

# Islands of Fertility: A Byproduct of Grazing?

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## ABSTRACT

Empirical work in arid shrubland systems has documented a distinct spatial pattern of soil nutrient distribution, with higher concentrations of nutrients under shrub canopies compared to bare ground interspaces between shrubs. This “fertile island” pattern is considered characteristic of arid ecosystems. However, recent work at a desertified shrubland site reported no island of fertility pattern for nitrogen inside a long-term grazing enclosure despite a strong fertile island pattern outside the enclosure, leading to a hypothesis that the pattern may be associated with grazing. In this paper we examine this hypothesis in two ways. First, we collected soil nitrogen data inside and outside two long-term livestock enclosures. Second, we examined published work on the fertile island pattern for nitrogen, phosphorus and carbon, and its association with livestock grazing. At the field sites, there was a strong fertile island pattern for soil nitrogen in the grazed area outside each enclosure but no fertile island pattern in the ungrazed area inside the fence. From the literature, we identified 49 studies, which represent 99 cases that examine differences in soil nutrients under

and between shrubs (that is, tests of the fertile island pattern). In 92 cases, fertile islands were present for at least one of the nutrients. All cases where livestock grazing was present exhibited fertile island patterns for nitrogen and most did so for carbon and phosphorus. In contrast, fertile islands were less consistent where livestock grazing was absent; all nine cases that had been ungrazed for more than 30 years did not exhibit fertile islands for nitrogen. Our empirical data and literature review suggest that the fertile island pattern may be an artifact of grazing rather than an inherent property of arid shrublands. Further, we suggest that the grazing history of a site needs to be explicitly considered when documenting spatial patterns of soil nutrients in arid systems. This has significant implications for our understanding of soil nutrient dynamics in arid systems, the management of rangelands, and the potential for reversal of desertification.

**Key words:** arid systems; desertification; fertile islands; livestock; soil nutrient patterns; shrublands.

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## INTRODUCTION

Fertile islands under shrub canopies are considered to be a characteristic pattern of desert shrublands; many soil nutrients, such as nitrogen, phosphorus, and carbon, are found in significantly higher concentrations under shrub canopies, compared to adjacent intershrub spaces (Garcia-Moya and McKell 1970; Tiedemann and Klemmedson 1986; Belsky and others 1989; Schlesinger and others

1990; Rostagno and others 1991; Moro and others 1997). Islands of fertility are hypothesized to form due to a combination of biotic and abiotic processes, including litter fall and decomposition (Charley and West 1977), atmospheric deposition (Garner and Steinberger 1989; Fenn and others 2003), aeolian processes (Li and others 2008), surface runoff (Parsons and others 1992; Schlesinger and others 1999), stemflow (Whitford and others 1997), and microbial activity (Charley and West 1977; Garner and Steinberger 1989). These mechanisms are thought to combine to create feedback loops that reinforce high nutrient levels under shrubs (Garner and Steinberger 1989; Schlesinger and Pilmanis 1998).

Fertile islands are also present in arid grassland sites that have been desertified recently; such sites have undergone a vegetation shift from grassland to shrubland condition, often as a consequence of overgrazing and climate change (Reynolds and others 2007). During this mode of desertification, as grass cover declines, soil nutrients are postulated to be reorganized via wind and water erosion into isolated pockets under the canopies of invading shrubs (Schlesinger and others 1990, 1996). Erosion, runoff, and lower microbial activity in bare ground intershrub areas prevent nutrient accumulation between shrubs (Kidron 2009; Li and others 2009). Conceptual models of desertification point to the increased spatial heterogeneity of soil properties as a key threshold in the desertification process (Schlesinger and others 1990; Cross and Schlesinger 1999) leading to a shift between alternate stable states (Westoby and others 1989; D'Odorico and others 2012). It is hypothesized that poor soil nutrient availability between shrubs prevents the recovery of grasses (Schlesinger and others 1990; D'Odorico and others 2007) leading to the irreversibility of desertification.

We recently quantified soil nutrient spatial patterns at a long-term livestock enclosure in southeastern Arizona (Allington and Valone 2010). This desertified site was experiencing reversal of desertification; after more than 40 years of rest from grazing perennial grass cover had increased significantly in intershrub areas (Allington and Valone 2010). Outside the grazing fence at this site, there was a strong fertile island pattern for nitrogen and organic carbon. But inside the fence, we found no significant difference in these nutrients under shrub canopies and in bare ground intershrub areas (Allington and Valone 2010). The contrasting soil nutrient patterns on either side of a grazing enclosure fence suggest that livestock grazing itself may play a role in the creation or perpetuation of this pattern.

Here, we evaluate the hypothesis that the fertile island pattern is associated with livestock grazing. This hypothesis allows us to make two predictions: (i) soil nutrients will be higher under shrub canopies compared to intershrub locations in shrubland systems exposed to livestock grazing; (ii) removal of livestock grazing will reduce the difference in soil nutrient levels between shrub canopies and intershrub locations. Based on this hypothesis, we predict that the difference in soil nutrient levels between canopy and intercanopy locations will decline with increasing time since livestock removal. Further, we predict that with sufficient time, there will be no significant difference in canopy–intershrub nutrients in ungrazed sites; the fertile island pattern will disappear.

To examine these predictions we collected data at two long-term enclosure sites that vary in vegetation structure and history. One is a desert shrubland with no evidence of recent desertification whereas the other is an arid grassland with scattered shrubs.

We also evaluate the predictions of the hypothesis by reviewing published data on spatial soil nutrient patterns in shrubland systems. Although the island of fertility pattern is considered characteristic of arid shrubland systems, empirical work documenting this pattern lacks a critical review. Particularly, the association between the fertile island pattern and the grazing history of a site has never been explicitly considered. This is somewhat surprising, given that livestock grazing is common in arid systems (Fleischner 1994) and livestock have the potential to significantly impact the physical and chemical properties of the soil (Snyman and Du Preez 2005; Castellano and Valone 2007; Allington and Valone 2010). Furthermore, in addition to removing biomass, livestock also trample (Abdel-Magid and others 1987) and compact soil, which can lead to decreased water infiltration (Thurow and others 1988; Castellano and Valone 2007) and increased runoff and erosion (Abrahams and others 1995). Although the severity of these effects depends largely on site conditions and grazing management practices (Reynolds and others 2007), these physical changes have the potential to drastically impact the accumulation and spatial distribution of nutrients in the soil.

## METHODS

We collected soil nutrient data from two long-term livestock enclosure sites in southeastern Arizona. One site is an arid grassland and the other is an historical shrub desert. At each site, we collected

cross-fence data (grazed and ungrazed sides of the fence) from both under shrub canopies and at intershrub spaces to test the hypothesis that long-term rest from grazing results in a loss of the fertile island pattern.

## Field Sites

The desert shrubland site (Site A) is a 20 ha livestock enclosure established in 1948 within the Walnut Gulch Experimental Watershed near Tombstone, AZ. United States General Land Office surveyor notes from the late 1800s describe the site as a desert shrubland and so we assume this site is an historical desert shrubland, at least over the timescales relevant to management. Soils are a gravelly loam of the Luckyhills series (Natural Resource Conservation Service 2003) and there is no noticeable biological or physical crust formation. Precipitation averages approximately 36 cm/year. The area outside the fence is open to livestock grazing, although livestock density is very low.

The dominant shrub is *Larrea tridentata*. To quantify the vegetation, we established 15 parallel, 20 m transects at least 5 m apart on each side of, perpendicular to, and at least 5 m from, the fenceline. We recorded canopy cover of shrub and basal cover of perennial grass and bare ground every 10 cm for a total of 200 points per transect ( $n = 3,000$  points per treatment), which we converted to percent cover. Shrub cover did not differ across the fence (50% inside and 62% outside;  $P = 0.08$ ,  $V = 28.5$ , Wilcoxon matched pairs test). We encountered only one intercept of perennial grass, *Muhlenbergia porteri*, which was located inside the fence. Data were collected in 2010 and thus the area inside the fence had been ungrazed by livestock for 62 years.

The arid grassland site (Site B) is the 3,160 ha Appleton-Whittell Research Ranch, near Elgin, AZ which has been ungrazed since 1968 (Bock and Bock 2000). The area on the opposite side of the fence is a privately held ranch that has been subject to rotational grazing by livestock for decades at a density of approximately one animal unit per 13 ha with a short grazing duration window (Bock and others 2007). The vegetation at this arid grassland site is dominated by a mix of native and exotic perennial grasses with scattered velvet mesquite shrubs (*Prosopis velutina* West.) (Bock and others 2007; Allington and Valone 2011). We have previously documented that perennial grass cover is significantly higher inside the fence (41%) than outside (30%), which is grazed, but grass is still the dominant vegetation outside the fence (Allington and Valone 2011). Shrub cover is less than 10% on

both sides of the fence, and does not differ significantly across the fence. Soils are a gravelly loam of the White House series (Breckenfeld and Robinett 2001) without crust formations and the average precipitation is approximately 48 cm/year. Data were collected in 2008 and thus areas inside the fence had been ungrazed by livestock for 40 years.

## Soil Sampling

To characterize fertile island patterns, we collected soil nitrogen data from paired soil samples: one from under a shrub canopy and one from 1 m north of the canopy at an intershrub bare ground location, from both inside and outside the grazing fence at each site. We collected  $n = 20$  pairs on each side of the fence at the shrubland site (Site A) and  $n = 10$  pairs on each side of the fence at the grassland site (Site B). Samples were collected from under creosote (*L. tridentata*) in the shrubland and from under velvet mesquite (*P. velutina*) in the grassland; shrubs were approximately equally sized on each side of the fence, and samples were collected from shrubs of similar size (approximately 2–3 m in height, and 1–1.5 m in canopy diameter). All samples were collected 15–25 m from the fence along relatively flat sections of fenceline to prevent downslope effects on patterns.

Each soil sample consisted of three soil cores (5 cm diameter  $\times$  5 cm deep) mixed together, from which a single sample was collected for analysis. Soil samples were analyzed for plant-available nitrogen ( $\text{NH}_4 + \text{NO}_3$ ). To account for potential cross-fence differences in bulk density due to trampling, soil samples were dried and sieved before analysis. Dried samples were sent to the Soil and Plant Testing Laboratory at the University of Missouri, Columbia, Missouri for analysis.

Paired shrub–intershrub samples were compared with paired  $t$ -tests. Cross-fence comparisons within a site were analyzed with  $t$ -tests. All analyses were conducted in the R environment for statistical computing (R Development Core Team 2009). We did not perform between-site comparisons due to differences in soils.

## Literature Review

We conducted a literature search for empirical studies documenting fertile islands in arid systems. We conducted searches in ISI Web of Knowledge and Google Scholar using the terms “island of fertility,” “fertile island,” “resource island,” and we restricted our search to arid or semi-arid ecosystems. We supplemented this with several papers that were cited by studies from our literature search. We selected only

empirical studies that made explicit comparisons of shrub versus intershrub soil nutrient values as well as studies that documented fertile islands using geostatistics or interpolation methods that included samples from both under shrub canopies and in the open. We excluded studies that only examined soil nutrients under shrub canopies (without an intershrub comparison) or that compared only shrubland and grassland sites in general without intershrub samples.

The nutrients that occur in soil have been studied to varying degrees in the context of fertile islands. We focus on three: nitrogen, phosphorus, and carbon. We focus on these because they are the most commonly sampled and because nitrogen and phosphorus are often limiting in arid systems (West and Skujins 1978; Crawford and Gosz 1982; Schlesinger and others 1996; Cross and Schlesinger 2001). Soil nitrogen is most commonly quantified as total nitrogen (TN) or plant available nitrogen. In some cases the components of plant-available nitrogen ( $\text{NH}_4$  and  $\text{NO}_3$ ) are reported separately, and some cases report only their combined value ( $N_{\text{avail}}$ ). TN content of the soil is either assessed using total Kjeldahl nitrogen ( $\text{TKN} = \text{organic N} + \text{NH}_3$ ), or as total N ( $\text{TKN} + \text{NO}_3 + \text{NO}_2$ ). Phosphorous is assessed as total P, or in its plant-available form,  $\text{PO}_4$ . We consider pools of organic carbon, which were quantified as soil or total organic carbon (TOC), or as the proxy, soil organic matter (SOM).

Concentrations of soil nutrients are typically highest in surface soils (Charley and West 1975; Yang and others 2011). Studies that examine samples at multiple depths use various cutoff points between samples, but for the purposes of this review we only considered data from the shallowest sample, typically from the first 0 to 5 cm of soil.

For each study included in our review, we recorded the location (continent), identity of the shrub used (by genus), grazing history, the nutrients sampled, and whether the island of fertility pattern was detected for each nutrient examined.

### Fertile Island Effect Sizes

Research on fertile islands reveals significantly higher concentrations of nutrients under shrubs compared to bare ground, but the magnitude of difference is not discussed. To quantify an estimate of relative effect size of fertile islands in grazed versus ungrazed treatments we calculated response ratios (RR) of different nutrients for each case as:

$$\text{Response ratio (RR)} = \left[ \frac{\text{mean shrub canopy value}}{\text{mean intershrub value}} \right].$$

However, work on fertile islands does not make an *a priori* hypothesis for the magnitude of difference that should exist under different grazing regimes. Further, there are a lack of data regarding the RR for any site prior to the cessation of grazing and so we lacked confidence in statistical tests of differences in RR for grazed and ungrazed sites that would need to be treated as independent replicates. Although the natural log of the RR is often used in quantitative analyses (Hedges and others 1999), we chose not to perform inferential statistical analyses on transformed RR's obtained from the literature and instead simply report the untransformed RR (Hurlbert 2004). We calculated RR only for those studies that provided mean values of nutrients in the text (as opposed to simply providing figures); this conservative approach eliminated several cases (Table 2).

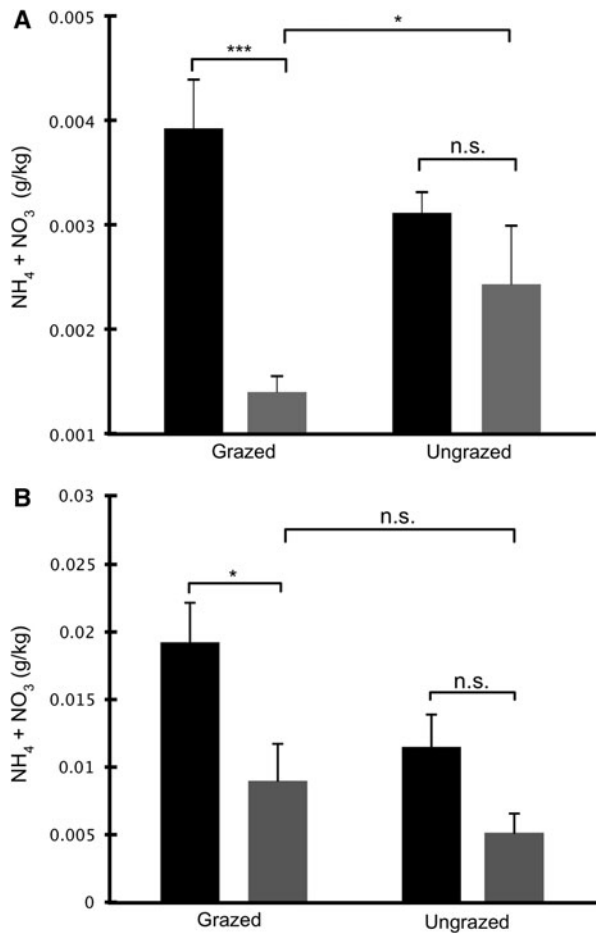
## RESULTS

### Field Sites

We found a strong island of fertility pattern outside the fence in the grazed areas in both the grassland and shrubland sites: soil nitrogen levels were significantly higher under shrub canopies compared to bare ground locations (Figure 1). However, inside each grazing enclosure, nitrogen levels did not differ between shrub canopy and bare ground locations; we did not find fertile islands inside the grazing enclosure fence at each site (Figure 1). At the shrub desert, soil nutrient levels in bare ground locations inside the fence were significantly higher than bare ground locations outside the fence, similar to the pattern identified by Allington and Valone (2010).

### Literature Review

To evaluate the generality of our findings in the previous section, we searched for corroborating evidence in the literature. We identified 99 examples of empirical tests of islands of fertility, which we define as "cases" in Table 1. These 99 cases come from the two sites presented here, (Sites A and B) plus 51 published studies, many of which include data from multiple sites, or data from under multiple shrub species and these were included as separate entries (cases) in Table 1. We excluded data collected from under juvenile or senescent shrubs, or from study sites that had experienced experimental manipulation (for example, nitrogen addition or fire) other than the presence or absence of livestock.



**Figure 1.** Mean ( $\pm$ SE) soil nitrogen levels at **A** an historic desert shrubland and **B** a non-desertified arid grassland with scattered shrubs. At each site, we compare paired under shrub (*black*) and between shrub (*gray*) locations outside (*grazed*) and inside (*ungrazed*) the livestock enclosure. \* $P < 0.05$ ; \*\*\* $P < 0.001$ . Grazed–ungrazed shrub comparisons at each site were non-significant.

Nitrogen was the most commonly assessed nutrient: researchers examined TN in 73 cases, whereas plant available nitrogen ( $\text{NH}_4$  and  $\text{NO}_3$ ) was examined in 40 cases (Table 1). Researchers examined soil carbon, via either TOC or SOM, in 62 cases. Total phosphorous (TP) was used in 37 cases, and plant-available phosphorous in 28 cases (Table 1).

The majority of the cases are from North America (71) and the second largest group was from Asia (10). Seven cases were from Australia, five were from Africa, five from South America, and three from Europe. Soil nutrient patterns were examined for 20 genera of shrubs (Table 1) from ten plant families, including: Fabaceae, Zygophyllaceae, Amaranthaceae, Asteraceae, Malvaceae, Cupressaceae, Rosaceae, Pinaceae, Aizoaceae, Combretaceae.

## Fertile Islands

The fertile island pattern is common but not ubiquitous. In 92 of the 99 cases, at least one soil nutrient was significantly higher under shrub canopies. With respect to each nutrient, a fertile island for TN was present in 62 of 73 cases (85%); for plant available nitrogen in 29 of 40 cases (73%); for carbon, the fertile island pattern was present in 52 of 62 cases (84%). For measures of phosphorus, the pattern was present in 22 of 37 cases (73%) that measured total P and 25 of 28 cases (89%) that measured  $\text{PO}_4$ .

## Association of Nutrient Patterns with Grazing History

We were able to obtain information on the grazing status for 52 of the 99 cases in our literature review (Table 1). Twenty-eight sites were grazed at the time of the study (cases 1–28 in Table 1). Four sites had been ungrazed for 5 years or less (cases 76–79). In 13 cases, grazing was absent for 10–30 years. Seven cases had been ungrazed for over 40 years (cases 93–99). Grazing history was not specified in almost half of the studies (cases 29–75).

A fertile island pattern was present for nitrogen in all 28 cases where grazing was ongoing. Twenty-five of these grazed cases also tested for carbon and all 25 exhibited the fertile island pattern for soil carbon. Of the 17 grazed cases that tested for phosphorous, a fertile island pattern was found for at least one of the measures of phosphorous in 15 of the cases (Table 1).

In the 42 cases with no information on grazing, fertile islands were common but not ubiquitous. Nitrogen islands were present in 35 of 42 of these cases (83%) whereas carbon islands occurred in 18 of 24 cases (75%). Only 18 of these cases examined phosphorous and the fertile island was present in 12 (67%).

Fertile island patterns were even less common at sites without current livestock grazing (cases 74–95 in Table 1). For nitrogen, the 13 cases in which livestock had been removed for less than 30 years exhibited a fertile island pattern whereas the fertile island pattern was found in only two of eleven cases in which livestock had been absent for at least 30 years. For carbon, a fertile island was present in six of six cases where livestock has been removed for less than 30 years but was absent in two of eight cases where livestock had been absent for at least 30 years. In contrast, livestock had less effect on phosphorus fertile islands: approximately two thirds of ungrazed sites had higher concentrations

Table 1. Empirical Tests of the Island of Fertility Pattern Collected in Our Literature Review

Case	Grazing status	Nitrogen				Carbon			Phosphorous		Shrub Genus	Continent	Mean annu. precip. (mm) <sup>1</sup>	References
		TN	NH <sub>4</sub>	NO <sub>3</sub>	N <sub>avail</sub>	TOC	SOM	TP	P <sub>avail</sub>					
										Y				
1	Grazed	Y		Y		Y		Y		<i>Acacia</i>	Africa	400–500	Belsky and others (1989)	
2	Grazed	Y				Y				<i>Artemisia</i>	Asia	260–450	Li and others (2008a)	
3	Grazed	Y				Y				<i>Artemisia</i>	Asia	260–450	Li and others (2008a)	
4	Grazed	Y				Y				<i>Artemisia</i>	Asia	260–450	Li and others (2008a)	
5	Grazed	Y				Y				<i>Artemisia</i>	Asia	345	Qi and others (2010)	
6	Grazed	Y				Y				<i>Artemisia</i>	Asia	345	Qi and others (2010)	
7	Grazed	Y				Y		Y		<i>Multiple</i>	Asia	362	Su and others (2004)	
8	Grazed	Y				Y		N	N	<i>Acacia</i>	Australia	230	Facelli and others (2000)	
9	Grazed	Y				Y		N	N	<i>Acacia</i>	Australia	230	Facelli and others (2000)	
10	Grazed	Y				Y		Y	Y	<i>Acacia</i>	Australia	230	Facelli and others (2000)	
11	Grazed	Y				Y		Y	Y	<i>Acacia</i>	Australia	230	Facelli and others (2000)	
12	Grazed	Y				Y		Y	Y	<i>Acacia</i>	Australia	230	Facelli and others (2000)	
13	Grazed	Y				Y		Y	Y	<i>Acacia</i>	Australia	230	Facelli and others (2000)	
14	Grazed	Y				Y		Y	Y	<i>Cytisus</i>	Europe	1330	Escudero and others (2004)	
15	Grazed	Y				Y		Y		<i>Larrea</i>	North America	350	Allington and Valone (2010)	
16	Grazed				Y					<i>Larrea</i>	North America	360	This study; Site A	
17	Grazed				Y					<i>Prosopis</i>	North America	480	This study; Site B	
18	Grazed	Y				Y		Y	Y	<i>Artemisia</i>	North America	300	Charley and West (1975)	
19	Grazed	Y				Y		Y	Y	<i>Atriplex</i>	North America	300	Charley and West (1975)	
20	Grazed	Y				Y		N	Y	<i>Atriplex</i>	North America	154	Charley and West (1975)	
21	Grazed	Y				Y		N	Y	<i>Coleogyne</i>	North America	300	Charley and West (1975)	
22	Grazed	Y				Y		N	Y	<i>Coleogyne</i>	North America	300	Charley and West (1975)	
23	Grazed	Y				Y		Y	Y	<i>Atriplex</i>	North America	300	Charley and West (1975)	
24	Grazed	Y				Y		Y	Y	<i>Larrea</i>	North America	NA	García-Moya and Mckell (1970)	
25	Grazed	Y				Y				<i>Acacia</i>	North America	NA	García-Moya and Mckell (1970)	
26	Grazed	Y				Y		Y		<i>Artemisia</i>	North America	NA	Jackson and Caldwell (1993)	
27	Grazed	Y				Y		Y	Y	<i>Juniperus</i>	North America	250	Miwa and Reuter (2010)	
28	Grazed	Y				Y		Y		<i>Prosopis</i>	North America	370	Throop and Archer (2008)	
29	Not specified	Y				Y				<i>Prosopis</i>	North America	240	Ravi and others (2007)	
30	Not specified	Y						N	N	<i>Rushia</i>	Africa	~50	Stock and others (1999)	
31	Not specified	N						N	N	<i>Rushia</i>	Africa	~50	Stock and others (1999)	
32	Not specified	N						N	N	<i>Stoebertia</i>	Africa	~50	Stock and others (1999)	
33	Not specified	Y				Y		Y	Y	<i>Guitera</i>	Africa	350–650	Wezel and others (2000)	
34	Not specified	N						Y	Y	<i>Pinus</i>	Asia	450	Chen and others (2006)	
35	Not specified	Y		Y				Y	Y	<i>Haloxylon</i>	Asia	450	Chen and others (2007)	
36	Not specified	Y				Y		Y	Y	<i>Retama</i>	Europe	259	Moro and others (1997)	
37	Not specified					Y		Y	Y	<i>Retama</i>	Europe	218	Pugnaire and others (1996)	

Table 1. continued

Case	Grazing status	Nitrogen			Carbon			Phosphorous		Shrub Genus	Continent	Mean annu. precip. (mm) <sup>1</sup>	References
		TN	NH <sub>4</sub>	NO <sub>3</sub>	N <sub>avail</sub>	TOC	SOM	TP	P <sub>avail</sub>				
38	Not specified	Y								<i>Larrea</i>	North America	109	Bolling and Walker (2002)
39	Not specified	Y								<i>Larrea</i>	North America	109	Bolling and Walker (2002)
40	Not specified	Y								<i>Larrea</i>	North America	109	Bolling and Walker (2002)
41	Not specified	Y								<i>Larrea</i>	North America	109	Bolling and Walker (2002)
42	Not specified	N								<i>Larrea</i>	North America	109	Bolling and Walker (2002)
43	Not specified	Y								<i>Larrea</i>	North America	109	Bolling and Walker (2002)
44	Not specified	Y				N		N		<i>Artemisia</i>	North America	525	Burke and others (1989)
45	Not specified	Y				N		N		<i>Artemisia</i>	North America	525	Burke and others (1989)
46	Not specified	N				N		N		<i>Artemisia</i>	North America	525	Burke and others (1989)
47	Not specified		Y			N		Y		<i>Larrea</i>	North America	190	Butterfield and Briggs (2009)
48	Not specified	Y			Y					<i>Artemisia</i>	North America	100–250	Halvorson and others (1994)
49	Not specified	Y		Y	Y					<i>Artemisia</i>	North America	100–250	Halvorson and others (1997)
50	Not specified		Y		Y		Y			<i>Larrea</i>	North America	~200	Mccrackin and others (2008)
51	Not specified		N		Y		Y			<i>Larrea</i>	North America	~200	Mccrackin and others (2008)
52	Not specified	Y				Y				<i>Prosopis</i>	North America	380	Perroni-Ventura and others (2010)
53	Not specified	Y				Y				<i>Parkinsonia</i>	North America	380	Perroni-Ventura and others (2010)
54	Not specified		Y			Y				<i>Prosopis</i>	North America	~345	Schade and Hobbie (2005)
55	Not specified		Y		Y			Y		<i>Larrea</i>	North America	240	Schlesinger and others (1996)
56	Not specified		Y		Y			Y		<i>Larrea</i>	North America	240	Schlesinger and others (1996)
57	Not specified				N			Y		<i>Larrea</i>	North America	NA	Schlesinger and others (1996)
58	Not specified				Y			Y		<i>Larrea</i>	North America	NA	Schlesinger and others (1996)
59	Not specified				N			Y		<i>Artemisia</i>	North America	NA	Schlesinger and others (1996)
60	Not specified	Y					Y			<i>Ambrosia</i>	North America	188	Thompson and others (2005)
61	Not specified	Y					Y			<i>Coleogyne</i>	North America	188	Thompson and others (2005)
62	Not specified	Y					Y			<i>Larrea</i>	North America	188	Thompson and others (2005)
63	Not specified	Y		Y						<i>Prosopis</i>	North America	~65	Virginia and Jarrell (1983)
64	Not specified	Y		Y						<i>Prosopis</i>	North America	~65	Virginia and Jarrell (1983)
65	Not specified	Y		Y						<i>Prosopis</i>	North America	~65	Virginia and Jarrell (1983)
66	Not specified	Y		Y						<i>Prosopis</i>	North America	~65	Virginia and Jarrell (1983)
67	Not specified	Y		N						<i>Prosopis</i>	North America	~65	Virginia and Jarrell (1983)
68	Not specified	Y		Y						<i>Prosopis</i>	North America	~65	Virginia and Jarrell (1983)
69	Not specified	Y		Y						<i>Prosopis</i>	North America	65	Virginia and Jarrell (1983)
70	Not specified	Y		Y				Y		<i>Prosopis</i>	North America	~65	Virginia (1986)
71	Not specified	Y	Y							<i>Artemisia</i>	North America	296	Wikeem and Pitt (1982)
72	Not specified	Y								<i>Prosopis</i>	North America	234	Wright and Honea (1986)
73	Not specified				Y		Y			<i>Portieria</i>	South America	85	Gutierrez and others (1993)
74	Not specified	Y				Y				<i>Prosopis</i>	South America	300–500	Mazzarino and others (1991)

Table 1. continued

Case	Grazing status	Nitrogen				Carbon			Phosphorous	Shrub Genus	Continent	Mean annu. precip. (mm) <sup>1</sup>	References	
		TN		NO <sub>3</sub>		TOC SOM								TP
		NH <sub>4</sub>	NO <sub>3</sub>	N <sub>avail</sub>	TOC	SOM	TP							
75	Not specified	Y			Y	Y		Y	<i>Larrea</i>	South America	170	Rostagno and others (1991)		
76	Ungrazed for unk time	Y			Y	Y		Y	<i>Atriplex</i>	North America	154	Charley and West (1975)		
77	Ungrazed 2 years	Y			Y	Y			<i>Atriplex</i>	Australia	380	Rixon (1971)		
78	Ungrazed ~5 years <sup>2</sup>	Y	Y					Y	<i>Prosopis</i>	North America	240	Li and others (2008b)		
79	Ungrazed ~5 years <sup>2</sup>	Y	Y					Y	<i>Prosopis</i>	North America	240	Li and others (2009)		
80	Ungrazed 10 years	Y	Y					Y	<i>Artemisia</i>	North America	NA	Ryel (1996)		
81	Ungrazed 10 years	Y	Y					Y	<i>Artemisia</i>	North America	NA	Ryel (1996)		
82	Ungrazed 10 years	N	Y					Y	<i>Artemisia</i>	North America	NA	Ryel (1996)		
83	Ungrazed 13 years	Y				Y		Y	<i>Caragana</i>	Asia	366	Zhao and others (2007)		
84	Ungrazed 13 years	Y				Y		N	<i>Salix</i>	Asia	366	Zhao and others (2007)		
85	Ungrazed ~20 years <sup>2</sup>	Y						Y	<i>Larrea</i>	North America	250	Gross and Schlesinger (1999)		
86	Ungrazed ~20 years <sup>2</sup>	Y						Y	<i>Larrea</i>	North America	250	Gross and Schlesinger (2001)		
87	Ungrazed ~20 years <sup>2</sup>	Y	Y		Y	Y			<i>Larrea</i>	North America	250	Kieft and others (1998)		
88	Ungrazed ~20 years <sup>2</sup>	Y				Y		Y	<i>Larrea</i>	North America	250	Schlesinger and others (1996)		
89	Ungrazed ~30 years <sup>2</sup>	Y			Y	Y		N	<i>Prosopis</i>	North America	330	Tiedemann and Klemmedson (1973)		
90	Ungrazed ~30 years <sup>2</sup>	Y			Y	Y		N	<i>Prosopis</i>	North America	330	Klemmedson and Tiedemann (1986)		
91	Ungrazed 30 years	N	Y				Y		<i>Prosopis</i>	South America	329	Abril and others (2009)		
92	Ungrazed 30 years	N	N				Y		<i>Larrea</i>	South America	329	Abril and others (2009)		
93	Ungrazed 40 years								<i>Larrea</i>	North America	480	This study; Site B		
94	Ungrazed ~50 years <sup>2</sup>	N	N				Y	Y	<i>Larrea</i>	North America	200	Titus and others (2002)		
95	Ungrazed ~50 years <sup>2</sup>	N	N					Y	<i>Larrea</i>	North America	235	Whitford and others (1997)		
96	Ungrazed ~50 years <sup>2</sup>	N			N			N	<i>Larrea</i>	North America	240	de Soyza and others (1997)		
97	Ungrazed ~50 years <sup>2</sup>	N			Y			Y	<i>Larrea</i>	North America	240	de Soyza and others (1997)		
98	Ungrazed 50 years	N			N				<i>Larrea</i>	North America	350	Allington and Valone (2010)		
99	Ungrazed 60 years				N				<i>Prosopis</i>	North America	360	This study; Site A		

Full references for studies cited in this table are available in Appendix A (supplementary material).

Cases represent individual tests of nutrient concentrations under shrub canopies compared to adjacent bare ground locations. (Y) indicates that the nutrient concentrations under shrub canopies are significantly higher than in intershrub soil; (N) indicates that the nutrient concentrations under shrub canopies are not significantly different from intershrub soil.

TN = total nitrogen; N<sub>avail</sub> = NH<sub>4</sub> + NO<sub>3</sub>; TOC = total organic carbon; SOM = soil organic matter; TP = total phosphorous; P<sub>avail</sub> = PO<sub>4</sub>.

<sup>1</sup>Precipitation data based on values reported in the manuscript, where applicable. Studies without precipitation data available are listed as NA.

<sup>2</sup>Estimates based on information provided in the citation or personal communication with the author. The number represents the minimum amount of time that livestock had been removed from the site.



**Table 2.** Mean Canopy and Intershrub Values and RR for TN, TOC, TP, and Available Phosphorous (P<sub>avail</sub>) in Grazed and Ungrazed Cases

	TN (mg/kg)			TOC (mg/kg)			TP (mg/kg)			P <sub>avail</sub> (mg/kg)		
	Canopy	Intershrub	RR	Canopy	Intershrub	RR	Canopy	Intershrub	RR	Canopy	Intershrub	RR
<b>Grazed</b>												
Belsky and others (1989)	-	-	-	36000.00	20000.00	1.75	13.60	5.00	2.72	-	-	-
Li and others (2008a)	125.00	65.00	1.92	-	-	-	-	-	-	-	-	-
Li and others (2008a)	45.00	25.00	1.80	-	-	-	-	-	-	-	-	-
Li and others (2008a)	45.00	35.00	1.29	-	-	-	-	-	-	-	-	-
Qi and others (2010)	800.00	320.00	2.50	900.00	380.00	2.37	-	-	-	-	-	-
Qi and others (2010)	360.00	250.00	1.44	4250.00	2250.00	1.89	-	-	-	-	-	-
Su and others (2004)	340.00	234.00	1.45	3740.00	2620.00	1.43	155.00	123.00	1.26	-	-	-
Escudero and others (2004)	3900.00	3000.00	1.30	73000.00	47800.00	1.53	142.86	92.90	1.54	-	-	-
Allington and Valone (2010)	84.80	71.20	1.14	833.30	614.00	1.36	-	-	-	-	-	-
Charley and West (1975)	2330.00	1510.00	1.54	20200.00	13500.00	1.50	840.00	902.00	0.93	27.00	17.00	1.59
Charley and West (1975)	1740.00	1360.00	1.28	13000.00	11700.00	1.11	946.00	864.00	1.09	33.00	26.00	1.27
Charley and West (1975)	1700.00	1300.00	1.30	16000.00	10300.00	1.55	878.00	886.00	0.99	40.00	27.00	1.48
Charley and West (1975)	7200.00	580.00	12.41	9600.00	4500.00	2.13	566.00	574.00	0.99	15.00	7.00	2.14
Charley and West (1975)	1110.00	550.00	2.02	12600.00	3700.00	3.41	626.00	636.00	0.98	17.00	5.00	3.40
Charley and West (1975)	370.00	300.00	1.23	2300.00	2000.00	1.15	548.00	632.00	0.87	3.00	2.00	1.50
Site A	392.92	140.37	2.80	-	-	-	-	-	-	-	-	-
Site B	19.31	9.00	2.15	988.30	783.60	1.25	-	-	-	-	-	-
		Mean	2.35		Mean	1.72		Mean	1.26		Mean	1.90
		SEM	0.68		SEM	0.17		SEM	0.19		SEM	0.32
<b>Ungrazed</b>												
Charley and West (1975)	400.00	310.00	1.29	3900.00	1700.00	2.29	450.00	650.00	0.69	4.00	2.00	2.00
Rixon (1971)	1190.00	860.00	1.38	12240.00	7670.00	1.60	-	-	-	-	-	-
Zhao and others (2007)	140.00	100.00	1.40	2300.00	1600.00	1.44	160.00	130.00	1.23	9.01	7.75	1.16
Zhao and others (2007)	70.00	60.00	1.17	1200.00	1000.00	1.20	130.00	120.00	1.08	3.34	3.02	1.11
Gross and Schlesinger (1999)	16.47	14.51	1.14	-	-	-	312.16	304.16	1.03	71.91	62.65	1.15
Gross and Schlesinger (2001)	-	-	-	-	-	-	193.98	189.66	1.02	167.28	164.83	1.01
Tiedemann and Klemmedson (1973)	750.00	270.00	2.78	7300.00	2500.00	2.92	370.00	310.00	1.19	-	-	-
Tiedemann and Klemmedson (1986)	800.00	260.00	3.08	8000.00	3000.00	2.67	300.00	230.00	1.30	-	-	-
Site B	11.51	5.16	2.23	1023.00	678.00	1.51	-	-	-	-	-	-
Abril and others (2009)	2200.00	2600.00	0.85	24010.00	8900.00	2.70	-	-	-	-	-	-
Abril and others (2009)	2600.00	2600.00	1.00	18600.00	8900.00	2.09	-	-	-	-	-	-
Whitford and others (1997)	500.00	400.00	1.25	-	-	-	4.60	2.90	1.59	-	-	-
de Soyza and others (1997)	550.60	420.40	1.31	5800.00	4300.00	1.35	11.00	9.74	1.13	-	-	-
de Soyza and others (1997)	628.00	399.20	1.57	7900.00	4800.00	1.65	14.60	8.00	1.83	-	-	-
Allington and Valone (2010)	89.70	83.10	1.08	840.60	760.20	1.12	-	-	-	-	-	-

Table 2. continued

	TN (mg/kg)			TOC (mg/kg)			TP (mg/kg)			P <sub>avail</sub> (mg/kg)		
	Canopy	Intershrub	RR	Canopy	Intershrub	RR	Canopy	Intershrub	RR	Canopy	Intershrub	RR
Site A	311.97	243.59	1.28	-	-	-	-	-	-	-	-	-
		Mean	1.52		Mean	1.91		Mean	1.21		Mean	1.29
		SEM	0.17		SEM	0.19		SEM	0.10		SEM	0.18

Full references for studies cited in this table are available in Appendix A (supplementary material). Data come from cases in Table 1 in which the authors had provided means in a table or the text; studies with results presented only in figures were not included.

of phosphorous under shrub canopies, irrespective of time since livestock removal.

Our review identified nine cases in which nitrogen fertile islands were absent. Two came from Sites A and B, described above. The remaining seven cases come from four other long-term livestock enclosure sites: (i) the Ñacuñán Biosphere Reserve in Argentina (Abril and others 2009; case 90, 91 in Table 1); (ii) the Mojave Global Change Experiment Site (MGCE) in Nevada (case 92 in Table 1; Titus and others 2002), (iii) the Jornada Basin Long Term Experimental Research Program (Jornada) in New Mexico (cases 93–95 in Table 1; de Soyza and others 1997; Whitford and others 1997), and (iv) an enclosure located in the San Simon Valley in southeastern Arizona (case 96 in Table 1; Allington and Valone 2010).

### Magnitude of the Fertile Island Effect

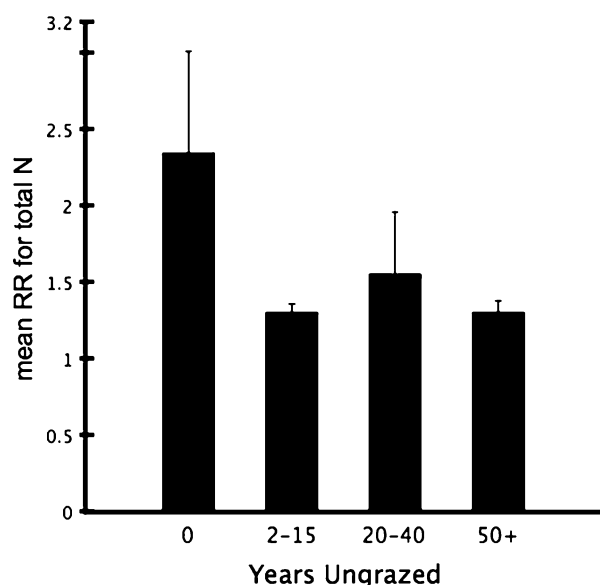
We were able to gather mean RR data from 16 grazed cases and 15 ungrazed cases for TN; 13 grazed cases and 12 ungrazed cases for carbon; nine grazed and 10 ungrazed cases for TP; and six grazed cases and five ungrazed cases for available phosphorous (Table 2).

RRs exhibited much variation but most (75/81) were greater than 1.0, indicating higher nutrient levels under shrubs compared to intershrub locations (Table 2). For nitrogen and available phosphorus, the mean RR was higher at sites subjected to ongoing grazing compared to ungrazed sites (nitrogen: grazed RR = 2.35, ungrazed RR = 1.52; available phosphorus: grazed RR = 1.90, ungrazed RR = 1.29). For TOC and total phosphorus, the presence or absence of grazing had no consistent effect on mean RR (Table 2).

We examined the effect of time since livestock removal on soil nitrogen patterns by categorizing ungrazed cases into three categories (2–15, 20–40, and > 50 years ungrazed) that contained a similar number of cases ( $n = 4, 6,$  and  $5,$  respectively). We plotted the mean RRs for these categories along with that from the  $n = 16$  grazed sites (0 years ungrazed) (Figure 2). The figure illustrates that the RR is lower in sites with no recent history of livestock grazing, although there is no discernable consistent decline in RR with time following livestock removal.

### DISCUSSION

In this study we investigate the relationship between grazing by livestock and spatial patterns of soil nutrients with respect to shrubs: islands of fertility. We find general support for the hypothesis



**Figure 2.** Mean ( $\pm$ SE) RR for TN for sites ungrazed for different periods of time. Values obtained from Table 2.

that the presence of livestock is associated with the fertile island pattern, and that long-term livestock exclusion is related to a decrease in the presence of fertile islands. All sites with ongoing grazing exhibited a fertile island pattern for at least one soil nutrient. In contrast, all sites that lack a fertile island pattern have been ungrazed for several decades.

The identification of several arid sites that lack a fertile island pattern is noteworthy because this pattern is considered characteristic of shrubland systems. What can explain the absence of fertile islands? We consider six possibilities. First, shrub morphology, size or age can influence litter accumulation under shrub canopies, and thus fertile island formation (de Soyza and others 1997; Butterfield and Briggs 2009). Creosote (*L. tridentata*) shrubs with a conical, upright canopy capture much less debris compared to hemispherical-shaped creosote with branches close to the ground (de Soyza and others 1997), which could affect the formation of fertile islands. In fact, de Soyza and others (1997) did not detect fertile islands for carbon under hemispherical shrubs. Thus, it is possible that studies did not detect islands of fertility because they had selected shrubs with an upright growth habit. However, examination of Table 1, as well as our new empirical data (Figure 1), does not support that explanation. For example, the creosote found at the sites used by Allington and Valone (2010) primarily exhibit an upright canopy; although they failed to detect islands of carbon or nitrogen under these shrubs inside the grazing

closure (case 96), we did detect strong fertile islands under similarly shaped creosote directly outside the fence in the grazed area (case 16). Our new data from an historical shrubland of creosote with upright canopies also exhibit a similar pattern; islands under conical shrubs in the grazed area but not under conical shrubs inside the enclosure (Figure 1A). We sampled from shrubs of similar sizes, and cross-fence data from similarly sized shrubs at the same sites are likely not vastly, systematically, different in age. In addition, although the carbon data from de Soyza and others (1997) support the shrub-shape hypothesis for carbon (that is, fertile islands for carbon were only found under the upright shrubs), soil nitrogen was not significantly higher under either upright or hemispherical canopies, both of which were sampled within a long-term grazing enclosure. Thus, it is unlikely that the patterns of presence and absence of fertile islands that we detected in our review could be solely attributed to differences in shrub size, morphology, or age.

A second possible explanation for the absence of fertile islands is that variation in soil nutrients across sites is due to seasonal fluctuations in nutrient availability. Soil nitrate and ammonium concentrations are particularly prone to fluctuation over time, depending on soil moisture, C:N ratios, and the mineralization and immobilization of organic nitrogen by microbes in the soil (Ryel and others 1996; Kieft and others 1998; Schade and Hobbie 2005). Indeed, this likely explains some variation in fertile islands in plant available nitrogen across sites. However TN, which is a much more temporally stable measure of soil nitrogen (Ryel and others 1996; Butterfield and Briggs 2009), was consistently found to be higher under shrubs across all sites, except those that had been ungrazed for many decades. There is little evidence of seasonality of fertile island pools in general (Reynolds and others 1999; Butterfield and Briggs 2009). Further, the data from Allington and Valone (2010) (Table 1) and our new data (Figure 1) come from paired cross-fence sites sampled at the same time. Thus, it is unlikely that the patterns that we detect in both our review and new data can be solely attributed to differences in the season of sampling, or seasonal variation in nutrient pools. Indeed, this is one of the inherent values of cross-fence studies.

A third possibility is that variation in islands of fertility is due to differences in the age or degree of weathering of soils across sites, particularly for TP patterns. Total soil phosphorous declines with increasing soil age and the relative concentrations

of labile and occluded fractions changes through time (Walker and Syers 1976; Selmants and Hart 2010). Shrub canopies have a greater influence on the spatial distribution of labile/biologically available phosphorous (Selmants and Hart 2010). Therefore, soil age could impact whether islands are detected because the proportion of available phosphorous will change with the age of the soil. This could also account for why islands are occasionally detected for one measure of phosphorous, but not another, and why the RRs for one measure are significantly higher in grazed cases but not the other measure (Table 2). However, this does not account for the association that we detect between soil nitrogen spatial patterns and the presence of livestock grazing.

Fourth, the presence or formation of biological soil crusts (BSCs) could contribute to elevated soil nutrients between shrubs. The organisms present in BSCs are capable of fixing both carbon and nitrogen, and the presence of the crusts can stabilize soil and slow erosion (Harper and Pendleton 1993; Johansen 1993; Belnap and others 2001). However, BSCs have also been found to decrease infiltration in some systems, depending on soil texture (Chamizo and others 2012). Disturbance of BSCs by livestock trampling could have complex impacts on soil nutrient cycling and hydrology (Belnap 2003) and the potential timescale for recovery of soil physical and chemical properties at a site. We cannot be certain about the presence or absence of BSCs at most of the cases in Table 1. However, these crusts are not present on either of the sites we sampled for this study, nor in the site from Allington and Valone (2010). Therefore the lack of fertile islands cannot be explained solely by the presence of BSCs.

A fifth possibility is that variation in the presence and magnitude of islands of fertility is linked to gradients in aridity across the study sites. Grazing and rainfall interact to influence the degree to which the canopy of desert shrubs facilitates the growth of forbs; facilitation in the presence of grazing is strongest in the most arid sites (Soliveres and others 2012). It is possible that the canopy effects of shrubs that contribute to fertile islands are also strongest in the most arid systems (for example, D'Odorico and others 2007), and that this is contributing to the association we detect with grazing (Table 1). However, again, we point to our three cross-fence studies that experience the same climate in both the grazed and ungrazed areas at each site and vary only in their grazing history. Increased precipitation could potentially enhance rates of recovery at certain sites, if rates of infil-

tration are greater than runoff. It would be worthwhile to perform future experimental studies to investigate the interactions of aridity and grazing on the magnitude of this fertile island pattern and how long it may take for the pattern to be lost, post-grazing cessation.

Finally, it is also possible that variation in the presence of fertile islands across sites could be due to differences in shrub species. However, the data from Allington and Valone (2010) as well data from sites A and B here, all consider the same species of shrub across a grazing fence (grazed versus long-term ungrazed). The same genera (*Larrea*, *Prosopis*) that failed to exhibit islands inside the fence exhibited fertile islands outside the fence in grazed locations (Table 1). Further, *Prosopis* is a nitrogen-fixing species, and might be expected to have a greater degree of island formation; nevertheless, we did not detect islands under *Prosopis* in the ungrazed treatment (Figure 1). It is unlikely that the pattern of fertile island occurrence is solely due to differences in shrub species across sites. Thus we conclude that time since livestock grazing is likely an important mechanism associated with the lack of the fertile island pattern.

Allington and Valone (2010) postulated that when livestock are removed from highly degraded sites, there is a slow release from soil compaction, resulting in an increase in infiltration of water into the soil (see also Castellano and Valone 2007). Over time, an increase in infiltration can lead to both a decrease in erosion and increased microbial activity due to higher soil moisture (Steffens and others 2008). Lower erosion rates should promote the retention of accumulated nutrients on the surface. Over many decades, soil nutrient levels between shrubs increase to the point that there is no longer a significant difference between under canopy and intershrub soil (Figure 1). We suggest that this same mechanism may explain the lack of island of fertility patterns at other long-term livestock exclosures. We propose that the fertile island pattern is lacking in long-term livestock exclosures because nutrients have accumulated in the soil between shrubs to the point that there is no longer a difference between shrub and intershrub samples.

A second prediction of the hypothesis is that the strength of the fertile island pattern should decline with time since livestock removal. One approach to evaluating this prediction is to compare RRs from sites currently grazed to those from ungrazed sites. Examination of Table 2 reveals that for nitrogen and available phosphorus, RRs for the grazed sites tend to be higher than those for ungrazed sites whereas no such pattern is apparent for total

carbon and total phosphorus. As we noted above, such comparisons must be made with caution because we do not know the RR of the ungrazed sites prior to livestock removal, rendering statistical tests problematic (Hurlbert 2004).

The best approach to test this prediction is to characterize soil nutrient patterns before and after livestock removal. To our knowledge, no such data exist. An alternative is to compare RRs from a single site in which canopy–intercanopy soil nutrient values were measured on both sides of the grazing enclosure fence. Such cross-fence shrub–intershrub soil nitrogen data are available from three sites—Allington and Valone (2010) and sites A and B. For the first two of these we see that RR for the longest ungrazed areas are lower than that from the grazed area; at site A the difference is over 100% (Table 2; Figure 2). Furthermore, intershrub soil nitrogen levels were elevated inside compared to outside the enclosure, just as the hypothesis predicts (Figure 1). However, at site B the RR is virtually the same on both sides of the fence ( $rr = 2.15$  grazed,  $2.23$  ungrazed; Table 2). This is an arid grassland with slightly higher precipitation rates than the other two sites (Table 1) and also has a higher frequency of livestock in the grazed area. Livestock often rest in the canopy of the shrubs and the higher rates of waste deposition at this site are likely contributing to the pattern detected here.

We acknowledge that in the absence of livestock grazing, positive feedbacks can still promote nutrient retention and increased soil moisture under shrub canopies. However, we suggest that in the absence of trampling by livestock, soil physical properties *between* shrub canopies change over decadal timescales (Castellano and Valone 2007), at least in the North American arid rangeland systems that predominate the literature reviewed. Eventually this leads to a lack of difference in soil nutrients in shrub and intershrub areas (and thus a lower RR). We postulate that, rather than an inherent property of arid systems, islands of fertility are tied to the activities of livestock. Or, more precisely, fertile islands are a consequence of the physical changes to the soil caused by livestock (Allington and Valone 2010, 2011).

The impact of grazing on vegetation and soil properties has been explored in many systems (Walker and others 1981; Warren and others 1986; Zhao and others 2005; Steffens and others 2008), but the role of livestock in shaping fertile island patterns has never been explicitly considered. Our review highlights the generality of the island of fertility pattern; ninety out of 99 cases documented fertile islands under shrub canopies for at least one

nutrient measure. We discovered that many cases documenting the fertile island pattern have been conducted in systems with an extensive history of grazing by livestock, but also that many published studies do not mention the grazing history of the site. All locations with a current or recent history of grazing (less than 30 years) exhibited fertile island patterns. In contrast, none of the livestock enclosures in which livestock had been absent for more than 40 years exhibited fertile islands for nitrogen. Furthermore, at three of these enclosures (Cases 93, 98, and 99), fertile islands were present in the grazed area directly outside the fence (Cases 15–17) (see also Figure 1). This association between livestock grazing and the concentrations of soil nutrients under shrub canopies is a major result of our study.

Our novel finding that islands of fertility are absent from long-term livestock enclosures has significant ramifications for our understanding of the dynamics shaping soil nutrient spatial distributions in deserts, the role of soil nutrient patterns in desertification, and the potential for desertification reversal. Rangeland management theory has recently focused on identifying indicators of impending degradation and thresholds between alternate stable states (Suding and others 2004; Biggs and others 2009; Scheffer and others 2009; Bestelmeyer and others 2011). These attempts focus on changes in the variance in community dynamics and the increased spatial heterogeneity of vegetation and soil properties to identify transitions from grassland to shrubland vegetation (Carpenter and Brock 2006; Scheffer and others 2009; Bestelmeyer and others 2011). These theoretical models share one important factor: all are focused on identifying transitions or thresholds toward a degraded state, or from homogenous to heterogeneous conditions. The data presented here from nine sites that exhibit no resource islands within long-term ungrazed areas complicate this binary view of arid systems by suggesting the possibility of another pattern, one in which soil properties exhibit a more homogenous distribution despite the presence of heterogeneous vegetation. Geostatistical analyses of fine-scale soil nutrient distributions within long-term enclosures are needed to explore this further. Data from sites with paired cross-fence grazed data would be particularly informative.

Future work on spatial nutrient patterns in arid systems should consider grazing and other land-use histories. Our review highlights the importance of considering grazing history of a site when interpreting data on soil nutrient distributions. Of the 99 cases included in our literature review, 47 did not

specify the grazing history of the sites. However, we know that in general, grazing is ubiquitous in arid rangelands and it is likely that most sites have had some livestock present in the region at some point in recent history. All nine of the cases we identified in which long-term absence of livestock was associated with a lack of fertile island patterns are located in the southwestern US. To better understand the ubiquity of this relationship between livestock and fertile islands we need data from additional sites on other continents. The potential for that work is hampered by the general and widespread lack of long-term livestock exclosures. One possibility is to monitor soil nutrient and vegetation dynamics and spatial patterns at existing exclosures over time. Through such emerging datasets we will be able to better understand the effects of livestock on the spatial patterns of soil nutrients in arid ecosystems.

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