Soil seed bank characteristics on buffelgrass-seeded, retired farmland in Avra Valley, Arizona

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Abstract

Soil seed bank samples were collected in June/July 2006, 2007 and 2008 from a formerly farmed parcel in Avra Valley, Arizona, that was seeded to *Pennisetum ciliare* (buffelgrass) pasture sometime in the 1980s. Management goals for the property were to eradicate *P. ciliare*, allowing for the establishment of native vegetation either autogenically or through active restoration. By studying the soil seed bank characteristics before and after *P. ciliare* treatments were applied, we hoped to detect any differences in *P. ciliare* and native soil seed bank densities that could be attributed to management practices. Unfortunately, planned treatments either did not occur or were sufficiently erratic and applied in unplanned combinations as to confound the original study design. Ultimately, within the comparisons that could be made, soil seed bank samples showed significantly less *P. ciliare* seed densities in 2008 versus 2006, though no differences were detected among different treatment combinations. Overall soil seed densities declined from 2006 to 2008 only for one treatment combination (burning and tractor-applied herbicides, followed by mowing the following year), and this was likely attributable to a sharp decline in *Schismus* spp. in those fields. No other differences in overall soil seed densities or species richness were observed between 2006 and 2008 samples or among different treatment combinations. Only 1 native perennial species was observed in the samples.

Introduction

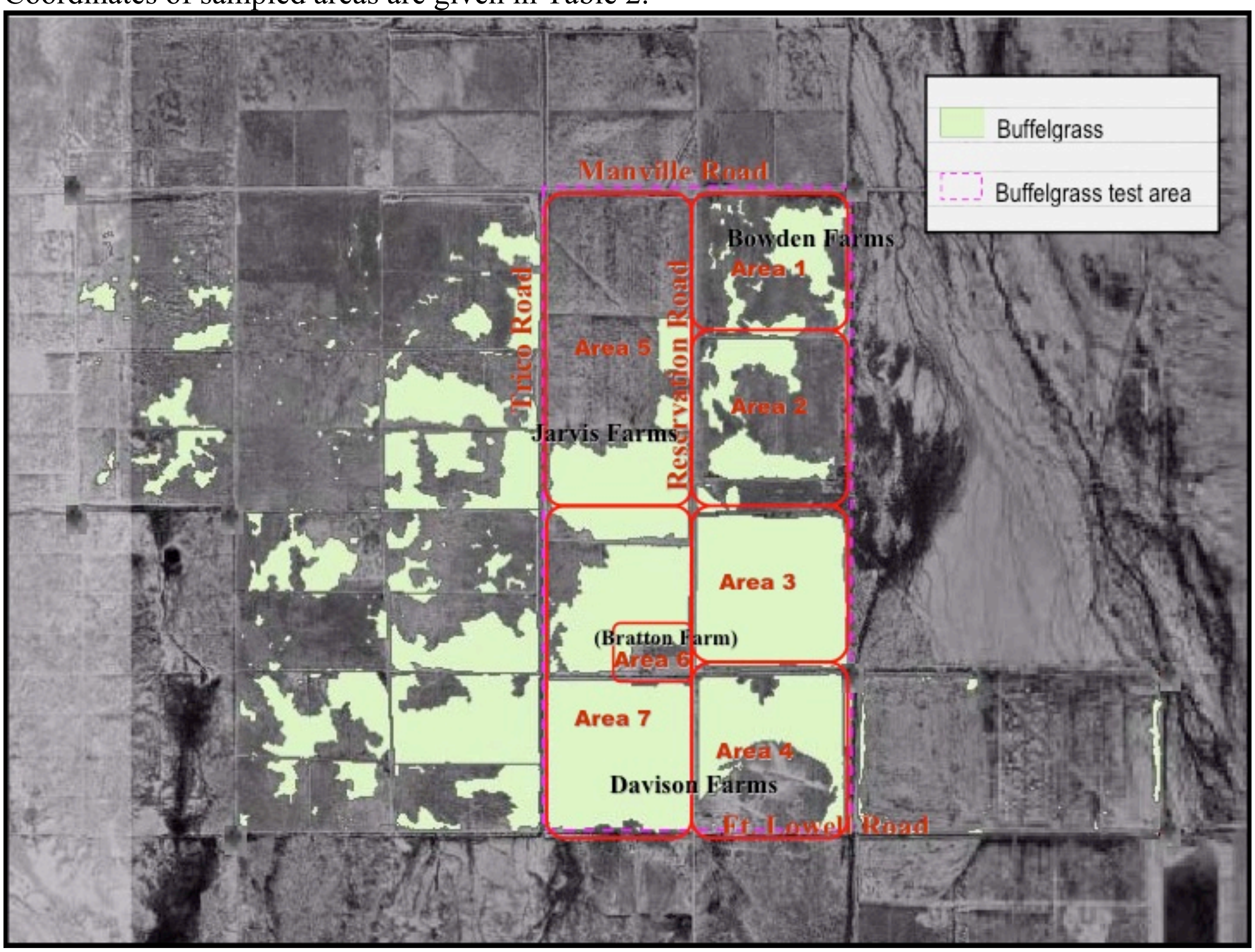
Tucson Water has undertaken to control *P. ciliare* on City-owned water properties in Avra Valley, Arizona, and to date have implemented various combinations of mowing, burning, and herbicide treatments. Following the successful removal of *P. ciliare*, COT's intention is to pursue active revegetation to establish a permanent cover of native plants on the site (Harold Maxwell, personal communication). However, without first eradicating or significantly reducing the buffelgrass soil seed bank, any revegetation efforts will likely be compromised by the aggressive *P. ciliare* due to its ability to outcompete native plants for water and nutrients and/or initiate a grass-fire cycle (D'antonio and Vitousek 1992, Rossiter et al. 2003, 2005), preventing the re-introduction of fire-intolerant Sonoran Desert vegetation. Not surprisingly, reduction in the *P. ciliare* soil seed bank following the mortality of the existing *P. ciliare* plants was associated with increased success of native plant establishment in restoration attempts in *P. ciliare*-infested areas in Texas and Hawaii (Daehler and Goergen 2005, Tjelmeland et al. 2008).

The original goal of the study was to support the *P. ciliare* control efforts of Tucson Water by assessing trends in the soil seed bank characteristics over time as treatments progressed, assuming treatments would be applied methodically and continued annually. The main questions to be addressed were 1) how long will viable *P. ciliare* seeds remain viable in the soil as treatments progress and 2) will *P. ciliare* seed in the soil seed bank be replaced by native species as treatments progress? Trends in the *P. ciliare* soil seed bank over time should give an indication of the effectiveness of the control efforts and possibly help estimate the length of time such efforts will have to continue to sufficiently reduce the *P. ciliare* soil seed bank. This will also help verify the assumption that *P. ciliare* seed inputs will directly affect the density of the *P. ciliare* soil seed bank. Finally, trends in the native soil seed bank will provide important information about the need for active revegetation efforts once the *P. ciliare* is removed.

Study area

The study area is located on a set of properties owned by the City of Tucson in Avra Valley, Arizona. These properties were formerly farmed and retired from active agriculture in the 1980s or before, and at approximately the same time, some were seeded to buffelgrass pasture (Thacker and Cox 1992). Buffelgrass has since escaped plantings, having invaded and become the dominant vegetation on much of the surrounding landscape (Figure 1). Since 2006, these properties have experienced sporadic buffelgrass control treatments consisting of mowing, burning, herbicides or some combination thereof (Table 1).

Figure 1: Map of study area. Numbered field delineations from Garcia and Conway (2007). Coordinates of sampled areas are given in Table 2.



Avra Valley is located between the Tucson Mountains and Saguaro National Park to the east and a series of smaller mountain ranges (Roskruge, Pan Quemado, Waterman, Silverbell, and Samaniego Hills) and Ironwood Forest National Monument to the west. The major drainage of the valley is the Brawley Wash, which enters the Santa Cruz River near the Samaniego Hills. Remnant vegetation is typical of the Lower Colorado River Valley Subdivision of the Sonoran Desert, dominated by *Larrea tridentata*, with smaller portions of Arizona Upland vegetation, dominated by *Parkinsonia microphylla* (Brown 1994). Both vegetation types are highly invaded by *Prosopis velutina*, *P. ciliare*, and a host of early successional native and introduced species.

Table 1: History of buffelgrass control treatments by City of Tucson in Avra Valley (compiled by Pat Quest, September 2007). Notes marked with an asterisk (*) are made by Travis Bean.

Treatment	Date	Area (Fig. 1)	Comments	Details	Result
Fencing	29 June 2002	1-7			Buffelgrass recovered quickly from overgrazing by trespass cattle
Controlled burn	29 March 2007	1	The burn was patchy due to shifting winds. The east side of Area 1 received less fire.	A 9.14-m perimeter was bladed to create a firebreak	Approximately 75% of the area burned.
Herbicide applied via tractor	1-10 May 2007	1	Approximately 32.4 ha sprayed	Used 74.7 l of Kleenup® diluted solution per 0.4 ha sprayed. 0.44 l of unmixed product per 0.4 ha	Very ineffective- plants were still dormant when herbicide applied.*
Herbicide applied via tractor	31 Jul-8 Aug 2007	1	Second round of herbicide application. The west side of area not sprayed because it contained mostly native grasses with isolated patches of buffelgrass, tumbleweed, and pigweed. "native" grass likely African *Eragrostis lehmanniana**	Used 2.5% Kleenup® solution; approximately 2.07-2.23 l per 0.4 ha; 69.48 l of mixed chemical per 0.4 ha	Pigweed still growing. This was first area sprayed after the monsoon started, when buffelgrass was approx. 0.46 m high. The pigweed was not mature at this time. New growth of buffelgrass appeared after this application. Patchy areas of buffelgrass dieback. Very ineffective- looked like herbicide was applied much later in season.*
Controlled burn	29 Mar 2007	2	The burn was patchy due to shifting winds. The east side of area 2 received less fire.	A 9.14-m perimeter was bladed to create a firebreak.	Approximately 50% of this area burned.
Herbicide applied via tractor	9-17 Aug 2007	2	First round of herbicide application	Used 2.5% Kleenup® solution; approximately 2.07 l per 0.4 ha.	Very ineffective.*
Controlled burn	29 Mar 2007	3	The burn was patchy due to shifting winds. The east side of area 3 received less fire. The burn was increasingly patchy at the south end of area 3.	A 9.14-m perimeter was bladed to create a firebreak.	Approximately 25% of this area burned.
Herbicide applied via tractor	20-27 Aug 2007	3		Used 2.5% Kleenup® solution; approximately 2.07 l per 0.4 ha. Raised the sprayer booms because the buffelgrass was too high.	Very ineffective.*
Controlled burn	29 Mar 2007	4	The burn was patchy due to shifting winds. The east side of area 4 received less fire. The burn was increasingly patchy at the south end of area 4.	A 9.14-m perimeter was bladed to create a firebreak.	Approximately 25% of this area burned.
Herbicide applied via tractor	28 Aug-5 Sep 2007	4		Used 2.5% Kleenup® solution; approximately 2.07 l per 0.4 ha. Raised the sprayer booms.	Very ineffective*

Treatment	Date	Area (Fig. 1)	Comments	Details	Result
Mowed	Aug 2006	5		A 9.14-m perimeter was bladed north of the farmhouse to create a firebreak.	
Mowed	Jan 2007	5			
Herbicide applied via airplane	2-4 Sep 2007	5	Area to be sprayed programmed into the flight plan using GPS. Sprayed a little less than 242.8 ha in 10 hours.	5% Kleenup® solution. Plane averages 18.9 l of diluted solution per 0.4 ha (compared to 64.3 l for tractor)	Effective- good kill rates.*
Bladed	27 Feb 2006	6	Area surrounding the Bratton farm.	A 61-m perimeter was bladed to create a firebreak	
Herbicide applied via tractor	10 Sep 2007	6	Area surrounding the Bratton farm.	Used 2.5% Kleenup® solution; approximately 2.07 l per 0.4 ha. Raised the sprayer booms.	Very ineffective.*
Mowed	Jul 2007	7	Approx 45.7 m were accidentally mowed parallel to Reservation Rd on the west side, area 7 otherwise not treated to date.		
Herbicide applied via airplane	2-4 Sep 2007	7	Area to be sprayed programmed into the flight plan using GPS. Sprayed a little less than 242.8 ha in 10 hours.	5% Kleenup® solution. Plane averages 18.9 l of diluted solution per 0.4 ha (compared to 64.3 l for tractor).	Effective- good kill rates.*
Herbicide applied via tractor	10 Sep 2007	7	Ground was sprayed 15.2 m west of eastern fence to avoid burrowing owls.	Used 2.5% Kleenup® solution; approximately 2.07 l per 0.4 ha. Raised the sprayer booms.	

Methods

The soil seed bank at the study site was sampled in June or July of 2006, 2007, and 2008. Coordinates for sampling locations are given in Table 2. 2006 samples came from areas 3, 4, and 7. 2007 samples came from areas 2, 5, and 7. 2008 samples came from areas 2-5 and 7. In June 2006, 10 1-dm^2 samples were collected from each of four untreated buffelgrass plots located randomly within 0.5 mi east and west of Reservation road 1-2 mi north of Mile Wide Rd. In July 2007, 15 1-dm^2 samples were collected in the mowed and burned areas, and another 15 in an area that was left untreated. In June 2008, 40 1-dm^2 samples were collected across the infested areas in an attempt to guard against erratic buffelgrass treatments to ensure that comparisons could be made where appropriate. The sampling device, a metal frame 10 × 10 × 2 cm, was pounded into the ground until flush with the soil surface. All soil inside the frame was removed to a depth of 2 cm with a trowel and placed in a labeled plastic bag. The bagged samples were stored at room temperature. It should be noted that although a volume of soil was sampled, seed densities are given on an area basis, as is the convention in most soil seed bank literature.

Table 2: Locations (coordinates in decimal degrees) of seed soil bank samples. Map locations refer to numbered fields from Garcia and Conway (2007).

Map location	ID	Latitude	Longitude
2	1	32.27968	111.27474
2	2	32.28077	111.27653
2	3	32.27875	111.27667
2	4	32.28027	111.27508
2	5	32.27940	111.27276

Map location	ID	Latitude	Longitude
3	6	32.27377	111.27828
3	7	32.27205	111.27399
3	8	32.27248	111.27170
3	9	32.27472	111.27837
3	10	32.27079	111.27652
3	11	32.27309	111.27175
3	12	32.27273	111.27070
3	13	32.27292	111.27630
3	14	32.27495	111.27764
3	15	32.27698	111.27698
4	16	32.26733	111.27666
4	17	32.26850	111.27224
4	18	32.26470	111.27827
4	19	32.26465	111.27076
4	20	32.26913	111.27067
7	21	32.26954	111.27966
7	22	32.26564	111.28258
7	23	32.26299	111.28062
7	24	32.26515	111.28205
7	25	32.26440	111.28350
7	26	32.26727	111.28053
7	27	32.26481	111.28564
7	28	32.26964	111.28686
7	29	32.26650	111.28432
7	30	32.26905	111.28390
6	55	32.27279	111.28050
6	56	32.27282	111.28291
6	57	32.27208	111.28269
6	58	32.27434	111.28282
6	59	32.27371	111.27928
5	43	32.27842	111.28458
5	44	32.27695	111.27923
5	54	32.27844	111.28070
5	46	32.27965	111.28085
5	47	32.27749	111.28329

Samples were first processed by sieving to remove rocks and debris. An iterative flotation and filtering technique was then used to separate seeds and organic matter from soil particles (Pake and Venable 1996). The organic fraction was then air dried at room temperature and stored in labeled plastic bags. Each organic fraction was then examined under a dissecting microscope to identify seeds and determine their viability.

The remaining seeds were identified by comparison with voucher specimens. Some seeds of certain genera, notably *Amaranthus, Cryptantha, Euphorbia, Lepidium, Mentzelia,* and *Plantago,* could not be identified to species with any confidence and were treated at the generic level. Both *Schismus arabicus* and *S. barbatus* were present in the seed bank, sometimes in the same sample, but were treated as *Schismus* spp. because seeds that had fallen from the florets could not be reliably identified to species. Identified seeds were tested for viability by cutting them in half with a razor blade, then inspecting them. Firm, plump, undamaged seeds with moist, fleshy, or oily embryos were considered viable; seeds with discolored, crumbly, chalky, shrunken, or missing embryos were deemed nonviable and discarded. For each sample, a running tally was kept of viable seeds by species.

Sawma and Mohler (2002) provide a brief discussion of the advantages and disadvantages of various tests for seed viability. One method involves germinating seeds in flats, then counting and identifying seedlings as soon as possible after emergence. Another is to cut seeds in half, moisten the cut surface with a tetrazolium solution, then place seeds at a suitable temperature and watch for the characteristic red staining of respiring tissues. Tetrazolium testing requires a temperature-controlled environment and is laborious when small seeds or many seeds must be tested. Germination testing requires a greenhouse or shadehouse with automatic irrigation equipment and, because some dormant seeds might never emerge as seedlings, tends to underestimate the viable seed bank. Visual inspection of cut seeds is less labor-intensive than the tetrazolium method and less apt to overlook dormant seeds than the germination method. Although visual inspection might pass some nonviable seeds as viable, it is a useful and efficient technique for seed-bank surveys (Sawma and Mohler 2002).

Wilcoxon Rank Sums tests were used to compare samples from 2006 (pre-buffelgrass treatments) and samples from 2008 (various combinations of mowing, burning, and tractor- and aerial- herbicide treatments) in terms of number of seeds dm^{-2}, number of species dm^{-2}, number of native seeds dm^{-2}, number of exotic seeds dm^{-2}, number of native species dm^{-2}, and number of exotic species dm^{-2}. 2007 samples were not included in the comparison with 2008 samples because the majority of the samples had been subjected to burning or mowing treatments, whereas the 2006 treatments were all collected before any treatments had been applied and thus gave a larger sample size and higher likelihood of detecting a difference between pre- and post-treatment samples.

To guard against the possibility of a significant treatment x time interaction, comparisons across years were restricted to samples taken in the same fields (Figure 1). The final treatment regimes (at the time of sampling in June 2008) of fields compared with 2006 (pre-treatment) samples were: 1) burned and herbicide applied with a tractor in 2007, mowed in 2008 (BTM), 2) mowed and herbicide applied aerially in 2007, burned in 2008 (MAB), 3) mowed and herbicide applied aerially in 2007, mowed in 2008 (MAM). Comparisons between 2006 and 2007 samples can be seen in the previous report. All means are reported along with standard deviation.

Results

A total of 27 species were identified in the 2006 and 2008 samples, along with another 7 distinct species that could not be identified (34 species present). Six of these species were exotic (not native to North America), including *Bromus rubens, Erodium cicutarium, Pennisetum ciliare, Salsola kali, Schismus* spp., and *Sisymbrium irio.* Only 2 species identified in the study are perennials (*P. ciliare* and *Porophyllum gracile*). A total of 20 species was found in 2006, 23 species were found in 2008 in areas 3 and 4 (BTM), 30 species in area 5 and the north ½ of area 7 (MAB), and 16 species in the south ½ of area 7 (MAM).

For the BTM samples (Table 3), there was a decline in seed density for *Euphorbia* spp., *P. ciliare*, and *Schismus* spp., as well as a decline in overall seed density, exotic seed density, and exotic species richness from 2006 to 2008. There was an increase in seed density for *Cryptantha angustifolia, E. cicutarium, P. patagonica,* and Unknown 9 between 2006 and 2008. For the MAB samples (Table 4), there was a decline in seed density for *Descurainia pinnata, Euphorbia* spp., *Pectocarya heterocarpa*, and *P. ciliare* between 2006 and 2008. There was an increase in seed density for *Leptochloa panicea, P. patagonica, S. irio,* and Unknown 9. For the MAM samples (Table 5), there was a decline in *Amsinkia menziesii, P. ciliare,* and *Plantago* spp.

between 2006 and 2009. No increases in seed densities or species richness were seen for the MAM samples.

Among the different treatment regimes (2008 samples, Table 6), no differences were seen in native, exotic, or overall seed density or species richness. *E. cicutarium* seed density was higher for BTM treatments than for MAB or MAM treatments. Seed density for *L. panicea, P. patagonica,* and *Veronica peregrina* was higher for MAM treatments than for BTM or MAB treatments.

Table 3: Mean viable seed densities (seeds dm^{-2}) and species richness (# species) of samples from areas 3 & 4 (burned & tractor-sprayed in 2007, mowed in 2008) taken in 2006 (pre-treatment) and 2008 (post-treatment). Means followed by different letters within a row are significantly different at $p < 0.05$ using Wilcoxon Rank Sums tests. An asterisk indicates a species not native to North America. "NP" is shorthand for "not present," meaning no viable seeds of that species were found in any samples for a given year or treatment combination. A value of 0.0 indicates that mean viable seed density was > 0 but < 0.05 seeds dm^{-2}.

Species	2006 Samples (n=20)		2008 Samples (n=15)	
	Mean	SD	Mean	SD
Amsinckia menziesii	3.9	8.6	3.5	8.7
Amsinckia tessellata	0.1	0.2	0.2	0.6
Antheropeas (Eriophyllum) lanosum	NP	NP	1.7	6.5
Bouteloua aristidoides	0.2	0.7	0.9	2.1
*Bromus rubens**	0.1	0.2	NP	NP
Cryptantha angustifolia	NP[b]	NP	3.1[a]	7.8
Cryptantha barbigera	0.1	0.2	0.4	1.6
Cryptantha spp.	0.1	0.2	3.5	8.7
Daucus pusillus	0.1	0.2	NP	NP
Descurainia pinnata	0.2	0.5	2.1	6.4
*Erodium cicutarium**	NP[b]	NP	5.2[a]	10.1
Euphorbia spp.	2.8[a]	3.8	NP[b]	NP
Lappula occidentalis	0.3	0.9	NP	NP
Lepidium spp.	NP	NP	0.1	0.3
Mentzelia affinis	NP	NP	0.1	0.3
Mentzelia spp.	0.7	0.6	0.1	0.3
Pectocarya heterocarpa	2.9	11.2	1.7	6.2
Pectocarya platycarpa	2.2	9.6	NP	NP
Pectocarya recurvata	2.7	11.2	NP	NP
*Pennisetum ciliare**	13.7[a]	15.6	1.7[b]	6.4
Plantago patagonica	NP[b]	NP	0.3[a]	0.6
Plantago spp.	5.9	12.9	0.3	0.6
*Salsola kali**	1.4	2.6	0.1	0.3
Schismus spp.*	33.2[a]	19.5	10.5[b]	11.1
Stylocline micropoides	0.1	0.4	0.5	1.3
Uropappus (Microseris) lindleyi	NP	NP	0.3	0.7
Unknown 5	0.1	0.3	NP	NP
Unknown 6	0.2	0.4	NP	NP
Unknown 7	NP	NP	0.1	0.5
Unknown 9	NP[b]	NP	2.1[a]	3.7
Unknown 10	NP	NP	0.3	0.9
Unknown 11	NP	NP	1.7	6.4
All Seeds	70.4[a]	53.0	36.5[b]	39.8
All Species	5.2	1.8	4.1	3.1
Native Seeds	22.2	41.4	19.0	28.2
Native Species	3.2	1.5	2.9	2.7
Exotic Seeds	48.2[a]	25.8	17.5[b]	17.9

Species	2006 Samples (n=20)		2008 Samples (n=15)	
	Mean	SD	Mean	SD
Exotic Species	2.1[a]	0.8	1.2[b]	0.9

Table 4: Mean viable seed densities (seeds dm^{-2}) and species richness (# species) of samples from area 5 & the north ½ of area 7 (mowed & aerial-sprayed in 2007, mowed in 2008) taken in 2006 (pre-treatment) and 2008 (post-treatment). Means followed by different letters within a row are significantly different at $p < 0.05$ using Wilcoxon Rank Sums tests. An asterisk indicates a species not native to North America. "NP" is shorthand for "not present," meaning no viable seeds of that species were found in any samples for a given year or treatment combination. A value of 0.0 indicates that mean viable seed density was > 0 but < 0.05 seeds dm^{-2}.

Species	2006 Samples (n=10)		2008 Samples (n=10)	
	Mean	SD	Mean	SD
Amaranthus spp.	NP	NP	0.1	0.3
Amsinckia menziesii	3.5	4.8	0.7	1.6
Amsinckia tessellata	0.1	0.3	NP	NP
Antheropeas (Eriophyllum) lanosum	0.1	0.3	0.1	0.3
Aristida adscensionis	NP	NP	0.1	0.3
Bouteloua aristidoides	NP	NP	1.9	5.7
Cryptantha angustifolia	NP	NP	2.6	7.9
Cryptantha micrantha	NP	NP	0.1	0.3
Cryptantha pterocarya	0.1	0.3	0.4	1.3
Cryptantha spp.	0.1	0.3	3.1	9.5
Daucus pusillus	NP	NP	1.8	3.6
Descurainia pinnata	6.8[a]	10.8	0.1[b]	0.3
*Erodium cicutarium**	NP	NP	3.9	8.2
Erodium texanum	NP	NP	0.2	0.6
Euphorbia spp.	3.4[a]	3.9	NP[b]	NP
Lappula occidentalis	NP	NP	0.1	0.3
Lepidium spp.	0.6	1.6	2.5	7.9
Leptochloa panicea	NP[b]	NP	3.1[a]	4.7
Pectocarya heterocarpa	1.8[a]	2.7	NP[b]	NP
*Pennisetum ciliare**	7.0[a]	5.4	2.1[b]	3.8
Plantago ovata	NP	NP	0.3	0.9
Plantago patagonica	NP[b]	NP	10.2[a]	12.7
Plantago spp.	6.2	7.3	10.5	13.2
Porophyllum gracile	0.2	0.6	NP	NP
*Salsola kali**	2.2	3.6	0.4	1.0
Schismus spp.*	15.1	12.2	14.3	10.5
*Sisymbrium irio**	NP[b]	NP	2.5[a]	5.0
Stylocline micropoides	14.8	21.8	0.6	1.9
Uropappus (Microseris) lindleyi	NP	NP	0.3	0.5
Veronica peregrina	NP	NP	0.4	1.0
Unknown 6	0.1	0.3	NP	NP
Unknown 7	NP	NP	2.1	6.6
Unknown 8	NP	NP	0.1	0.3
Unknown 9	NP[b]	NP	0.9[a]	1.5
Unknown 10	NP	NP	0.2	0.6
Unknown 11	NP	NP	0.5	0.3
All Seeds	62.0	36.4	52.6	34.1
All Species	7.0	2.8	6.8	3.9
Native Seeds	37.7	33.7	29.4	28.9
Native Species	4.8	2.1	4.6	3.7
Exotic Seeds	24.3	13.5	23.2	15.3

Species	2006 Samples (n=10)		2008 Samples (n=10)	
	Mean	SD	Mean	SD
Exotic Species	2.2	0.8	2.2	1.2

Table 5: Mean viable seed densities (seeds dm^{-2}) and species richness (# species) of samples from the south ½ of area 7 (mowed & aerial-sprayed in 2007, burned in 2008) taken in 2006 (pre-treatment) and 2008 (post-treatment). Means followed by different letters within a row are significantly different at $p < 0.05$ using Wilcoxon Rank Sums tests. An asterisk indicates a species not native to North America. "NP" is shorthand for "not present," meaning no viable seeds of that species were found in any samples for a given year or treatment combination. A value of 0.0 indicates that mean viable seed density was > 0 but < 0.05 seeds dm^{-2}.

Species	2006 Samples (n=10)		2008 Samples (n=10)	
	Mean	SD	Mean	SD
Amaranthus spp.	0.2	0.6	NP	NP
Amsinckia menziesii	1.7[a]	2.5	0.4[b]	1.3
Amsinckia tessellata	NP	NP	0.1	0.3
Antheropeas (Eriophyllum) lanosum	0.4	1.3	0.1	0.3
Bouteloua aristidoides	NP	NP	0.5	1.6
Cryptantha angustifolia	1.5	2.3	5.6	10.3
Cryptantha micrantha	NP	NP	0.4	1.3
Cryptantha spp.	1.6	2.3	6.0	11.2
Daucus pusillus	NP	NP	0.2	0.4
Descurainia pinnata	NP	NP	0.1	0.3
*Erodium cicutarium**	NP	NP	2.4	7.6
Euphorbia spp.	0.1	0.3	NP	NP
Lappula occidentalis	0.1	0.3	NP	NP
Lepidium spp.	NP	NP	0.1	0.3
Pectocarya heterocarpa	4.8	12.6	0.1	0.3
Pectocarya platycarpa	1.6	5.1	NP	NP
Pectocarya recurvata	0.3	0.9	0.5	1.6
*Pennisetum ciliare**	8.1[a]	11.2	0.1[b]	0.3
Plantago spp.	10.6[a]	15.9	NP[b]	NP
Stylocline micropoides	NP	NP	0.2	0.4
Unknown 5	0.3	0.7	NP	NP
Unknown 6	0.1	0.3	NP	NP
Unknown 9	NP	NP	2.5	7.9
Unknown 10	NP	NP	0.4	0.7
All Seeds	45.9	48.7	22.3	20.4
All Species	4.6	3.0	3.2	2.0
Native Seeds	21.8	36.6	11.1	13.0
Native Species	3.1	2.4	2.1	1.7
Exotic Seeds	24.1	18.3	11.2	9.6
Exotic Species	1.5	0.7	1.1	0.6

Table 6: Mean viable seed densities (seeds dm^{-2}) and species richness (# species) of 2008 samples from 3 different *P. ciliare* treatment regimes. Means followed by different letters within a row are significantly different at $p < 0.05$ using Wilcoxon Rank Sums tests. An asterisk indicates a species not native to North America. "NP" is shorthand for "not present," meaning no viable seeds of that species were found in any samples for a given year or treatment combination. A value of 0.0 indicates that mean viable seed density was > 0 but < 0.05 seeds dm^{-2}.

Species	2007 Burn + Tractor Spray, 2008 Mow (n=20)		2007 Aerial Spray, 2008 Burn (n=10)		2007 Aerial Spray, 2008 Mow (n=10)	
	Mean	SD	Mean	SD	Mean	SD
Amaranthus spp.	0.3	0.9	NP	NP	0.1	0.3

Species	2007 Burn + Tractor Spray, 2008 Mow (n=20)		2007 Aerial Spray, 2008 Burn (n=10)		2007 Aerial Spray, 2008 Mow (n=10)	
	Mean	SD	Mean	SD	Mean	SD
Amsinckia menziesii	3.5	8.0	0.4	1.3	0.7	1.6
Amsinckia tessellata	0.3	0.6	0.1	0.3	NP	NP
Antheropeas (Eriophyllum) lanosum	1.3	5.6	0.1	0.3	0.1	0.3
Aristida adscensionis	NP	NP	NP	NP	0.1	0.3
Bouteloua aristidoides	0.7	1.9	0.5	1.6	1.9	5.7
*Bromus rubens**	NP	NP	NP	NP	NP	NP
Cryptantha angustifolia	3.2	7.5	5.6	10.3	2.6	7.9
Cryptantha barbigera	0.3	1.3	NP	NP	NP	NP
Cryptantha micrantha	0.2	0.7	0.4	1.3	0.1	0.3
Cryptantha pterocarya	NP	NP	NP	NP	0.4	1.3
Cryptantha spp.	3.6	8.6	6.0	11.2	3.1	9.5
Daucus pusillus	NP	NP	0.2	0.4	1.8	3.6
Descurainia pinnata	1.6	5.6	0.1	0.3	0.1	0.3
*Erodium cicutarium**	4.8[a]	9.4	2.4[b]	7.6	3.9[b]	8.2
Erodium texanum	NP	NP	NP	NP	0.2	0.6
Lappula occidentalis	NP	NP	NP	NP	0.1	0.3
Lepidium spp.	0.1	0.2	NP	NP	2.5	7.9
Leptochloa panicea	NP[b]	NP	NP[b]	NP	3.1[a]	4.7
Mentzelia affinis	0.1	0.2	NP	NP	NP	NP
Mentzelia spp.	0.1	0.2	NP	NP	NP	NP
Pectocarya heterocarpa	1.5	5.4	0.1	0.3	NP	NP
Pectocarya recurvata	0.1	0.2	0.5	1.6	NP	NP
*Pennisetum ciliare**	1.3	5.6	0.1	0.3	2.1	3.8
Plantago ovata	NP	NP	NP	NP	0.3	0.9
Plantago patagonica	0.2[b]	0.5	0.0[b]	0.0	10.2[a]	12.7
Plantago spp.	0.2[b]	0.5	NP[b]	NP	10.5[a]	13.2
*Salsola kali**	0.1	0.2	NP	NP	0.4	1.0
Schismus spp.*	13.4	11.3	8.7	8.7	14.3	10.5
*Sisymbrium irio**	NP	NP	NP	NP	2.5	5.0
Stylocline micropoides	0.4	1.1	0.2	0.4	0.6	1.9
Uropappus (Microseris) lindleyi	0.2	0.6	NP	NP	0.3	0.5
Veronica peregrina	NP[b]	NP	NP[b]	NP	0.4[a]	1.0
Unknown 7	0.1	0.4	NP	NP	2.1	6.6
Unknown 8	NP	NP	NP	NP	0.1	0.3
Unknown 9	2.4	3.6	2.5	7.9	0.9	1.5
Unknown 10	0.3	0.8	0.4	0.7	0.2	0.6
Unknown 11	1.3	5.6	NP	NP	0.5	0.3
All Seeds	37.2	34.6	22.3	20.4	52.6	34.1
All Species	4.2	2.9	3.2	2.0	6.8	3.8
Native Seeds	17.6	25.2	11.1	13.0	29.4	28.9
Native Species	3.0	2.7	2.1	1.7	4.6	3.7
Exotic Seeds	19.6	16.6	11.2	9.6	23.2	15.3
Exotic Species	1.3	0.8	1.1	0.6	2.2	1.2

Discussion

The most apparent difference between the 2006 and 2008 samples is a consistent decline of *P. ciliare* seed density across all treatment regimes. It's unlikely, however, that this is an effect of the treatments, as the 2007 (Appendix 1) untreated samples showed a similar decline from the 2006 samples. A more plausible explanation is that losses from the *P. ciliare* soil seed bank were due to an emergence event (seeds germinated and either perished or established) or granivory (rodents, insects, or microbes consumed the seed) (Price and Joyner 1997). Inter-annual climatic variations are often related to episodic emergence events of native plant species (Bowers et al. 2004), as are boom and bust population dynamics of granivores (Reichman and Vandegra 1973, Reichman 1984, Price and Reichman 1987, Samson et al. 1992, Meyer and Pendleton 2005, Lima et al. 2008). Either could have been a factor here, but the important point is that the depressed soil seed bank of *P. ciliare* does suggest that this may be a critical opportunity for control on the site.

Seed densities of *Plantago* spp., likely *P. patagonica*, were different between the 2006 and 2008 samples for all treatment regimes, but the trajectory of the difference showed no consistent pattern. Similarly, several other species' seed densities varied significantly from 2006 to 2008 for some treatments, but this was most likely a factor of the tendency for annual species soil seed banks to vary highly over space and time (Freas and Kemp 1983, Henderson et al. 1988, Coffin and Lauenroth 1989, Pake and Venable 1996, Guo et al. 1999, Bowers et al. 2004). The only treatment that showed differences in overall species seed densities between 2006 and 2008 was BTM. This was probably due to the sharp decline in *Schismus* spp., which was very abundant in the 2006 samples for these areas (3 & 4). When present, *Schismus* spp. was the most abundant species present in the samples and therefore any differences in this species from 2006 to 2008 would strongly affect the overall soil seed bank density. Similarly, the exotic species richness for the BTM treatments declined from 2006 to 2008, also a likely result of the decline in *Schismus* spp.

For the 2008 samples, no differences were found among treatments for *P. ciliare, Schismus* spp., or the overall seed densities or species richness. Without singling out treatments (just mowing, just burning, just tractor- or aerially-applied herbicides) plus a control (area 7 was the control but it was burned in 2008), it's difficult to say more about the effects of the treatment combinations on soil seed characteristics. Nevertheless, it's apparent that many native annuals are present in the soil seed bank, and could increase if given space to occupy with the removal of buffelgrass. The lack of native perennials suggests that propagules will likely need to be re-introduced onto the site if some semblance of the native vegetation prior to farming is to be achieved.

Conclusions

The original objectives of the study were not met. A lack of consistent control treatments applied to *P. ciliare* has resulted in little or no reduction in *P. ciliare* density or cover within the study area. This violated an implicit assumption of the study design: that treatments would be applied as planned. Strong evidence exists from numerous *P. ciliare* control projects from Australia (Dixon et al. 2002), Hawaii (Daehler and Goergen 2005), Texas (C. Best, US Fish and Wildlife Service Restoration Ecologist, personal communication), and Arizona (C. Barclay- ADOT Natural Resources Manager, D. Backer- Saguaro National Park Restoration Ecologist, both personal communications) that dramatic reductions of living *P. ciliare* plants are easily achieved with at least 2 annually repeated herbicide treatments on a given site. No fields within the study area received more than one herbicide application, most of which had little or no effect (except for the aerial application), and applications were allowed to lapse completely in 2008.

Without a reduction in mature, seed-producing *P. ciliare* plants within the study area, the study was impossible to complete. Thus, no inferences were made about a link between a reduction in the *P. ciliare* seed source and the length of time that viable *P. ciliare* seeds remain in the soil. Nor was it possible to draw any conclusions about a link between a reduction in the

P. ciliare seed source and an increase in the density of native seed or species within the soil seed bank. Conclusions that are apparent from the data collected are that a viable native soil seed bank does exist for annual species but not perennials. If control treatments are resumed and *P. ciliare* is removed from or greatly reduced on site, and if restoration of the site to native vegetation is desired, propagules from native perennials may need to be introduced if native seed rain is deemed insufficient.

Continuance of this study is not warranted unless *P. ciliare* control activities are to resume and continue within the framework of a comprehensive restoration plan. Site managers have found aerial application of herbicides to be very effective in terms of control and cost efficiency. The very low occurrence of non-target native perennials in the study area makes this site a unique candidate for this technique. With repeat annual applications of herbicide, the study area could see dramatic reductions in buffelgrass by 2011. A dialogue with study area managers is strongly encouraged to assist in restarting the control process. Techniques used in this study may also prove useful for gauging the success of any future attempts at revegetation with native species.

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Appendix 1: Mean viable seed densities (seeds dm^{-2}) and species richness (# species) of 2006 and 2007 samples from area 7 (untreated at the time samples were taken in 2007). Means followed by different letters within a row are significantly different at $p < 0.05$ using Wilcoxon Rank Sums tests. An asterisk indicates a species not native to North America. "NP" is shorthand for "not present," meaning no viable seeds of that species were found in any samples for a given year or treatment combination. A value of 0.0 indicates that mean viable seed density was > 0 but < 0.05 seeds dm^{-2}. Burned (area 2) and mowed (area 5) treatments were excluded from 2007 data.

Species	2006 (n=40)		2007 (n=15)	
	Mean	SD	Mean	SD
*Pennisetum ciliare**	10.6[a]	12.8	1.8[b]	3.6
*Schismus arabicus, S. barbatus**	24.4[a]	19.4	0.9[b]	1.3
Amaranthus spp.	0.1	0.3	NP	NP
Amsinckia menziesii	3.2[a]	6.6	NP[b]	NP
Amsinckia tessellata	0.1	0.2	NP	NP
Aristida adscensionis	NP	NP	0.2	0.8
Boerhavia spp.	NP[b]	NP	0.5[a]	1.4
Bouteloua aristidoides	0.1[b]	0.5	5.1[a]	13.4
*Bromus rubens**	0.0	0.2	NP	NP
Cryptantha angustifolia	0.4	1.3	NP	NP
Cryptantha barbigera	0.0	0.2	NP	NP
Cryptantha pterocarya	0.0	0.2	NP	NP
Cryptantha spp.	0.0	0.2	NP	NP
Daucus pusillus	0.0	0.2	NP	NP
Descurainia pinnata	1.8[a]	6.0	NP[b]	NP
Eriophyllum lanosum	0.1	0.6	NP	NP
Euphorbia spp.	2.3[a]	3.5	0.1[b]	0.4
Lappula occidentalis	0.2	0.7	NP	NP
Lepidium spp.	0.2	0.8	0.1	0.4
Mentzelia spp.	0.4	1.2	NP	NP
Pectocarya heterocarpa	3.1	10.0	2.4	9.0
Pectocarya platycarpa	1.5	7.2	3.3	12.9
Pectocarya recurvata	1.4[b]	7.9	2.1[a]	5.1
Plantago spp.	7.2[a]	12.5	1.7[b]	4.9
Porophyllum gracile	0.1	0.3	NP	NP
*Salsola kali**	1.2[a]	2.6	NP[b]	NP
Stylocline micropoides	3.8	12.3	NP	NP
Unknown 1	NP	NP	0.1	0.3
Unknown 2	NP	NP	0.1	0.3
Unknown 3	NP[b]	NP	0.2[a]	0.6
Unknown 4	NP	NP	0.1	0.3
Unknown 5	0.1	0.4	NP	NP
Unknown 6	0.1	0.3	NP	NP
All seeds	62.2[a]	48.2	18.8[b]	37.8
All species	5.5[a]	2.5	2.8[b]	2.5
Native seeds	25.9[a]	38.1	16.1[b]	34.6
Native species	3.5[a]	2.0	1.9[b]	2.1
Exotic seeds	36.2[a]	24.3	2.7[b]	3.8
Exotic species	2.0[a]	0.8	0.9[b]	0.7