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Mineral content of forage plants of mountain sheep, Mojave Desert, USA

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The importance of trace minerals to living organisms is well established, albeit poorly studied in large, free-ranging mammals. We investigated concentrations of 11 minerals among 9 species of forage plants used by bighorn sheep (*Ovis canadensis*) in the Panamint Range, Inyo County, and at Old Dad Peak, San Bernardino County, California, USA. We sampled vegetation monthly, and used established protocols and analytical techniques to determine the concentrations of Ca, Cu, Fe, Mg, Mn, P, K, Na, S, Zn, and Se. Our analyses indicate that differences in concentrations of trace minerals and macro-minerals existed in forage plants, between those mountain ranges and likely portend similar differences among other geographic areas. Our results emphasize the potential importance of testing for levels of minerals in forage plants by specific geographic area rather than relying on published information from other areas when those elements are thought to play meaningful roles in population performance of bighorn sheep or other ruminants.

Key words: bighorn sheep, chemical composition, macro-minerals, micronutrients, Mojave Desert, nutrients, *Ovis canadensis*, ruminant nutrition, soil chemistry, trace minerals

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Forage quality is important in the dynamics of ungulate populations and, as such, is of interest to managers (Mahon 1969, Wallmo et al. 1977, Hobbs and Swift 1985, Robbins 1999). Nevertheless, minerals as a necessary component of ruminant diets (Davis 1968) are poorly understood (Robbins et al. 1985, Grasman and Hellgren 1993, Krausman et al. 1999, Barboza et al. 2009). Nutritional value and chemical composition of forage plants are influenced by many factors, yet few investigators have studied availability of trace minerals in forage plants used by bighorn sheep (*Ovis canadensis*). Although some authors (Seegmiller et al. 1990, Bleich et al. 1992) have investigated selected nutritional characteristics of forage plants, few (Morgart et al. 1986, McKinney et al. 2002, McKinney et al. 2006) have presented information on mineral concentrations.

Several variables influence forage abundance, forage quality, or mineral concentrations in forage plants. Among these are climate (Noy-Meier 1973, Beatley 1974, Marshal et al. 2005) and substrate chemistry (Carlisle and Cleveland 1958, Hunt 1966, Lisk 1972, Banuelos and Ajwa 1999). Further, rainfall patterns can influence the concentrations of minerals in vegetation (Greene et al. 1987, Sprinkle et al. 2000) resulting in seasonal variation in blood because of variation in mineral intake (Poppenga et al. 2012). Moreover, differences in habitat selection between male and female ruminants as a result of sexual segregation (Bowyer 2004) can result in the consumption of forages of differing quality by the sexes—even within plant species (Bleich et al. 1992). Sexual segregation has been particularly well-studied in desert bighorn sheep (Bleich et al. 1992, Bleich et al. 1997, Mooring et al. 2003, Bleich et al. 2016), and has important implications for the conservation of those specialized ungulates (Rubin and Bleich 2005). In all probability, each of those factors, when combined with the expense associated with mineral analyses, contributed to the conclusion of Duffy et al. (2009) that knowledge of biogeochemistry, food webs, and metals as stressors in bighorn sheep occupying arid environments is limited.

Minerals play a crucial role in overall animal health through disease resistance (Failla 2003), antler growth or strength (French et al. 1956, Bowyer 1983, Johnson et al. 2007), recruitment (O'Hara et al. 2001), and vital rates (Flueck 1994). As a result, availability of trace minerals is an important nutritional consideration (Fox et al. 2000, McKinney and Noon 2002, McKinney et al. 2006). Although many investigators emphasized protein, digestibility, and moisture content as primary indicators of forage quality, some (Morgart et al. 1986, McKinney and Noon 2002) have described mineral content of forages consumed by bighorn sheep. Others (Holl and Bleich 1987) analyzed mineral licks and inferred seasonal requirements of trace minerals from those data, or researched roles of the need for trace elements in declines in populations of bighorn sheep (Watts and Schemnitz 1985, McKinney et al. 2006). Nevertheless, there remains a paucity of information on the availability of micronutrients in forages of bighorn sheep, and information on geographic variation in mineral content of various forage species remains poorly researched.

In this paper, we quantify and compare availability of 5 trace minerals and 6 macrominerals in nine species of forage plants consumed by bighorn sheep in two Mojave Desert mountain ranges in which the ecology of bighorn sheep has been investigated in detail. Our purpose was to provide information on trace mineral availabilities in forage plants common to both locations and to test for overall differences in the concentrations of those minerals in forage plants between locations. We hypothesized that overall differences in the mean concentrations of minerals would not differ because both study areas were located in the Mojave Desert and supported healthy populations of bighorn sheep.

MATERIALS AND METHODS

Study areas.—We conducted research in the Panamint Range (36° 00′ N, 117° 10′ W), Inyo County, California and at Old Dad Peak (35° 05′ N, 115° 45′ W), San Bernardino County, California, USA (Bleich et al. 1992, Oehler 1999). The Panamint Range and Old

Dad Peak are situated in the northwestern part of the Mojave Desert. Bighorn sheep at both locations have been investigated intensively, and detailed descriptions of geology, topography, vegetation, fauna, and anthropogenic influences in each study area were provided by Bleich (1993), Bleich et al. (1992, 1997, 2016), Oehler et al. (2003, 2005), and Duffy et al. (2009).

Mean annual rainfall at Panamint Range was 51 mm, and it occurred in a unimodal pattern with 50% occurring from January to March. Temperatures ranged from 40°C during summer to -7°C during spring (Oehler et al. 2003). Mean annual rainfall near Old Dad Peak was bi-modal, and average annual precipitation was 101 mm; approximately half occurred as localized summer thundershowers, and the other half fell during November–March (Bleich et al. 1997). During summer, temperatures >38°C occur frequently at Old Dad Peak, and winter temperatures below freezing are not uncommon (Weaver et al. 1969).

Bighorn sheep are specialized ruminants that are strongly dependent on shrubs and grasses for forage at both locations (Bleich et al. 1992, Bleich et al. 1997, Oehler et al. 2005). Shrubs used in common by mountain sheep at Panamint Range and Old Dad Peak included *Ambrosia dumosa, Atriplex hymenelytra, Encelia farinosa, Ephedra nevadensis, Eriogonum fasciculatum, Galium stellatum, Prosopis glandulosa,* and *Sphaeralcea ambigua,* among others. Bighorn sheep at both locations also made heavy use of a perennial grass, *Stipa speciosa*, but grasses were less common in diets at the Panamint Range than at Old Dad Peak (Oehler et al. 2005, Bleich et al. 1997).

Collection and preparation of forage samples.—As a result of sexual segregation, diet quality differs between male and female bighorn sheep (Bleich et al. 1997), and some forages differ in quality between ranges used primarily by males when compared with ranges used primarily by females (Bleich et al. 1992). To minimize the potential for sexual segregation to influence availability of trace minerals in forage plants within each area, we collected forage plants from ranges inhabited primarily by females at Old Dad Peak (Bleich et al. 1992) and the Panamint Range (Oehler et al. 2005). We collected green leaves, grass seed heads, flowers, or otherwise new growth from each plant (Bleich et al. 1992) to minimize the potential influence of dead vegetation on mineral concentrations (Greene et al. 1987). We obtained samples (~100 g/sample) from five plants of each species from each area at mid-month throughout the year. Suitable samples (i.e., leaves or new growth) of *P. glandulosa*, however, were not available every month at Old Dad peak. As samples were collected, we placed them in paper bags and weighed them to the nearest 0.1 g; we then dried them in a convection oven at 50°C until a constant weight was reached (Bleich et al. 1992).

We used a Wiley mill to grind individual samples to <1-mm particle size, took equal volumetric measures from each monthly sample, and created a composite monthly sample for each forage species from each range (Bleich et al. 1992, Oehler et al. 2005). We mixed each composited monthly sample thoroughly, and then combined equal volumetric portions of each composited sample into six categories (Jan–Feb, Mar–Apr, May–Jun, Jul–Aug, Sep–Oct, Nov–Dec) for each plant, resulting in 54 and 51 composited samples of forage species from the Panamint Range and Old Dad Peak, respectively, because only three bimonthly composites of *P. glandulosa* were available from Old Dad Peak. Selenium (Se) for each of the nine forage species collected from each range was analyzed for three composited bimonthly samples.

Analytical methods.—Composited samples were analyzed for Calcium (Ca), Copper (Cu), Iron (Fe), Magnesium (Mg), Manganese (Mn), Phosphorus (P), Potassium (K), Sodium (Na), Sulfur (S), and Zinc (Zn) using inductively coupled plasma emission spectroscopy at Cumberland Valley Analytical Services (Maugansville, MD, USA 21767). Selenium was determined using capillary gas chromatography with electron capture detection (University of Arizona Veterinary Diagnostic Laboratory, Tucson, AZ, USA 85721). Concentrations of Fe, Zn, Mn, Cu, and Se are expressed as ppm; concentrations of all other elements are expressed as percent (%) dry weight.

The taxon was the sampling unit for most of our tests, and we predicted that there would be no overall difference in concentrations of 10 trace minerals between Panamint Range and Old Dad Peak among the nine plant species. For descriptive purposes, we calculated annual mean values of trace minerals for each species from the Panamint Range and Old Dad Peak (Table 1). With the exception of *P. glandulosa*, we used Wilcoxon Matched-pairs Signed-ranks tests (Zar 1984) to compare concentrations of Ca, Cu, Fe, Mg, Mn, P, K, Na, S, and Zn between areas for each of the forage species considered (Table 1).

We were interested in whether overall differences existed in mineral availabilities between Panamint Range and Old Dad Peak; hence, we used analytical results (Table 1) and a 2-tailed sign test to determine if mean annual values in one area differed from expectation when compared with mean annual values for the other area. Additionally, we used a Z-test for proportions (Zar 1984) to test for a difference in proportion of the number of pairs of plants in which mean annual values in one area differed significantly from those in the other area.

For Se, the 11th trace mineral we examined, we first used the 2×3 extension of Fisher's Exact Test (Freeman and Halton 1951) to test for an overall difference in the proportion of taxa in which Se levels at Panamint Range exceeded those at Old Dad Peak. Upon finding no difference, we compared all paired results for Se simultaneously with a sign test (Zar 1984).

Our analyses were confounded by the absence of new growth or leaves on *P. glandulosa* for part of the year at Old Dad Peak, and fiscal constraints that limited analyses of Se to three, rather than six, paired comparisons during the year. Each of the tests performed was, nevertheless, directed toward the null hypothesis of no overall difference in the concentrations of micro-nutrients among the forage species used in common by bighorn sheep at Panamint Range and Old Dad Peak. Thus, we used results of the combined probability test (Fisher 1925, Sokal and Rohlf 1981), where $X^2 = -2\Sigma\ln(P)$ with $2k$ degrees of freedom, and k = the number of individual tests as an index to the congruence among outcomes of tests of the null hypotheses. We recognize that not all tests in this meta-analysis were independent and, accordingly, we reduced alpha for this analysis to 0.02 (Bowyer et al., 2007). Meta-analyses of this type have been increasingly recognized as a valuable tool when probabilities are focused on single hypotheses (Arnqvist and Wooster 1995, Osenberg et al. 1999).

RESULTS

Mean annual value of trace nutrients in Panamint Range were greater than those at Old Dad Peak in 64 of 80 total comparisons, mean annual values at Old Dad Peak exceeded those at Panamint Range in 15 of 80 comparisons, and mean annual values were the same in only 1 of 80 pairwise comparisons ($P < 0.0001$; Table 1). Further, a chi-squared test indicated a striking and highly significant difference ($P < 0.001$) in the proportion of mineral concentrations that differed between areas: mean annual concentrations were significantly greater at Panamint Range in 37 pairwise comparisons and in three instances at Old Dad Peak (Table 1). For Se, concentrations in forage plants at Panamint Range exceeded those at Old Dad Peak ($P = 0.011$) in 18 of 23 pairwise comparisons (Table 2). The combined probability test yielded a highly significant result ($X^2_{20} = 53.782$, $P < 0.001$), indicating that results of all tests were consistent and, thus, we reject the hypothesis of no overall difference in trace mineral concentrations among forage plants between Panamint Range and Old Dad Peak.

TABLE 1.—Concentrations (x̅ and SD) of 10 trace elements in nine species of bighorn sheep forage plants from the Panamint Range (PR), Inyo County and Old Dad Peak (ODP), San Bernardino County, California, USA. Mean values for trace elements in each species that differed on an annual basis are denoted by paired matching superscripts (see footnotes 4 and 5).

		Calcium[2]		Phosphorus[2]		Magnesium[2]		Potassium[2]		Sodium[2]		Sulfur[2]		Iron[3]		Manganese[3]		Zinc		Copper	
Taxon[1]		PR	ODP	PR	ODP	PR	ODP	PR	ODP	PR	ODP	PR	ODP	PR	ODP	PR	ODP	PR	ODP	PR	ODP
Ambrosia	*x̅*	3.104	2.22[4]	0.11	0.15	0.47[4]	0.34[4]	2.42	2.13	0.18[4]	0.09[4]	0.33	0.30	332.47	405.52	127.81[4]	47.28[4]	56.76[4]	18.92[4]	11.57[4]	6.11[4]
	SD	0.63	0.11	0.03	0.02	0.04	0.06	0.21	0.38	0.04	0.03	0.02	0.04	145.71	135.70	42.02	9.52	12.08	2.99	1.87	0.88
Atriplex	*x̅*	2.81	2.23	0.06[4]	0.09[4]	0.89[5]	0.48[5]	3.40[4]	2.30[4]	7.55	7.88	0.42	0.39	440.34	238.86	278.54	90.44	33.74[5]	19.86[5]	13.69[5]	4.16[5]
	SD	0.84	0.42	0.01	0.04	0.17	0.43	0.43	0.38	1.12	0.85	0.04	0.07	461.04	116.49	124.09	24.33	17.16	4.68	4.89	0.93
Encelia	*x̅*	3.21	2.96	0.21[4]	0.14[4]	0.46[5]	0.30[5]	3.31[4]	1.98[4]	0.12[4]	0.06[4]	0.51	0.35	326.11	307.48	71.75	55.47	46.81[5]	18.57[5]	19.66[5]	9.12[5]
	SD	0.91	0.57	0.06	0.01	0.05	0.04	0.80	0.45	0.04	0.03	0.13	0.10	329.99	143.87	44.25	5.02	5.64	1.82	5.19	3.19
Ephedra	*x̅*	1.65[5]	2.46[5]	0.09	0.08	0.19	0.21	0.67	0.74	0.04	0.03	0.24	0.23	121.51[5]	86.27[5]	41.38	52.14	13.37	14.02	3.68	4.17
	SD	0.49	0.19	0.01	0.01	0.04	0.02	0.16	0.13	0.01	0.01	0.01	0.05	20.73	15.20	15.12	15.89	1.27	3.97	0.78	1.89
Eriogonum	*x̅*	1.65	1.57	0.07	0.07	0.27[4]	0.20[4]	0.98	0.79	0.07[5]	0.02[5]	0.22[5]	0.09[5]	325.83	313.57	53.61[4]	36.97[4]	16.58[5]	10.24[5]	5.94[5]	2.10[5]
	SD	0.18	0.24	0.02	0.02	0.03	0.01	0.16	0.12	0.01	0.004	0.01	0.02	197.84	61.29	11.37	2.74	1.90	1.54	0.65	1.12
Galium	*x̅*	2.66[4]	1.79[4]	0.12	0.09	0.37[4]	0.26[4]	2.26	1.02	0.20[4]	0.03[4]	0.25[4]	0.13[4]	390.52	681.80	72.05[4]	47.59[4]	24.82	58.53	11.83	4.47
	SD	0.35	0.19	0.06	0.02	0.10	0.03	0.17	0.17	0.17	0.005	0.02	0.02	309.12	171.65	22.77	7.39	13.42	68.34	6.69	1.88
Prosopis[6]	*x̅*	1.12	1.20	0.14	0.09	0.42	0.31	1.36	1.19	0.03	0.02	0.49	0.62	146.27	126.60	65.23	60.21	53.17	49.60	22.18	13.95
	SD	0.27	0.27	0.16	0.02	0.08	0.03	0.39	0.04	0.01	0.005	0.10	0.14	74.79	28.10	13.74	14.31	8.48	5.91	5.29	4.52
Sphaeralcea	*x̅*	1.96[4]	1.76[4]	0.24	0.17	0.41[4]	0.32[4]	1.98	1.93	0.17	0.04	0.38	0.36	1181.08	555.76	99.63[4]	46.92[4]	36.38	30.26	13.16[5]	7.45[5]
	SD	0.15	0.06	0.06	0.03	0.05	0.03	0.26	0.25	0.15	0.01	0.03	0.07	1199.83	279.19	41.59	6.41	5.52	9.00	3.76	1.72
Stipa	*x̅*	0.40	0.37	0.04[4]	0.07[4]	0.09[5]	0.07[5]	0.54	0.62	0.04[5]	0.01[5]	0.23[5]	0.15[5]	257.16	354.37	51.33[5]	30.53[5]	14.66	20.50	9.13[5]	3.21[5]
	SD	0.07	0.04	0.01	0.01	0.02	0.01	0.13	0.18	0.01	0.002	0.01	0.01	158.45	80.34	11.29	8.89	4.21	7.99	5.16	0.47

[1] Taxa are identified to species in the text
[2] Expressed as percent dry weight
[3] Expressed as parts per million (ppm)
[4] $P \leq 0.10$
[5] $\mathrm{P} \leq 0.05$
[6] No statistical comparison was made because plants were bare of leaves during 6 sampling periods at Old Dad Peak.

TABLE 2.—Concentrations of Selenium in nine species of bighorn sheep forage plants from the Panamint Range (PR), Inyo County and Old Dad Peak (ODP), San Bernardino County, California, USA. The detection limit for Selenium using capillary gas chromatography with electron capture was ≥0.04 PPM

		Selenium (ppm)	
Taxon[1]	Period[2]	PR	ODP
Ambrosia	M–A	0.12	<0.04
	J–A	0.08	0.056
	N–D	0.11	0.04
Atriplex	M–A	0.11	<0.04
	J–A	0.13	0.11
	N–D	0.13	0.08
Encelia	M–A	0.06	0.043
	J–A	0.08	0.058
	N–D	0.10	0.049
Ephedra	M–A	0.04	<0.04
	J–A	<0.04	<0.04
	N–D	<0.04	0.04
Eriogonum	M–A	0.07	<0.04
	J–A	<0.04	<0.04
	N–D	0.05	<0.04
Galium	M–A	0.08	<0.04
	J–A	0.08	<0.04
	N–D[3]		<0.04
Prosopis	M–A[4]	0.06	
	J–A	0.08	0.28
	N–D	0.10	0.54
Sphaeralcea	M–A	0.07	0.54
	J–A	<0.04	0.04
	N–D	0.24	<0.04
Stipa	M–A	0.04	<0.04
	J–A	0.06	<0.04
	N–D	0.06	0.043

DISCUSSION

To the best of our knowledge, we are the first to examine availability of micronutrients in forage plants used by bighorn sheep inhabiting different mountain ranges. Our tests yielded consistent results, and we reject our overall hypothesis that there were no differences in trace-mineral concentrations of forage plants used by bighorn sheep at Panamint Range and Old Dad Peak. Given the similarities in vegetation between the two ranges, our results were unexpected. Climatological differences, however, have important consequences for the population ecology of bighorn sheep at Panamint Range and Old Dad Peak (Oehler et al. 2003). Rainfall patterns can influence the concentrations of minerals in vegetation (Greene et al. 1987, Sprinkle et al. 2000), with the result that seasonal variation in mineral concentrations among individual animals are likely due to variation in mineral intake (Poppenga et al. 2012). Although differences in timing and amount of rainfall between Panamint Range and Old Dad Peak are not substantial, they likely affected the availability of micronutrients in forage plants in each geographic area (Greene et al. 1987, Sprinkle et al. 2000). In addition, we surmise that structural or compositional differences in substrate (Hunt 1966, Hall 1971, Dunne 1977, Curry and Resigh 1983) contributed to differing availabilities of micronutrients at Panamint Range and Old Dad Peak. Indeed, substrate chemistry plays a role in availability of trace elements (Hunt 1966) with resultant effects on the availability of those nutrients in plants (Carlisle and Cleveland 1958) and, ultimately, their availability to herbivores (Lisk 1972, Banuelos and Ajwa 1999).

Few investigators have analyzed the mineral content of forage plants used by wild ruminants in desert environments, and even fewer have considered differences in those measures among geographic areas. Our results are similar to those of Fox et al. (2000), who described substantial differences in availability of several trace minerals in forage plants in two geographic areas used by Sonoran pronghorn (*Antilocapra americana sonoriensis*). Collectively, our results and those of Fox et al. (2000) emphasize the importance of considering nutrient availability and its potential importance to ungulate populations on a geographic basis. Thus, we caution other investigators not to assume that published values from other study areas are universally representative.

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