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Simulated photovoltaic solar panels alters the seed bank survival of desert annual plant species

Supporting Information

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Supporting Information - Methods

Supporting Methods I - Artificial photovoltaic installation. Thirty-two of these panels were installed in 2011 and were reallocated to this experiment in 2016, when we also installed four additional panels per site, for a total of twenty per site. We covered all panels with clear plastic sheeting (4 mm Coroplast, corrugatedplastics.net, New Jersey, USA) in summer 2016 to emulate the smooth surface of a PV panel and facilitate rainfall runoff. Within sites, plots were selected to minimize heterogeneity of substrate and slope; due to patchy distribution of annual species in shrub interspaces, plot locations were chosen non-randomly to contain threshold numbers of focal species, ensuring habitat conditions suitable for seed germination. All plots were established in areas where they would not be shaded by nearby shrubs or the infrastructure associated with nearby plots.

Supporting Methods II - Staining Assays. Formal assays were carried out during summer on seed recovered from packets collected the previous spring, with one exception: resource constraints delayed assay of the 2016 cohort collected in spring 2017 until the summer of 2018. However, staining results for this cohort do not suggest that additional storage time negatively affected seeds. Specifically, we found no differences in staining rate for *E. mohavense* cohorts recovered in 2017, and observed a higher staining rate for the 2016 *E. wallacei* cohort recovered in 2017. Before formal assays, intact seeds were imbibed in deionozized water for 24 hours. We prepared a 1% solution of 2,3,5-triphenyltetrazolium chloride and deionized water, and cut seeds longitudinally using a precision knife (Xacto #11 blade) to expose the embryo and pericarp. *E. wallacei* seeds were soaked in solution for 24 hours at 17º C, and *E. mohavense* seeds were soaked for 6 hours at 35º C. Within 1 h following soak, all exposed embryos were examined under a high-power stereoscope (SMZ800, Nikon Inc., Tokyo, Japan). The intensity and completeness of embryo staining varied among individuals as well as across species, so we classified seed according to presence or absence of stain. Individuals with completely white embryos were considered retained dead seed, and those exhibiting any stain were considered retained live seed (**Fig. 2b**). Effectiveness of seed viability assays may differ across species and thus similar methodological assessments should be performed to evaluate the accuracy of viability-based observations for individual plant species.

Supporting Methods III - Statistical Analysis. We built quasibinomial generalized linear models (GLMs) with logit link functions to evaluate retained seed pools and seed staining rates (version 1.2.5042, Rstudio, Boston, Massachusetts, USA). We used the Anova function in the car package (Fox and Weisberg 2011) to evaluate models and generate Type III p-values, and conducted post-hoc tests on estimated marginal means using the emmeans package (Lenth 2019).

In the GLM evaluating the retained seed pool (Fig. 2a, see C), the proportion of retained seed per packet was the response, and proportions were weighted by the number of seeds recovered from a given microhabitat and plot (combining seed of the same cohort where multiple packets were collected in the same location). Year, species, microhabitat, seed cohort, and all interactions were included as fixed effects; plot was not included as a blocking effect because blocks were incomplete. Although quasibinomial approaches are recommended to compensate for overdispersion (Carruthers *et al*., 2008), overdispersion could not be eliminated, so p-values should be regarded as approximate.

The GLM evaluating seed survival (Fig. 2a, see D) used stain presence on individual seeds as the response variable (stain present or absent). Fixed effects included year, species, microhabitat, seed cohort, and all interactions. To test for differences in seed bank survival by burial duration (2017 - one growing season, 2018 - two growing seasons) between the rare and common species (including differences across all treatments and within control plots only), we used a nonparametric Mann-Whitney U test on two medians using ranks of the sample data, as comparative datasets were not normal (e.g., W =0.52317, p-value = 0.00112, Shapiro-Wilk normality test). To test for differences in seed bank survival across microhabitats by burial duration (2017 - one growing season, 2018 - two growing seasons), we used a Kruskal-Wallis test (with Dunn's multiple comparison post hoc test) on the equality of medians, as these datasets were also not normal (Shapiro-Wilk normality test).

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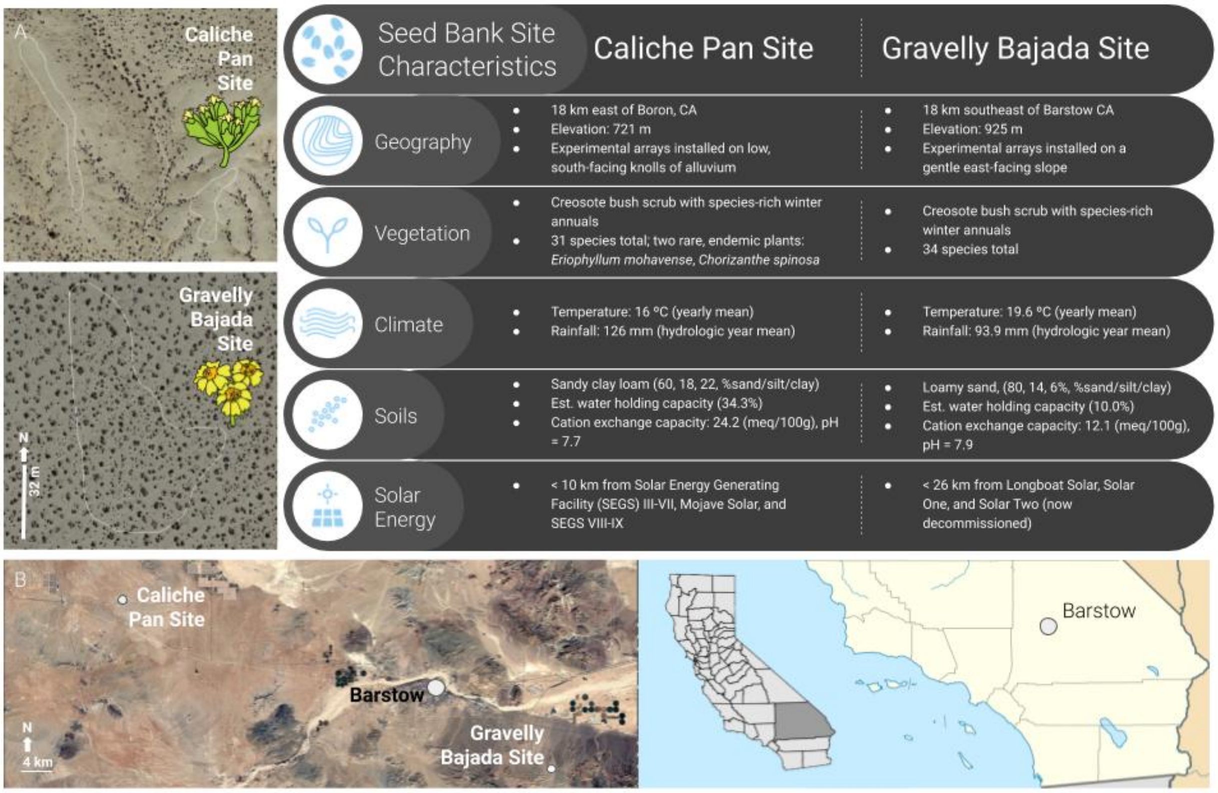

Figure S1. Site-level maps and characteristics of the Caliche Pan and Gravelly Bajada Sites in the Western Mojave Desert, California, USA (A - Google Earth, 222 m alt.; B - Landsat/Copernicus, 721 m alt.).

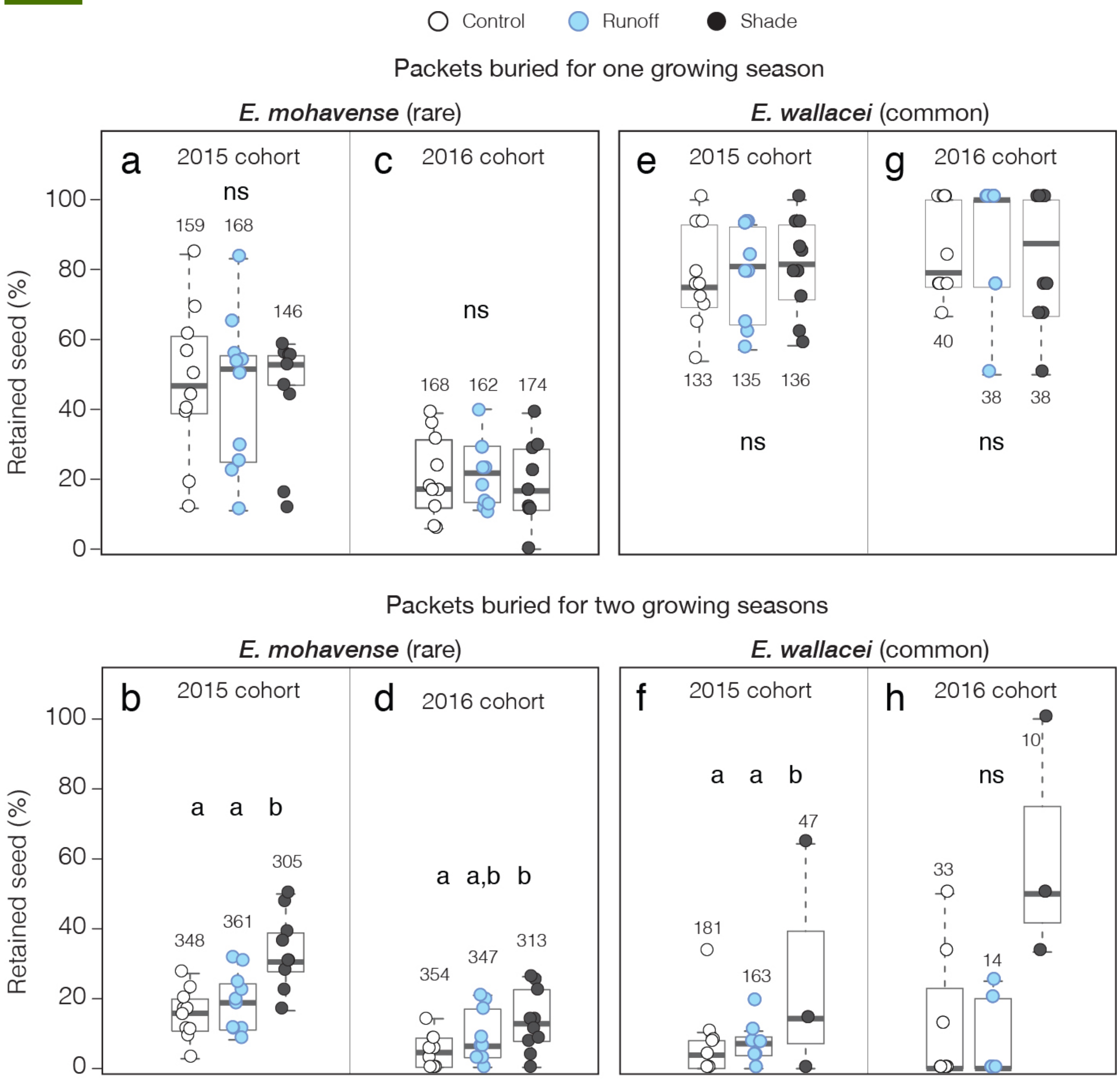

Figure S2. The retained seed pool from seed bank packets collected in 2017 (top row) and 2018 (bottom row). Percentages of retained, intact *E. mohavense* seed are shown in (a, b) for the 2015 seed cohort, and (c, d) for the 2016 seed cohort. Percentages of retained *E. wallacei* seed are shown in (e, f) for the 2015 seed cohort, and (g, h) for the 2016 seed cohort. Data points overlaid on boxplots show the number of packets collected from each microhabitat, and the numbers above each boxplot show the total number of seeds recovered from collected packets. Where letters above boxplots differ, the percentages of retained seed recovered were significantly different at the p <0.05 level. Retained seed pools broken down by species, cohort, and microhabitat are provided in Table S3.

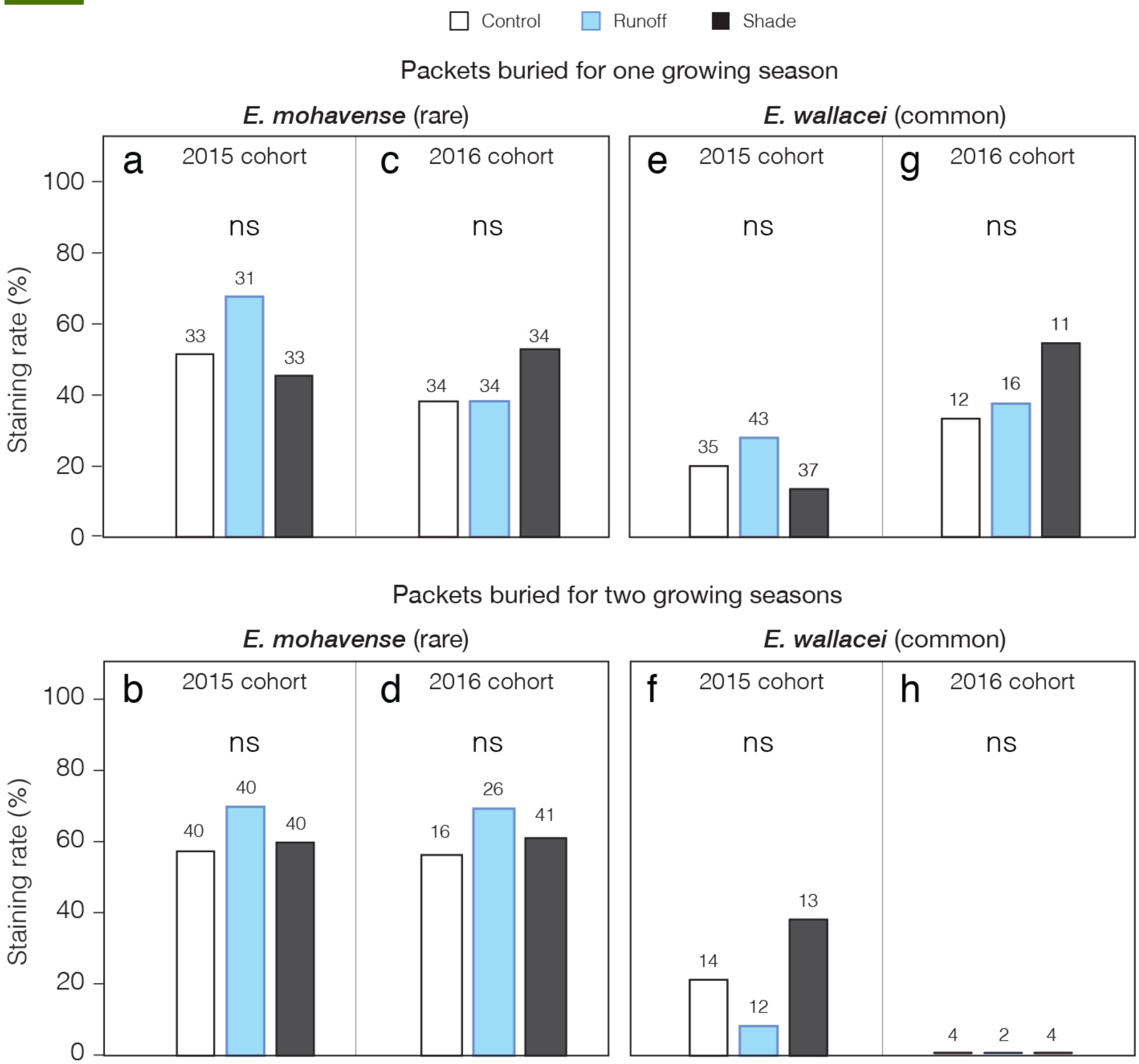

Figure S3. Staining rate (%) for the subsets of retained seed from packets collected in 2017 (top row) and 2018 (bottom row); percentages of stained *E. mohavense* seed are shown in (a, b) for the 2015 seed cohort, and (c, d) for the 2016 seed cohort. Percentages of stained *E. wallacei* seed are shown in (e, f) for the 2015 seed cohort and (g, h) for the 2016 seed cohort. Numbers above bar plots represent the total number of intact seeds subjected to tetrazolium assays. Final seed bank survival (%) is calculated by multiplying the retained seed pool by the proportion (i.e., decimal form of the percent) of the staining rate (see Supplementary Information, Table S5 for full seed bank survival calculations).

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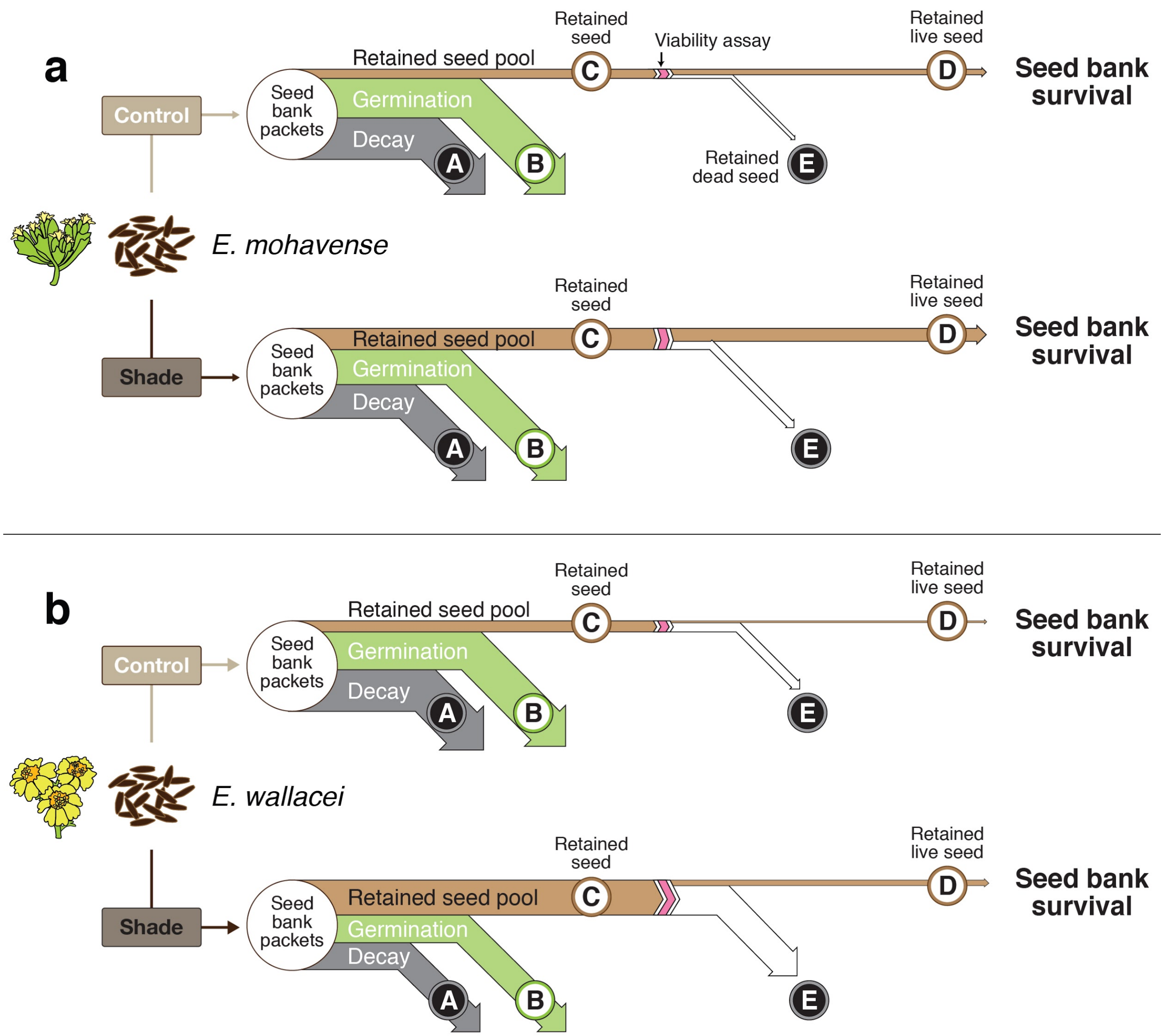

Figure S4. The seed bank survival model showing empirical seed bank pools and types in the Control and Shade microhabitats for (a) *E. mohavense* and (b) *E. wallacei* (averaged across cohorts for each species) after two years of burial. We observed higher seed retention in the Shade compared to the other two microhabitats (we show only Shade and Control flows here; flows in the Runoff microhabitat are very similar to Control flows). We cannot confidently partition decayed seed (A) from germinated seed (B) in the expended seed pool (due to the delay between the winter annual germination period and collection of packets in spring), so we visualize these flows as equivalent in size. Flows exiting the staining assay (pink chevron) visualize the percentage of live seed for a subset of the retained seed pools (C) exposed to staining assays.

Table S1. Allocation of 2015 and 2016 seed cohorts to seed bank packets by species.

	Species	Seed cohort	Number of seed bank packets	Number of seeds per packet	Total seeds
a)	*E. mohavense*	2015	90	18	1620
		2016	180	9	1620
b)	*E. wallacei*	2015	90	14	1260
		2016	180	2	360

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Table S2. Sample sizes for packets recovered at the (a) caliche pan (*E. mohavense*) and (b) gravelly bajada (*E. wallacei*) site.

	Year collected	Seed cohort	Microhabitat	Total seeds	Total packets
(a) *E. mohavense*					
	2017	2015	Control	159	10
			Runoff	168	10
			Shade	146	9
		2016	Control	168	19
			Runoff	162	20
			Shade	174	20
	2018	2015	Control	348	20
			Runoff	361	20
			Shade	305	17
		2016	Control	354	40
			Runoff	347	40
			Shade	313	34
(b) *E. wallacei*					
	2017	2015	Control	133	10
			Runoff	135	10
			Shade	136	10
		2016	Control	40	21
			Runoff	38	20

		Shade	38	20
2018	2015	Control	181	14
		Runoff	163	12
		Shade	47	4
	2016	Control	33	18
		Runoff	14	8
		Shade	10	5

Table S3. Average retained seed pool for each species broken down by year of packet collection, seed cohort, and microhabitat. Rows where packets were collected at less than 10 plots indicate a loss of packets in the field. Rabbits were observed chewing the fabric and were the likely culprits of their disappearance (Tanner, pers. observ.).

	Species	Year packets collected	Seed Cohort	Microhabitat	Number of plots	Number of seeds recovered	Retained seed pool	Retention rate
a)	***E. mohavense***	2017	2015	Control	10	159	74	0.47
				Runoff	10	168	75	0.45
				Shade	9	146	65	0.45
			2016	Control	10	168	34	0.20
				Runoff	10	162	35	0.22
				Shade	10	174	32	0.18
		2018	2015	Control	10	348	53	0.15
				Runoff	10	361	68	0.19
				Shade	9	305	99	0.32
			2016	Control	10	354	16	0.05
				Runoff	10	347	30	0.09
				Shade	10	313	44	0.14
b)	***E. wallacei***	2017	2015	Control	10	133	103	0.77
				Runoff	10	135	107	0.79
				Shade	10	136	110	0.81
			2016	Control	10	40	34	0.85
				Runoff	10	38	34	0.89
				Shade	10	38	32	0.84

2018	2015	Control	9	181	17	0.09
		Runoff	7	163	13	0.08
		Shade	3	47	13	0.28
	2016	Control	7	33	5	0.15
		Runoff	5	14	2	0.14
		Shade	3	10	5	0.50

Table S4. Average seed staining rates for each species broken down by year of packet collection, seed cohort, and microhabitat.

	Species	Year packets collected	Seed Cohort	Microhabitat	Number of seeds assayed	Retained live seed pool	Staining rate
a)	***E. mohavense***	2017	2015	Control	33	17	0.52
				Runoff	31	21	0.68
				Shade	33	15	0.45
			2016	Control	34	13	0.38
				Runoff	34	13	0.38
				Shade	34	18	0.53
		2018	2015	Control	40	23	0.58
				Runoff	40	28	0.70
				Shade	40	24	0.60
			2016	Control	16	9	0.56
				Runoff	26	18	0.69
				Shade	41	25	0.61
b)	***E. wallacei***	2017	2015	Control	35	7	0.20
				Runoff	43	12	0.28
				Shade	37	5	0.14
			2016	Control	12	4	0.33
				Runoff	16	6	0.38
				Shade	11	6	0.55
		2018	2015	Control	14	3	0.21
				Runoff	12	1	0.08

	Shade	13	5	0.38
2016	Control	4	0	0
	Runoff	2	0	0
	Shade	4	0	0

Table S5. Retained seed pools, staining rates, and calculated seed bank survival (%) from field data. (a) Empirical values by year and species (averaged across cohorts and microhabitats); (b) empirical values by year and microhabitat (averaged across species and cohorts). Retained seed pools and seed staining rates broken down by species, year, cohort, and microhabitat are provided in Tables S3 and S4.

	Year collected	Retained seed pool	Staining rate	Seed bank survival
a) By species, all microhabitats combined				
E. mohavense	2017	32.7%	49.0%	16.7%
E. wallacei	2017	82.7%	31.1%	26.1%
E. mohavense	2018	15.6%	62.3%	9.8%
E. wallacei	2018	20.7%	11.4%	2.2%
b) By microhabitat, both species combined				
Control	2017	57.3%	35.8%	18.9%
Runoff	2017	58.7%	42.8%	23.5%
Shade	2017	57.0%	41.6%	21.7%
Control	2018	11.1%	33.8%	3.3%
Runoff	2018	12.4%	36.9%	5.0%
Shade	2018	31.0%	39.9%	9.7%