}$ = 53.3 days) tracers, in combination with aeolian horizontal flux measurements, to provide information regarding lateral movement of sediments in the landscape. The objective of this study was to investigate the impact of Con-Mods on wind blown sediment transport through and within these shrubland sites to enhance the understanding of how connectivity impacts desertification processes.

2. Methods

2.1. Study area and site characteristics

The Jornada Basin (32.3° N; 106.4° W, 1188 m asl) is located in the Basin and Range Province of southern New Mexico on the northern boundary of the Chihuahuan Desert (Schmidt, 1979; Peterson, 1981) (Fig. 1). Our field experiment took place on two landform units that are common to this region: (a) basin floor and (b) bajada (piedmont slope). Both study areas are located within the Jornada Experimental Range (JER, 58,600 hectares) in southern New Mexico. These landforms are among those that have been most sensitive to shrub encroachment and have exhibited a dramatic decline in the spatial coverage of grasslands since 1858 (Rachal et al., 2012). The basin floor study area consists of sandy to sandy loam soils that are occupied by grass (primarily *Sporobolus* spp.) and a shrub mix (primarily *Prosopis glandulosa*, honey mesquite) with bare interspaces that have limited herbaceous cover (Monger, 2006; Peters and Gibbens, 2006). The bajada study area is positioned on the middle portion of the piedmont slope and consists of a series of gravelly alluvial surfaces that are composed of fine sandy loam soils with a slope of $\leqslant$4% (Monger, 2006). This site is dominated by a *Larrea tridentata* (creosotebush) shrubland that contains bare interspaces with sparse herbaceous cover (Gardner, 1951; Peters and Gibbens, 2006). Furthermore, bajada site is located in a zone where upslope sediment is deposited and drainage channels emerge onto the piedmont slope (Wondzell et al., 1996).

The Jornada Basin experiences hot, arid conditions (mean daily temperatures vary between 15 °C and 37.8 °C) with highly variable annual precipitation ($\sim$246 mm year^{-1}). Seventy percent of rainfall occurs during the monsoon season between July and September from intense convectional thunderstorms (Synder et al., 2006). The remainder of the rainfall is primarily from frontal storms off the Pacific Ocean (Wainwright, 2006; Synder et al., 2006). Significant winds are generated by both the summer convective storms and winter frontal systems that result in seasonal variations of wind driven sediment fluxes (Bergametti and Gillette, 2010). This seasonal difference creates specific sediment transport seasons that differ in magnitude. For instance, the highest velocity winds from the southwest most frequently occur in March and April and are associated with dry upper-level lows passing through the region. These events result in the highest seasonal sediment fluxes with significant transport. Significant transport also occurs during the monsoon season in association with convective storms, which generate locally high wind velocities (Warner, 2004).

2.2. Experimental design

Four pairs of (8 × 8 m) treatments and control plots, positioned with one set of edges parallel to the prevailing wind, were

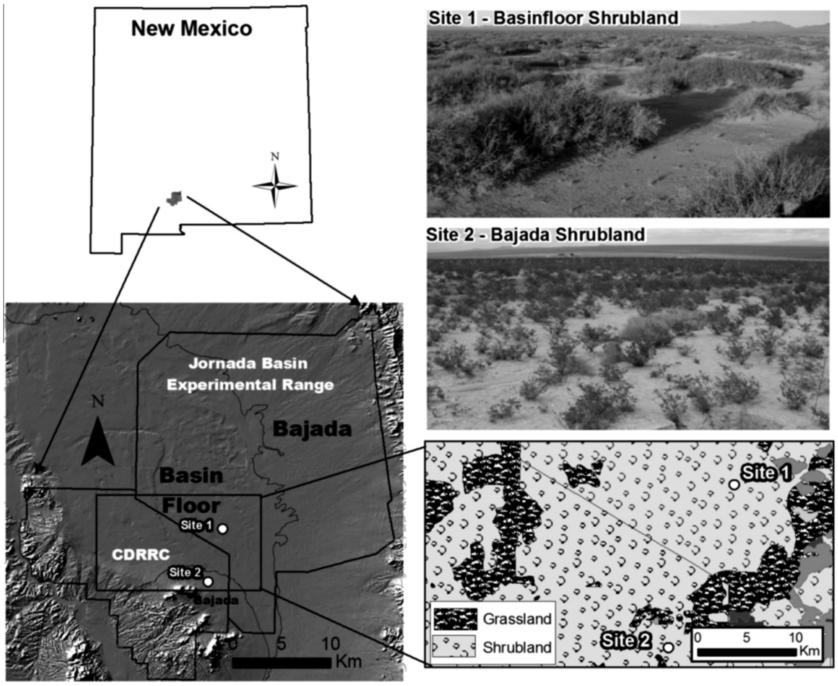

Fig. 1. Location of the Jornada Long-term Ecological Reserve (JLTR) in southern New Mexico and the location of the two study sites within Jornada Basin LTR. Site 1 is a mesquite duneland site located on the basin floor, while site 2 is located on the neighboring bajada.

established on the basin floor and bajada landform units in the Jornada Basin in 2008. Paired plots were selected to minimize differences in initial soil surface conditions and vegetation composition and structure, and treatments were randomly assigned to one member of each pair. This manipulative experiment is part of a larger multi-scale landscape experiment assessing soil redistribution by wind and water transport and associated vegetation feedbacks (Okin et al., 2015). Con-Mods were placed in bare interspaces within the treatment plots. Although they do not exactly simulate vegetation, they provide an opportunity to investigate how these obstructions impact sediment transport and deposition. Con-Mods consist of 0.63 cm mesh galvanized hardware cloth attached to five 1/4″ diameter steel rods to form a 20 cm high × 55 cm wide cross (one rod in the center, four rods equidistant from the central rod and forming two orthogonal lines bisected by the central rod) (Fig. 2).

Placement of the Con-Mods was determined by the cover-based approach described by Huenneke and others (2001). Based on these criteria, Con-Mods were centered in all 1 m^2 quads where perennial canopy was visually estimated to be less than 15%. Steel rods, without a mesh frame, were placed in the control plots using the same placement criteria. Nineteen to 41 Con-Mods were placed in the treatment plots on the basin floor, whereas 35–52 was placed on the bajada site. Two Big Springs Number Eight (BSNE) aeolian sediment samplers permanently fixed in the direction of the prevailing winds were installed upwind and downwind of each plot. Sediment traps were positioned at 10 cm and 30 cm aboveground to collect sediments moving through the plots. These windblown sediment samplers have a capture efficiency of >90% and were used to provide an estimate of horizontal flux entering and leaving the plot (Fryrear, 1986; Field et al., 2012).

2.3. Radioisotopes and residence time

The short-lived radionuclides $^{210}Pb_{ex}$ ($t_{1/2} = 22.3$ years), ^{137}Cs ($t_{1/2} = 30.3$ years) and ^{7}Be ($t_{1/2} = 53.3$ days) were used to examine soil erosion and redistribution by wind transport over varying timescales (Zapata et al., 2002). All of these isotopes are deposited onto the surface from the atmosphere. Therefore, they have the potential to be used as tracers of surface processes.

$^{210}Pb_{ex}$ has been used extensively in disturbed and natural systems to assess long-term (>60 years) soil redistribution rates (Walling et al., 2003; Blake et al., 2009; Wakiyama et al., 2010). ^{210}Pb is a naturally occurring radioisotope that is a by-product of the ^{238}U decay series (Zapata et al., 2002). ^{210}Pb is produced when ^{238}U in bedrock or soil decays, eventually forming ^{222}Rn gas ($t_{1/2} = 3.8$ days). When ^{222}Rn gas in the soil diffuses into the atmosphere and decays, the resulting ^{210}Pb is deposited back onto the landscape by dry and wet precipitation (Krishnas et al., 1971). This fallout product is called unsupported or excess $^{210}Pb_{ex}$.

^{137}C is the most widely used radioisotope tracer that provides a medium-term (⩽50 years) assessment of soil erosion. It was produced during atmospheric thermonuclear weapon testing that peaked between the mid-1950s to the 1960s (Carter and Moghissi, 1977). The fallout from these detonations was dispersed globally and then deposited onto the landscape by precipitation (Tamura, 1964).

^{7}Be ($t_{1/2} = 53.3$ days) is a radioisotope tracer that can be used to assess short-term or seasonal (⩽6 months) soil redistribution rates (Walling et al., 2009; Schuller et al., 2010). It is a naturally occurring radioisotope that is formed by cosmic ray spallation of atmospheric oxygen and nitrogen molecules in the upper portions of the troposphere and stratosphere (Kaste et al., 2002). ^{7}Be in the atmosphere is adsorbed onto atmospheric aerosols and then deposited on the landscape by wet and dry deposition (Olsen et al., 1985). Wet deposition is responsible for the majority of ^{7}Be inputs onto the landscape in both arid and mesic systems (Wallbrink and Murray, 1994; Kaste et al., 2011). Studies that use ^{7}Be as a sediment tracer often use it as an event-based tracer, where sampling follows overland flow events that occur after intense rainstorms (e.g., Wilson et al., 2003). However, recent studies have demonstrated the use of ^{7}Be as a tracer that is effective in reconstructing seasonal soil redistribution rates (e.g., Walling et al., 2009; Schuller et al., 2010).

The mechanisms that are responsible for the production and the timing of inputs of $^{210}Pb_{ex}$, ^{137}Cs and ^{7}Be differ, but their behavior as soil particle tracers are similar (Mabit et al., 2008). Once these tracers are deposited on the soil surface they become attached to mineral and organic soil particles and plant litter (You et al., 1989; Ritchie et al., 2003). These labeled soil particles can be moved vertically down through the soil profile by bioturbation (Kaste et al., 2007) and/or infiltration (Pelletier et al., 2005) or they can be horizontally redistributed by wind and water transport (Ritchie et al., 2003; Van Pelt et al., 2007). Lateral movement of these labeled soil particles, in conjunction with their different half-lives, provide a relative timeframe to understand seasonal sediment transport dynamics. The isotopes with the longer half-lives, ^{137}Cs and $^{210}Pb_{ex}$ provide information about sediment redistribution since the installation of the Con-Mods, because their half-lives are significantly longer than the time since the experiment was established. Differences in surface activities between the control and Con-Mod plots represent the integration of all sediment redistribution that has occurred since establishment. ^{7}Be, with its much shorter half-life, provides information on sediment

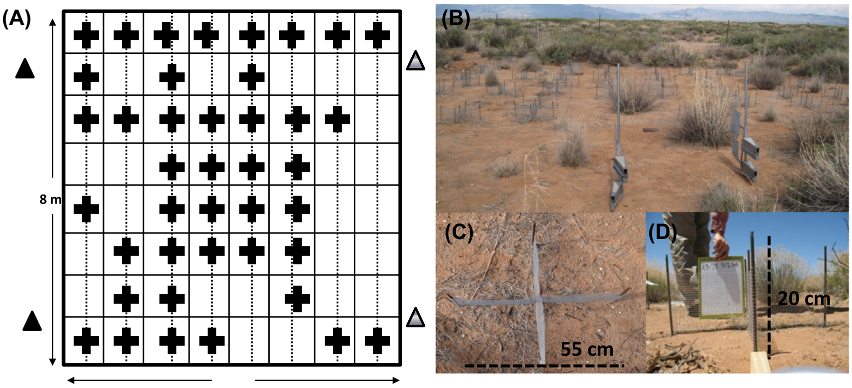

Fig. 2. (A) Experimental layout of plots. (A) ▲ Symbol represents upwind/upslope BSNEs, while △ represents downwind/down slope location of the BSNEs. Dotted lines represents the radionuclide sampling transects. (B) A photo illustrating the layout of the experimental plots. (C) and (D) Photographs of Con-Mods located within the plots (Photograph courtesy of John Anderson).

movement in the few months before sample collections. Samples were collected after the monsoon season (July–November) and windy season (December–May), approximately 6 months apart. This is approximately 3.5 half-lives of ^{7}Be, resulting in little or no overprinting of the signal between collection dates.

2.4. Sediment sampling and radionuclide analysis

Sediments in the BSNEs were collected in November 2010 and May 2011. Collected BSNE sediment samples were weighed and horizontal sediment fluxes (q_z in g m^{-2} d^{-1}) for each height were calculated by dividing the amount of sediment collected by the inlet area (1000 mm^{2}) and sampling time interval (Breshears et al., 2003; Li et al., 2009). The average of the two BSNE traps at a specific height, either up- or downwind, was then calculated. Net sediment flux (Δq_z) rates were determined by subtracting the mean upwind horizontal flux from mean downwind horizontal flux. This calculation provided a plot-level flux measurement of sediment losses/gains at two heights. Positive (+) values indicate that more sediment is entering the plot and being deposited then what is leaving it, whereas negative (−) values indicate that more sediment is being transported from the plots.

Surface sediment in the control and Con-Mod plots were also analyzed for ^{210}Pb$_{ex}$, ^{137}Cs, and ^{7}Be surface concentrations (Bq m^{-2}). The residence time, in combination with different environmental sources and input rates, leads to characteristic depth distributions for each fallout radionuclide (Mabit et al., 2008). Past studies implemented coring techniques that collected a bulk sample to a depth of 20–30 cm that represented a composite sample at a given point. However, in the context of this experiment, sampling in the Con-Mods deeper than 1 cm could misrepresent the effectiveness of the structures by averaging the surface radionuclide content with the residual concentration deeper in the soil profile. In addition, coring within the treatment and control plots would also lead to more disturbance and an increase in potential erosion within the treatment and control plots. Therefore, a 30 g composite surface sample was obtained for each plot by performing eight transects, positioned perpendicular to the prevailing winds that intersected the center of each sediment retention structure. Four 1-cm diameter shallow surface scoops (<0.5 cm depth) were collected in each Con-Mod and were pooled together for treatment and control plot. A final composite sample was collected in the Con-Mod and control interspaces to determine if any intraplot soil redistribution could be occurring during the sampling intervals.

Surface sediments were air dried, passed through a 2 mm sieve and an open pan riffle sampler for 10 min to homogenize the radionuclide content of each sample. Sediment samples were then ground into a fine powder using a Shatterbox model # 8515–11 (SPEX CertiPrep, Methuchen, NJ) and then placed into 30 ml screw-top polypropylene counting jars for analysis. Sediments that were analyzed for ^{210}Pb$_{ex}$ content were allowed an additional 20 days for the ^{226}Rn, daughter ^{222}Rn gas and other short lived radionuclides to equilibrate with ^{210}Pb before measuring the radioactivity. Gamma spectroscopy was used to determine the radioactivities of ^{210}Pb, ^{214}Bi, ^{137}Cs, and ^{7}Be. Total ^{210}Pb activities in the sediment samples were directly determined by measuring the 46.5 keV gamma peak (Cutshall et al., 1983) and supported levels of ^{210}Pb were determined from the activities of ^{214}Pb and ^{214}Bi (at 295, 352 and 609 keV). ^{137}Cs and ^{7}Be activities were determined by measurement of the 661.6 keV gamma peak (Kuehl et al., 1986), and 477 keV gamma peaks (Larsen and Cutshall, 1981). Due to the small number of samples, a non-parametric statistical test is indicated. Therefore, a non-parametric Kruskal–Wallis test was used to test for statistical significances ($P < 0.05$) (Kruskal and Wallis, 1952). The least significant difference between mean ranks *post hoc* test was used to evaluate differences among radionuclide activities in JMP®.

3. Results and discussion

3.1. Aeolian net sediment flux measured at 10 and 30 cm heights

Net sediment flux rates at 10 cm height (Δq_{10}) did not differ significantly between the Con-Mod and control plots for both landform units during the monsoon (Jul–Nov) season ($P > 0.05$, Figs. 3 and 4). Δq_{10} rates for the Con-Mod and control plots for both landform units were negative and ranged from −2.5 to −14.2 g m^{-2} d^{-1}, indicating that more sediment is being removed from the plots at this sampling height during this monsoon (Jul–Nov) season. However, during the windy season at the basin floor site, Δq_{10} was positive (16.5 g m^{-2} d^{-1}) indicating that less sediment is leaving than entering the plots from upwind. Δq_{10} for the control plots were negative, (−35.2 g m^{-2} d^{-1}) signifying that more sediment is being removed from the plots during this transport season. During the windy (Dec–May) season, Δq^{10} rates were positive for both the Con-Mod (9.8 g m^{-2} d^{-1}) and control (10.3 g m^{-2} d^{-1}) plots on the bajada, indicating that less sediment is leaving the plot than entering the plots upwind ($P > 0.05$).

Net sediment flux (Δq_{30}) rates at 30 cm height did not differ significantly between the Con-Mod and control plots for both landform units during the monsoon (Jul–Nov) season ($P > 0.05$, Figs. 3 and 4). Δq_{30} rates for the Con-Mod and control plots for both landform units were negative and ranged from −1.7 to −3.9 g m^{-2} d^{-1}, demonstrating that more sediment is being eroded from the plots. However, during the windy season for the basin floor site, Δq_{30} was positive (6.2 g m^{-2} d^{-1}), indicating that less sediment is leaving the plot than what is entering the plots upwind. Δq_{30} for the control plots were negative (−1.74 g m^{-2} d^{-1}), representing that more sediment is being eroded from the plots during this transport season. For the bajada site during the windy (Dec–May) season, Δq_{30} rates were negative for both the Con-Mod (−1.5 g m^{-2} d^{-1})

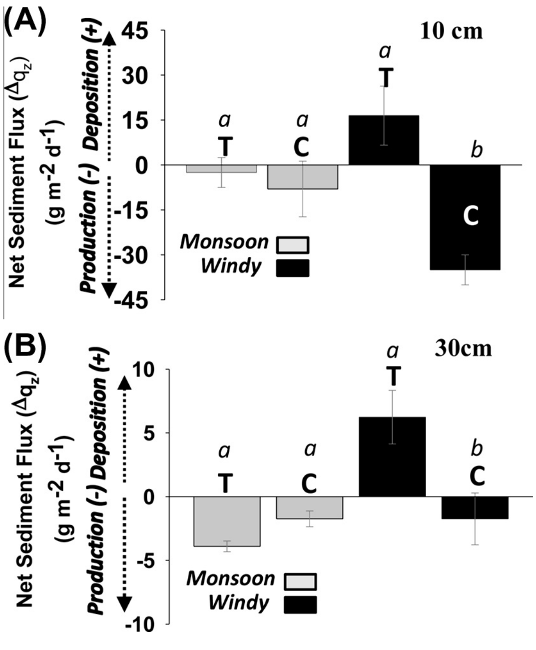

Fig. 3. Net sediment flux estimates indicating seasonal loss or gains at 10 cm (A) and 30 cm (B) for treatment (T) and control (C) plots for both the monsoon (Jul–Nov) and windy (Dec–May) seasons for the basin floor. Error bars represent the standard error of the mean; means with the same letter do not differ significantly ($P < 0.05$).

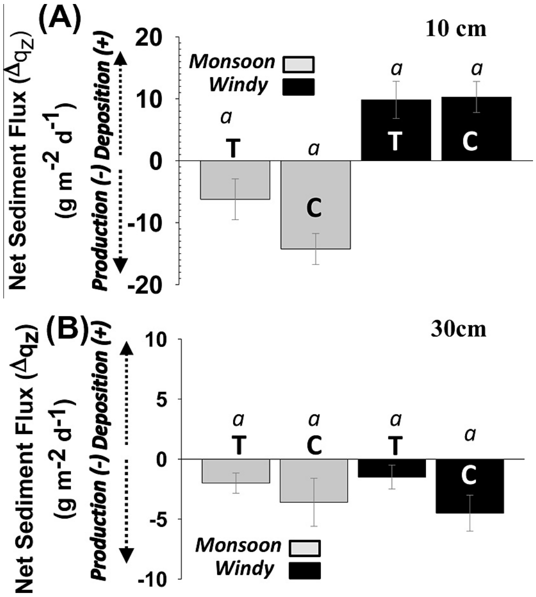

Fig. 4. Net sediment flux estimates indicating seasonal loss or gains at 10 cm (A) and 30 cm (B) for treatment (T) and control (C) plots for both the monsoon (Jul–Nov) and windy (Dec–May) transport seasons for the bajada site. Error bars represent the standard error of the mean; means with the same letter do not differ significantly ($P < 0.05$).

and control (−4.5 g m^{-2} d^{-1}), indicating that less sediment is leaving the plot than entering the plots upwind.

3.2. Radionuclide concentrations of different landform units

Radionuclide surface concentrations for the basin floor and bajada sites indicate that both landform units have unique radioisotopic signatures (Table 1). The basin floor contains much lower surface levels of radionuclides than the bajada site. ^{137}Cs activities ranged from 0.5–17 Bq m^{-2} with a mean of 7.5 ± 0.05 Bq m^{-2} (±indicates standard error of the mean), while ^{210}Pb$_{ex}$ activities ranged 164–278 Bq m^{-2} with a mean of 208 ± 10 Bq m^{-2} for the basin floor. ^{137}Cs and ^{210}Pb$_{ex}$ concentrations for the bajada site ranged from 12–20 Bq m^{-2} and 274–369 Bq m^{-2} with a mean of 20 ± 16 Bq m^{-2} and 332 ± 24 Bq m^{-2}. These surface activities were 62% and 40% lower on the basin floor than the neighboring bajada site. ^{7}Be surface concentrations ranged from 20–178 Bq m^{2} with a mean of 84 ± 12 Bq m^{-2}, while the bajada ranged from 0–92 Bq m^{-2} with a mean of 44 ± 8.5 Bq m^{-2}. Surface concentrations for ^{7}Be were 53% higher on the basin floor than the bajada.

3.3. Seasonal surface radionuclide concentrations

Con-Mods on the basin floor contained sediments with much higher radionuclide surface activities for all three tracers when compared to the neighboring control plots (Table 2). In the Con-Mods, surface activities were 58%, 74% and 50% higher for ^{7}Be, ^{210}Pb$_{ex}$, and ^{137}Cs, respectively, when compared to the control structures and control interspaces. However, the surface concentrations, within the Con-Mod interspaces, did not show a consistent pattern across all three radionuclides tracers for this site. ^{7}Be was 42% lower within the Con-Mod interspaces than in the control structures ($P < 0.05$), while Cs^{137} and ^{210}Pb$_{ex}$ levels did not differ significantly ($P > 0.05$).

Con-Mods plots on the basin floor also exhibited the most seasonal change in radionuclide surface quantities (Table 2). ^{7}Be decreased between the monsoon (July–Nov) and the windy (Dec–May) seasons by 81% from 222 ± 40 Bq m^{-2} to 42 ± 16 Bq m^{-2} within the structures. However, this decline in surface concentration was not exhibited by ^{210}Pb$_{ex}$ and ^{137}Cs surface levels, which increased negligibly by 2% for that period of time. The most pronounced seasonal change in surface concentration of all tracers occurred within the Con-Mod interspaces. ^{7}Be, ^{210}Pb$_{ex}$, and ^{137}Cs surface concentration all declined 60% to 80% between the monsoon (July–Nov) and the windy (Dec–May) seasons. A similar rapid decline in surface concentrations was also documented in the control structures and control interspaces over that time period.

Con-Mods on the bajada did not exhibit higher surface concentrations than the neighboring control plots (Table 2). Surface concentrations, within the Con-Mods, were 33% higher in ^{7}Be, whereas ^{210}Pb$_{ex}$ and Cs^{137} were 13% and 23% higher in the control structures. The surface concentration of ^{7}Be, ^{210}Pb$_{ex}$ and Cs^{137}, within Con-Mod interspaces, did not differ significantly from Con-Mods measurements for this landform. Con-Mods plots on the bajada exhibited limited seasonal change in radionuclide surface concentrations. ^{210}Pb$_{ex}$ and Cs^{137} slightly increased by 7% and 9% between that time period. However, this landform also experienced a similar decline in ^{7}Be concentration that was documented on the basin floor. ^{7}Be concentration decreased between the monsoon (July–Nov) and the windy (Dec–May) seasons and could not be detected after the windy season within the Con-Mods, Con-Mod interspaces, or control structures.

3.4. Seasonal sediment redistribution and Connectivity Modifiers

Changes in the connectivity of bare erodible surfaces associated with long-term shrub encroachment can lead to a non-linear increase in wind and water erosion (Li et al., 2007; Turnbull et al., 2010; Munson et al., 2011). Preventing the growth and coalescence of these bare areas by reducing the connectedness of

Table 1
Summary statistics of excess ^{210}Pb, ^{137}Cs, and ^{7}Be surface concentrations.

Landform units	^{7}Be (Bq kg^{-1})	^{7}Be* (Bq m^{-2})	^{210}Pb$_{ex}$ (Bq kg^{-1})	^{210}Pb$_{ex}$* (Bq m^{-2})	^{137}Cs (Bq kg^{-1})	^{137}Cs* (Bq m^{-2})
Basin floor						
Mean	16.6	84.9	51.32	208.77	1.81	7.5
Range	3.3–39.1	20–178	39–73	164.5–278.8	0.1–3.8	0.5–17.5
Standard deviation	9.1	44.0	8.74	34.68	1.37	5.74
Standard error	2.6	12.7	2.5	10.01	0.5	1.65
Number of samples (n = 14)						
Bajada						
Mean	8.89	44.07	72.90	332.2	4.43	20.16
Range	0–20.9	0–92	60.3–82.2	274–369	2.67–6.32	12.15–20.16
Standard deviation	7.04	29.75	7.83	35.69	1.11	5.05
Standard error	2.03	8.58	2.2	10.3	0.3	1.5
Number of samples (n = 12)						

* Bulk density measurements are based on soil texture and were used to convent the activities to Bq m^{-2}.

Table 2
Summary statistics of seasonal excess ^{210}Pb, ^{137}Cs, and ^{7}Be surface concentrations.

Radionuclide activities[1]	Basin floor					Bajada				
	Transport season*					Transport season*				
	Monsoon (Bq m^{-2})*	Windy (Bq m^{-2})*	Seasonal decay correction ^{7}Be†	Difference (Bq m^{-2})	% Change **	Monsoon (Bq m^{-2})*	Windy (Bq m^{-2})*	Seasonal decay correction ^{7}Be†	Difference (Bq m^{-2})	% Change **
^{7}Be Activities										
Con-Mods	222 ± 37^{a}	42 ± 16a	28 ± 4^{a}	−200	−90%	52.4 ± 15	0	0	52	−100
Con-Mods interspaces	59 ± 16^{b}	17.5 ± 10^{b}	13 ± 6^{b}	−47	−80%	14.76 ± 8	0	0	15	−100
Control structures	129 ± 19^{c}	29.3 ± 5.4^{b}	17.2 ± 6^{b}	−111	−87%	52.82 ± 11	0	0	53	−100
Control interspaces	115 ± 15^{c}	23.8 ± 2.4^{b}	18.5 ± 6^{b}	−102	−89%	45.76 ± 23	0	0	45	−100
^{210}Pb$_{ex}$ Activities										
Con-Mods	282 ± 17^{a}	282 ± 24^{a}		0	0%	310 ± 31^{a}	332 ± 27^{a}		22	7
Con-Mods interspaces	200 ± 16^{b}	105 ± 4^{b}		−95	−52%	337 ± 21^{a}	331 ± 9.1^{a}		−6	−2
Control structures	209 ± 23^{b}	78 ± 5^{b}		−131	−63%	354 ± 8^{a}	329 ± 12^{a}		−25	−8
Control interspaces	216 ± 14^{b}	98 ± 15^{b}		−118	−55%	325 ± 14a	318 ± 25^{a}		−7	3
^{137}Cs Activities										
Con-Mods	14 ± 8^{a}	17 ± 9^{a}		3	18%	5.28 ± 1.8^{a}	$7\ .9 \pm 1.2^{a}$		4	33
Con-Mods interspaces	9.8 ± 3^{b}	4.4 ± 1^{b}		−5	−62%	18.26 ± 2.7^{a}	26.5 ± 2^{b}		8	31
Control structures	5.98 ± 3^{b}	1.85 ± 1^{b}		−4	−70%	21.07 ± 2.7^{a}	20.3 ± 1.2^{a}		−0.7	5
Control interspaces	5.13 ± 2^{b}	2.01 ± 1^{b}		−3	−61%	21.16 ± 2.5^{a}	26 ± 4^{a}		−5	20

[1] Concentrations with the same letter do not differ significantly (Least significant difference between mean ranks *post hoc* test; ($P < 0.05$).
* Sediment transport seasons: Monsoon (Jul–Nov) and Windy (Dec–May).
** "–" and "+" indicate the increase and decrease change in surface concentrations between seasons.
† All ^{7}Be values during the windy season were corrected for the natural decay of the tracer.

these transport corridors could alter the trajectory of the landscape away from desertification (Okin et al., 2009). Sediment flux rates and the amount radionuclides indicate that Con-Mods can interact with aeolian sediment transport within bare gaps to block sediment movement and increase sediment deposition/retention overtime.

Con-Mods on the basin floor contained sediments with higher (30–50%) radionuclide surface concentrations for both the monsoon and windy seasons for all tracers when compared to the control plots and Con-Mod interspaces. This indicates that the structures are suppressing wind erosion and trapping material derived from the area upwind of the plot and from the Con-Mod interspaces within the plot. Greater radionuclide surface concentrations in the Con-mods could be the result of higher sediment deposition within the structures, but it could also be from the accumulation of plant litter that is labeled with these radioisotopes. Herrick and others (2009) documented that the Con-Mods accumulated plant litter over a three year period that resulted in a 26% and 22% reduction in bare area in the structures for the basin floor sand sheet and the bajada sites. The accumulation of sediment, in combination with plant litter, may result in soil/vegetation feedbacks by creating microsites that are favorable for long-term plant growth within the Con-Mods. These microsites could increase the likelihood of reestablishment of native grasslands or could cause a state change shift to a more novel ecosystem with lower wind erosion rates.

If sediments, within the Con-Mods, were blown out during the windy season and/or washed out during the monsoon season, then there would be a sharp decline of surface concentrations, within the structures, followed by greater amounts of these tracers, within the Con-Mod interspaces, indicating intraplot scale soil redistribution. No evidence of this process was found on this landform unit. Furthermore, Δq_{10} rates also corroborate this finding with 13.5 g m^{-2} d^{-1} being deposited in the Con-Mod plots, while the control plots lost 27.2 g m^{-2} d^{-1} between the monsoon and windy seasons. However, relative sediment loss measured sediment traps positioned at 30 cm height between these seasons was more similar in the treatments and controls, which suggests that the structures are only trapping saltating sediments near the soil surface with sediments bypassing the plots above 30 cm.

The radionuclide tracers also provide a relative timeframe to understand the lateral movement of sediments through the Con-Mods. The presence of ^{137}Cs and ^{210}Pb$_{ex}$, within the Con-Mods, demonstrate that long-term sedimentation has been occurring, within the structure, since the inception of the experiment over the last four years. This is corroborated by ^{7}Be indicates that sediment deposition within the structure, has occurred over the last 6 months for both transport seasons for the basin floor.

In contrast to the basin floor, radionuclide concentration of the Con-Mods provided little evidence that the sediments are being deposited on the bajada site. Activities of ^{7}Be, ^{210}Pb$_{ex}$, and ^{137}Cs demonstrated an inconsistent pattern with ^{7}Be being the only radionuclide with greater concentration (>30%) within the Con-Mods than the control structures. There was no significant difference in ^{210}Pb$_{ex}$ activities between the Con-Mods and control structures. However, ^{137}Cs concentration was greater (>21%) in the Con-Mod interspaces and control plots. This variation in concentration of tracers, within the plots, could be the result of erosion/depositional processes associated with small-scale fluvial events. Gravelly surface characteristics and overland flow that is spatially confined to localized channels are present on the piedmont slope and are most likely influencing the spatial patterns of radionuclide surface concentrations (Wallbrink and Murray, 1994; Poesen et al., 1994; Gaspar et al., 2013). However, Δq_{10} rates indicated 3.59 g m^{-2} d^{-1} was deposited in the Con-Mod plots, while the control plots lost 4 g m^{-2} d^{-1} between the monsoon and windy seasons. Sediment loss was also greater in sediment traps positioned at 30 cm height between these seasons.

Con-Mod plots on the basin floor exhibited the most seasonal change in radionuclide surface activities and sediment fluxes. Although the concentration of ^{7}Be declined by 81% between the monsoon and windy seasons, ^{137}Cs and ^{210}Pb$_{ex}$ exhibited very little change within the Con-Mods. The drop in ^{7}Be surface concentration is largely due to the in situ radioactive decay of the tracer and not the removal of sediments from Con-Mods by wind erosion. Ninety percent of the initial surface concentration of ^{7}Be has decayed away between the monsoon and windy season. Ten percent of residual concentration of ^{7}Be was still present within the Con-Mods from the monsoon season that makes up 33% of the total surface concentration detected during the windy season.

Correcting for the seasonal decay activity of ^{7}Be indicates that only 28 ± 3.5 Bq m^{-2} was present within the structures after the windy transport season. Lower ^{7}Be activities in the Con-Mods during the windy season are most likely the result of lower production and input rates for that time period.

^{7}Be production and deposition is largely controlled by sunspot cycles and precipitation (McNeary and Baskaran, 2003; Papastefanou and Ioannidou, 2004). Sunspot activity for the 2010 monsoon season was 60% lower than the 2011 windy season (data from ISOON Telescope and National Solar Observatory, Sunspot, New Mexico). ^{7}Be in the upper atmosphere can be reduced by high sunspot activity due to the deflection of cosmic rays required for production (Koch and Mann, 1996). Increases in solar activity have been documented to lower seasonal soil concentrations of ^{7}Be (Schuller et al., 2010) and could explain the dramatic decline of ^{7}Be between both transport seasons.

No rainfall events were recorded between the two sampling dates (Nov–May) but the Jornada Basin headquarters weather station recorded snowfall equivalent to 4.3 mm melt water over a two-day period in February 2011. Snow is thought to be a more efficient scavenger of dust particles that are labeled with ^{7}Be, compared to the radionuclide concentration in rainfall events (Olsen et al., 1985; Ioannidou and Papastefanou, 2006). Even though snow deposition was limited, it is most likely responsible for labeling the soil surface with ^{7}Be early in the windy season. Thus, despite the absence of rain events during the windy season, sufficient ^{7}Be was added to the samples to explain the amount of redistribution that is the differences between the Con-Mod and Con-Mod interspaces, observed on the plots. Indeed, the fact that snowmelt, particularly in these low amounts, does not produce overland flow argues strongly that the observed redistribution is due to aeolian sediment transport rather than small-scale fluvial processes.

The most seasonal change in concentration occurred in both the Con-Mod interspaces and control structures. ^{137}Cs and ^{210}Pb$_{ex}$ concentrations declined by 52% and 62% after the windy season. Net sediment flux (Δq_z) rates over this time period indicated more sediment was entering the plot than leaving the plot with 13.5 g m^{-2} d^{-1} (10 cm) of sediment being deposited in the Con-Mod plots during that transport season. The depleted surface concentration of these tracers suggests the Con-Mod interspaces and controls structures are areas vulnerable to wind erosion. However, it is possible that sediment deficient in ^{137}Cs could have been deposited in these areas resulting in the decrease in ^{137}Cs concentration between the transport seasons.

Con-Mods were designed to separate plant scale processes from larger, patch-scale connectivity-controlled aeolian processes (Okin et al., 2015). These structures have altered an area that is prone to wind erosion at a finer scale but have not completely shut off sediment transport at the patch scale. The decline in radionuclide concentration most likely suggests that the structures themselves are altering the distribution of shear stress of the wind on the surface with some areas (e.g. Con-Mod Interspaces) acting as sources for sediments, while others (e.g. Con-Mods) are acting as depositional sinks. This is consistent with Okin's et al. (2008) model of aeolian transport in vegetated landscapes, where the overall shear stress may not have been decreased enough to turn off transport, but it alters the patterns of sediment transport. Altering the spacing and shape of the structures would minimize this effect, such as increasing the surface area of the structure within the direction of the prevailing wind or by increasing the number of structures. Past studies that have used radionuclides to trace the lateral movement of sediments through erosion control barriers have documented similar results (Schuller et al., 2010). However, little research has been conducted to quantify the effects of shape and structure spacing on sediment accumulation.

Con-Mod plots on the bajada did not exhibit any seasonal change in ^{137}Cs and ^{210}Pb$_{ex}$ surface activities. However, the bajada site displayed a major decline in ^{7}Be concentration between the monsoon and windy seasons. ^{7}Be concentration from the monsoon season had decayed away and was not replenished during the snowfall event that labeled the basin floor sediments. Lower snow accumulation and gravelly surface conditions, at the bajada site, could have reduced the input of this tracer placing any amount below the analytical detection limit, while sediment flux estimates indicate sediment deposition in the structures for the bajada site, and ^{210}Pb$_{ex}$ did not increase between seasons. ^{137}Cs increased by ~33%, indicating deposition occurred during the windy season at the bajada site, which corroborates the net sediment flux estimates that indicate deposition in the Con-Mod plots. Variation in concentration of tracers, within the plots, could be the result of erosion/depositional processes associated with water transport, which has been dominant on the piedmont slope rather than wind transport. While all Con-Mod plots reduced sediment transport at 10 cm height during the windy season, all plots on both landforms lost sediments during the monsoon. Sediment redistribution during this season could be from dust devils or down drafts, associated with summer thunderstorms, that are blowing sediment out of the Con-Mods (Warner, 2004; Bergametti and Gillette, 2010).

4. Conclusion

Climate model predictions indicate an increase in future drought frequency for the southwestern United States that could impact vegetation cover (Seager et al., 2007; Munson et al., 2012). Drought conditions would result in the growth and coalescence of bare erodible soil surfaces that could lead to an increase in wind and water erosion overtime (Li et al., 2007; Turnbull et al., 2010; Munson et al., 2011). This cascading effect brought on by crossing non-linear thresholds would have regional to global consequences (Peters et al., 2004). Increased dust emissions, associated with this change in land cover, would impact the timing of alpine snowmelt (Painter et al., 2007), removal of soil nutrients (Leys and McTainsh, 1994), impact downwind respiratory health (Griffin et al., 2001) and alter global climate (Tegen et al., 1996).

Changing the connectivity of bare erodible surfaces could alter the trajectory of a landscape away from desertification potentially reducing these future effects. This study tests this hypothesis by reducing the connectedness of sediment transport pathways that would result in more deposition/retention by placing sediment retention structures (aka Con-Mods) within bare interspaces of two shrublands. Seasonal aeolian sediment flux rates and short-lived radionuclide measurements indicate that these structures interact with aeolian sediment transport within bare gaps to block sediment movement and increase sediment deposition/retention. Furthermore, short-lived radionuclide measurements also indicate that the structures are collecting sediments between transport seasons. The capture, retention and long-term storage of sediments/nutrients could influence ecosystem processes, such as nutrient cycling, increase soil moisture availability, and microclimate. The alteration of these processes could result in soil/vegetation feedbacks that could increase the likelihood of reestablishment of native grasslands or could cause a state change shift to a more novel ecosystem with lower wind erosion rates.

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