A Systematic Review of Wild Burro Grazing Effects on Mojave Desert Vegetation, USA

Scott R. Abella

Abstract Wild burros (*Equus asinus*), protected by the 1971 Wild Free-Roaming Horse and Burro Act on some federal lands but exotic animals many ecologists and resource mangers view as damaging to native ecosystems, represent one of the most contentious environmental management problems in American Southwest arid lands. This review synthesizes the scattered literature about burro effects on plant communities of the Mojave Desert, a center of burro management contentions. I classified 24 documents meeting selection criteria for this review into five categories of research: (i) diet analyses directly determining which plant species burros consume, (ii) utilization studies of individual species, (iii) control-impact comparisons, (iv) exclosure studies, and (v) forage analyses examining chemical characteristics of forage plants. Ten diet studies recorded 175 total species that burros consumed. However, these studies and two exclosure studies suggested that burros preferentially eat graminoid and forb groups over shrubs. One study in Death Valley National Park, for example, found that *Achnatherum hymenoides* (Indian ricegrass) was 11 times more abundant in burro diets than expected based on its availability. Utilization studies revealed that burros also exhibit preferences within the shrub group. Eighty-three percent of reviewed documents were produced in a 12-year period, from 1972 to 1983, with the most recent document produced in 1988. Because burros remain abundant on many federal lands and grazing may interact with other management concerns (e.g., desert wildfires fueled by exotic grasses), rejuvenating grazing research to better understand both past and present burro effects could help guide revegetation and grazing management scenarios.

Introduction

Wild burros (*Equus asinus*) have been one of the most contentious environmental management issues in arid lands of the southwestern United States. Considered native to arid northeastern Africa and domesticated more than 5000 years ago, burros are believed to have been brought to the American Southwest in the sixteenth century by Spanish explorers (McKnight 1958; Carothers and others 1976; Wagner 1983). Owing to their desert hardiness, burros were deemed excellent pack animals and were used extensively to assist with mining operations in the 1800s in the deserts of Arizona, California, Nevada, and neighboring states (Thomas 1979). Following a decline in mining and the development of other transportation methods in the late 1800s, many burros were released or escaped and became feral (Zarn and others 1977a). With few predators, burro density increased in the Southwest in the early and mid-1900s, alarming ecologists and resource managers who believed that these nonnative animals negatively affected desert soils, native bighorn sheep (*Ovis canadensis nelsoni*), and plant communities (Dixon and Sumner 1939; Weaver 1973; Sanchez 1974). Resource managers of some public lands initiated shooting, translocation, and other control measures in attempts to reduce burro density and perceived impacts on desert ecosystems (McKnight 1957; Carothers and others 1976). However, public outcry about

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population control activities resulted in the U.S. government passing the 1971 Wild Free-Roaming Horse and Burro Act (Public Law 92-195). This act declared that wild burros were part of national heritage and should be considered where found as integral components of federal public land, with the exception that national parks and wildlife refuges were exempt. However, burros continued to reside on these exempt lands, partly by movement from other adjacent public land, lack of public support for population control measures, and costs and constraints on control (Carothers and others 1976; Douglas and Leslie 1996).

By containing the highest burro concentrations in the Southwest and several national parks, the Mojave Desert region has been a center of discord about burro management (Fig. 1). Due to prodigious fecundity and an ability to travel long distances, burros remain abundant today in the Mojave Desert despite effective removal efforts in targeted areas (U.S. National Park Service [USNPS] 1994; Tiller 1997). However, as concluded by early authors (Sumner 1959; Welles and Welles 1961; Smith 1969), even a cursory examination of the literature on effects of burros on vegetation of the Mojave Desert reveals the literature to be scattered and to sometimes include sweeping generalizations that burros negatively impact native ecosystems. These generalizations are often based on no data or on data seemingly not warranting broad generalizations (e.g., due to a lack of replication). Furthermore, general statements that "burros negatively impact vegetation" may have little utility for environmental planning or for the ecological restoration of burro-inhabited areas. More specific information, such as which plant functional groups have been most affected, may be more accurate and useful (Bowers 1997; Beever and Brussard 2000).

Understanding burro effects on plant communities is important for at least three environmental management reasons: (i) there is potential that burros have had large past effects that have drastically shaped contemporary ecosystems even in areas where active burro management removals have since taken place, (ii) predicting vegetation

Fig. 1 Distrubution of burros in the western United States in 1957. Modified from McKnight (1958), who made distributional estimates by surveying local resource managers, and who believed that the 1957 distribution was less extensive than in the previous several decades due to implementation of population control measures. The Mojave Desert is shaded in gray, and north is up
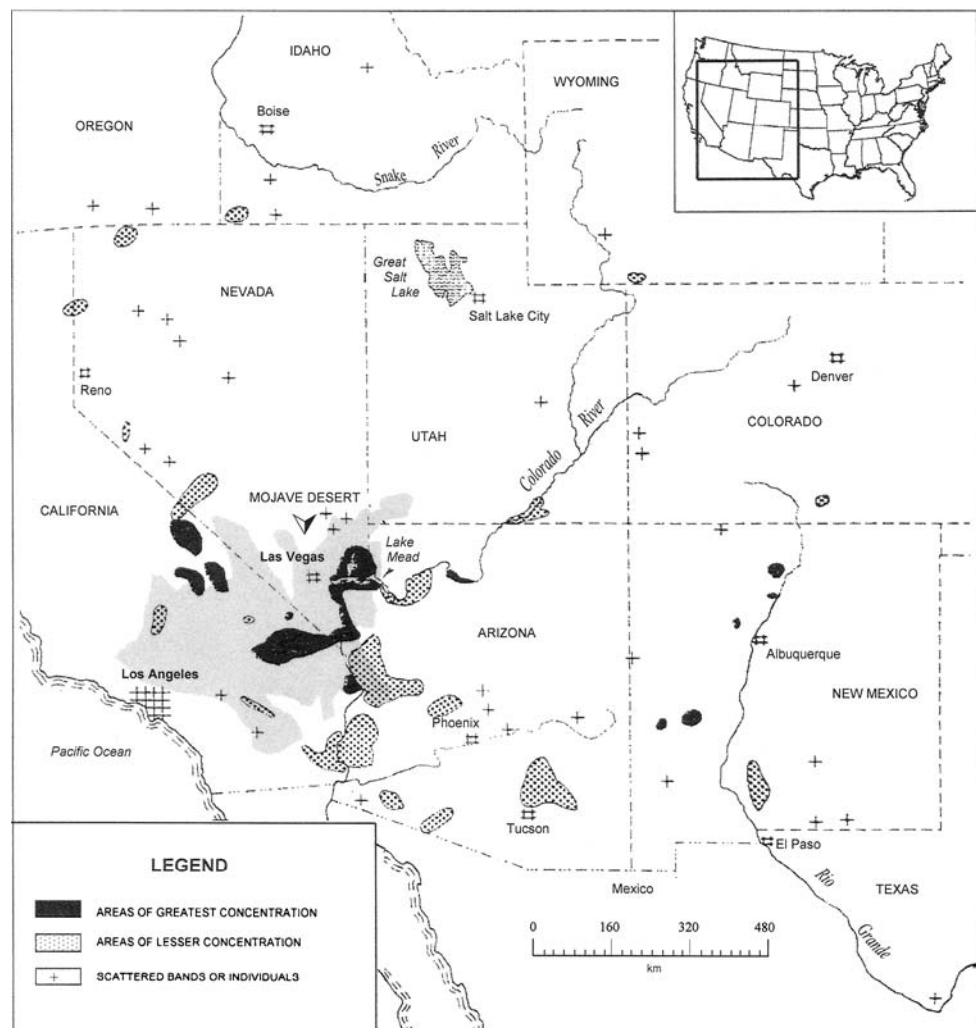
changes after burro removal or different burro management scenarios could assist environmental management planning, and (iii) balanced perspectives may be needed for producing objective legal documents dealing with burro management, such as in environmental impact statements required before many management activities can occur by U.S. land management agencies. There also are management issues emerging of concern to many resource managers in southwestern deserts, such as climate change and recent, large desert wildfires fueled by exotic annual grasses, with which burro grazing may interact. The objective of this review was to synthesize documented literature to summarize what is and is not known about burro effects on vegetation of the Mojave Desert, critique methodology employed by reviewed studies, and suggest research directions for advancing our knowledge about burro effects and their management.

Methods

Study Region

The approximately 124,000-km^2 Mojave Desert (Rundel and Gibson 1996) occupies parts of southeastern California, southern Nevada, southwestern Utah, and western Arizona in the southwestern United States (Fig. 1) This desert encompasses a range of topography and plant communities, spanning low-elevation *Larrea tridentata* (creosote bush) communities to higher-elevation pinyon-juniper (*Pinus-Juniperus*) woodlands and mixed conifer forests (Rowlands and others 1982). Annual precipitation and temperatures vary across the Mojave Desert. In Las Vegas, Nevada, for example, in the eastern Mojave Desert, precipitation averages 11 cm/year, January high temperatures 14°C, and July high temperatures 40°C (1937–2006 records; Western Regional Climate Center, Reno, NV). McKnight (1958) provided an early map of relative burro density in the Mojave and surrounding regions based on population estimates provided by resource managers of these lands (Fig. 1). His map provides a historical context for past burro grazing, as burro densities fluctuated spatially and temporally during the 1900s (Ginnett and Douglas 1982; Wagner 1983; individual studies in Table 1). Burros remain prevalent in the Mojave Desert. For example, the U.S. Bureau of Land Management (2006) reported that approximately 900 burros inhabited the 312,000-ha Spring Mountains Herd Management Complex in 2006 in the north-central Mojave Desert. In addition to burros, cattle, sheep, and wild horses have grazed or continue to graze many areas (Lovich and Bainbridge 1999). The Mojave Desert transitions to the Sonoran Desert to the south and to the Great Basin Desert to the north, regions which also contain burros.

Burro Traits

In a population in the northwestern Mojave Desert, mature burros (Fig. 2) weighed 167 kg on average (Norment and Douglas 1977). Maximum ages estimated by Johnson and others (1987) for a population of western Mojave Desert burros were 15 years for females and 20 years for males. Zarn and others (1977a), however, report that burros can live for 40 to 50 years. Burros have high reproductive capacities, with measured annual recruitment rates in two late 1970s and early 1980s studies of 11%–20% (Seegmiller and Ohmart 1981, Ruffner and Carothers 1982). Seegmiller and Ohmart (1981) found that sizes of social groupings in an Arizona population ranged from 1 to 21 burros, with a mean size of 5 burros. Estimates of mean home range sizes of adult burros include 10 km^2 in Butte Valley of Death Valley National Park (White 1980), 5–24 km^2 in western Arizona (Seegmiller and Ohmart 1981), and 68 km^2 in California's Panamint Mountains (Douglas and Norment 1979). Seegmiller and Ohmart (1981) observed that burros watered every 24 h in summer, with the mean distance from water of burro sightings averaging ≤1.6 km in May–October and increasing to 3.5 km in the winter months of November–April. Burros have a cecal digestive system, allowing them to be more general grazers and to eat foods higher in fiber than ruminants (Zarn and others 1977a). Longshore and Douglas (1988) anecdotally mentioned that adult burros can consume 4.5 kg of forage per day.

Literature Search and Analysis

To locate literature on burro grazing effects on Mojave Desert vegetation, I searched the article databases of Agricola, Biological Sciences, Science Direct, and Google Scholar, and the archives of the *Journal of Range Management*. I used combinations of key words including burro, feral ass, grazing, Mojave, vegetation, plant, impact, and effect. I also examined reference lists within articles, two earlier bibliographies of wild burros (Zarn and others 1977b, Douglas and Hurst 1993), and an environmental impact statement of burro management (USNPS 1994). This search returned over 75 references, of which 24 met the criteria for inclusion in the review. The requirements for inclusion were that a document must (i) report on a study conducted within the Mojave Desert or in adjacent transition areas containing Mojave plant species, (ii) provide some quantitative data on burro diets, forage, or effects on plants, and (iii) include documentation of methods. References not meeting inclusion criteria often did not contain quantitative data or dealt with burro relationships with bighorn sheep and did not include vegetation data. Both published and unpublished documents were

Table 1 Studies measuring burro effects on Mojave Desert vegetation

Study	Location[a]	Burro numbers
Diet analysis		
Browning 1960	Cottonwood Mtns., DVNP	–[b]
Douglas and Hiatt 1987	BV, DVNP	High density in DVNP
Ginnett 1982	Cottonwood Mtns., DVNP	–
Hansen and Martin 1973	Grand Canyon, LMNRA	–
Jordan and others 1979	Bedrock/Lower Canyons, GCNP	–
McMichael 1964a	Black Mtns., AZ	100 ("high")
Potter and Hansen 1979	10 canyons, GCNP	0.6/km^2
Seegmiller and Ohmart 1981	Bill Williams Mtns., AZ	0.9–3.3/km^2
Walker 1978	Black Mtns., AZ	3/km^2
Woodward and Ohmart 1976	Chemehuevi Mtns., CA	80
Utilization		
Douglas and Norment 1977	Panamint Mtns., DVNP	–
Farrell 1973	Alamo State Park, AZ	∼100 near waterholes
Hanley and Brady 1977b	Havasu Resource Area, AZ	50
O'Farrell 1978	LMNRA	0.2–0.4/km^2
White 1980	BV, DVNP	3.8/km^2
Yancey and Douglas 1983	WC/Nemo Canyon, DVNP	–
Control-impact comparison		
Bennett and others 1981	GCNP	–
O'Farrell 1978	LMNRA	0.2–0.4/km^2
Carothers and others 1976	GCNP	400–700/km^2
Exclosure		
Fisher 1975	WC, Panamint Mtns., DVNP	220
Hanley 1976	Havasu Resource Area, AZ	50
Longshore and Douglas 1988	BV/WC, DVNP	Heavy/moderate
White 1980	BV, DVNP	3.8/km^2
Yancey and Douglas 1983	WC, DVNP	–
Forage analysis		
Douglas and Hiatt 1987	BV, DVNP	High density in DVNP
Farrell 1973	Alamo State Park, AZ	∼100 near waterholes
Hanley and Brady 1977a	Havasu Resource Area, AZ	50
Norment and Douglas 1977	Panamint Mtns., DVNP	0.4/km^2
Watkins 1976	Havasu Resource Area, AZ	–
White 1980	BV, DVNP	3.8/km^2

[a] AZ, state of Arizona; BV, Butte Valley; CA, state of California; DVNP, Death Valley National Park (California); GCNP, Grand Canyon National Park (Arizona); LMNRA, Lake Mead National Recreation Area (Nevada-Arizona); WC, Wildrose Canyon

[b] Not provided in the document

included. If both an unpublished and a published document of the same study were produced, I cite the published document in this review unless the unpublished document contained additional data not contained in the published version. Methods were assessed for replication and randomization of sample/experimental units, and for the establishment of controls. I originally intended to synthesize studies using a statistical meta-analysis. Instead, I analyzed the 24 documents using descriptive statistics, because many studies did not provide measures of variability (e.g., standard deviations) typically required for calculating effect sizes in meta-analyses (Gurevitch and others 2001), some categories of research had few studies,

and data characteristics in different categories of research differed. Plant nomenclature and classification of species as native or exotic follows U.S. National Resources Conservation Service (USNRCS; 2007).

Results and Discussion

Description of the Literature

Production dates of 24 documents included in this review ranged from 1960 to 1988, with 8% produced in the 1960s, 63% in the 1970s, and 29% in the 1980s (Table 1). Eighty-
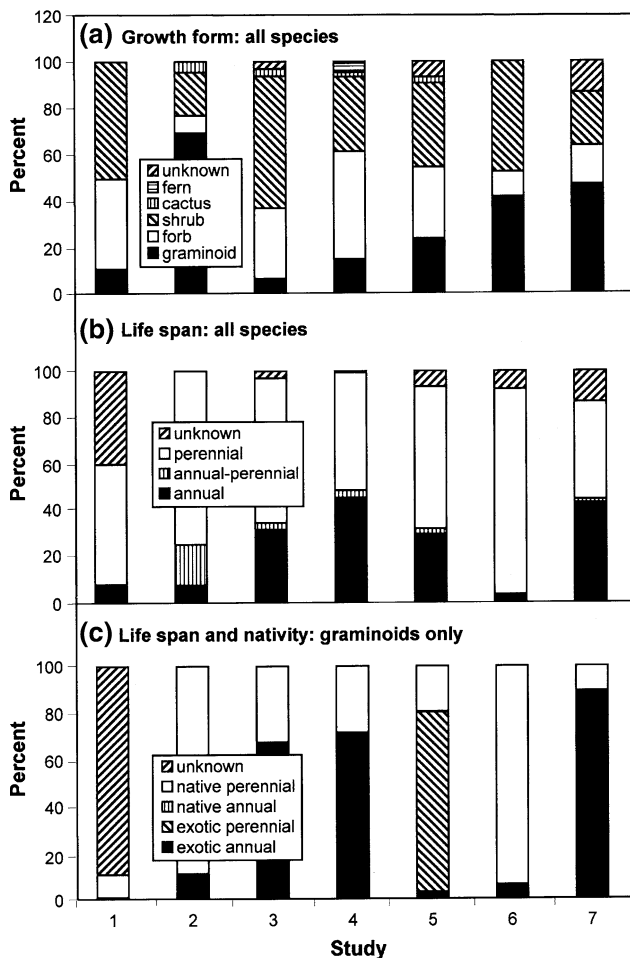
Fig. 2 Summary of seven studies that measured annual burro diets three or more times within a year in the Mojave Desert, USA. (**a**) Graminoids and forbs comprised ≥50% of annual diets in six of seven studies. (**b**) On average, perennials comprised 62% and annuals 24% of burro diets. (**c**) Considering graminoids only, native perennials dominated diets in two studies, while exotic annuals dominated diets in three studies. Species categorizations follow USNRCS (2007). Study 1, Browning 1960; 2, Hansen and Martin 1973; 3, Woodward and Ohmart 1976; 4, Walker 1978; 5, Seegmiller and Ohmart 1981; 6, Ginnett 1982; 7, Douglas and Hiatt 1987

three percent of the documents were produced in a 12-year period following the passage of the 1971 Wild Free-Roaming Horse and Burro Act. Half of the documents were unpublished or theses. The 24 documents included a total of 30 studies, which I classified into five categories of research: diet analysis, utilization, control-impact comparison, exclosures, and forage analysis.

Diet Analysis

Nine studies measured burro diets by analyzing fecal or stomach samples, and one study (McMichael 1964a, b) also made direct visual observations of burro foraging

(Table 1). Several studies that measured burro diets by month found that diet composition varies seasonally within years. This is not unexpected based on factors such as differences among plant species in growth periods and seasonal movements of burros (Farrell 1973; Hanley and Brady 1977a). In the eastern Mojave Desert, for example, Woodward and Ohmart (1976) found that the annual *Plantago ovata* (desert Indianwheat) constituted 64% of burro diets in March but only 0.5% in December. The time of peak consumption of this species by burros corresponded to this plant's period of active growth, when protein and nutrient concentrations were highest (Hanley and Brady 1977a). In another example, grasses comprised 66%–76% of summer diets from May to August in the Cottonwood Mountains of Death Valley National Park, while consumption switched to shrubs (50%–81% of diets) from September to April (Ginnett and Douglas 1982). Woodward and Ohmart (1976) reported a different seasonal pattern, where shrubs comprised the majority of diets (58%–84%) in all months except for the spring months of February–May when burros focused on annual forbs.

In the seven of nine studies that characterized annual burro diets at least three times within a year using fecal or stomach analysis, the number of species detected in fecal or stomach samples averaged 33 (SD = 17) and ranged from 11 to 54. There were 175 total species detected in burro diets in the 10 total diet studies, consistent with earlier reports that burros can eat a variety of plant species (Douglas and Hiatt 1987).

The proportions of different plant growth forms and life spans in annual burro diets varied widely among studies (Fig. 2). Graminoids constituted 6% to 69% (mean = 30%) of annual burro diets. Forbs also varied widely in importance, ranging from 8% to 47% (mean = 26%). Shrubs ranged from 19% to 58%, averaging 38%. Cacti and ferns were small components of diets in some studies, while 5% of plant material on average in diets could not be identified to growth form. The proportion of annuals in diets ranged from 3% to 45% (mean = 24%), and perennials from 42% to 89% (mean = 62%). Considering graminoids only, which consisted of >95% grasses, exotic annuals ranged from 1% to 89% (mean = 35%), and native perennials from 10% to 94% (mean = 41%). Native annual graminoids were documented in diets in only one study (Seegmiller and Ohmart 1981), and constituted only 0.2% of the graminoid component in that study. The wide variation in the importance of different plant species recorded in diets probably reflects versatility in foraging of burros, different vegetation types and forage availability within and among study areas, differences in burro seasonal movements among vegetation types, and differences in climate characterizing study periods (Seegmiller and Ohmart 1981).

The native annual forb *Plantago ovata* constituted the greatest proportion of annual burro diets (Table 2) and was the single most important species in three of seven annual diet studies (Woodward and Ohmart 1976, Walker 1978, Seegmiller and Ohmart 1981). Although this species was primarily consumed in spring and in low amounts throughout the year, its extremely high consumption in spring propelled it to be the most heavily consumed on an annual basis. *Bromus rubens* (red brome), an exotic annual grass, was the second most important species on average, largely due to its high importance (41%) in one study (Douglas and Hiatt 1987). *Ambrosia dumosa* (white bursage), *Atriplex confertifolia* (shadscale saltbush), and *Sphaeralcea ambigua* (desert globemallow) were the most important shrubs. Three native perennial grasses (*Muhlenbergia porteri* [bush muhly], *Aristida* spp., and *Tridens* spp.) also were among the most abundant species in burro diets. Other native perennial grasses were relatively important in specific studies. For example, the importance of *Achnatherum hymenoides* (Indian ricegrass), *Achnatherum speciosum* (desert needlegrass), *Elymus multisetus* (big squirreltail), *Pleuraphis jamesii* (James' galleta), and *Phragmites australis* (common reed) ranged from 5% to 25%.

Diet analysis studies provide information on plants burros are eating, but they provide no measure of potential selective foraging unless diets are compared to forage

Table 2 The 17 most abundant species (of 156 total species), based on fecal or stomach analyses, documented in burro diets of the Mojave Desert, USA

Species	Mean (%)	Max. (%)	No. studies
Plantago ovata	10.9	28	4
Bromus rubens	9.0	41	5
Ambrosia dumosa	5.9	33	5
Atriplex confertifolia	4.5	29	2
Sphaeralcea ambigua	3.8	14	6
Muhlenbergia porteri	3.8	25	2
Eriogonum fasciculatum	3.0	11	3
Parkinsonia florida	2.5	15	2
Aristida spp.	2.3	15	5
Tridens spp.	2.0	14	2
Pluchea sericea	2.0	9	3
Opuntia spp.	1.4	5	4
Hymenoclea salsola	1.4	6	4
Krameria grayeri	1.3	7	3
Larrea tridentata	0.7	3	4
Coleogyne ramosissima	0.7	2	3
Bebbia juncea	0.5	2	4

Note: Data based on seven studies that measured diets three or more times within a year. Means are the average percentage, by weight, in annual burro diets in seven studies. No. of studies represents in how many of the seven studies a species was detected in burro diets

Table 3 Summary of limitations specific to five categories of research of burro grazing effects on vegetation of the Mojave Desert, USA

Category	Limitations
Diet analysis	3 of 10 studies did not characterize diets for ≥1 yr
	Only 1 of 10 studies quantitatively compared annual diets to field availability
Utilization	No control (caged) plants
	Only shrubs measured
	No partitioning among different herbivores
Control-impact	2 of 3 studies unreplicated
	Sites not randomly selected
	Only 1 of 3 studies matched environmentally similar sites
Exclosure	Pretreatment data collected in only 1 of 5 studies
	Limited replication
	No partitioning among different herbivores
Forage analysis	Few comparisons of forage characteristics with actual grazing
	Uncertain selection of species for analysis

availability (Table 3). Unfortunately, only one of the seven annual diet studies measured forage availability. That study (Ginnett 1982), conducted in the Cottonwood Mountains of Death Valley National Park, found that grasses were represented in burro diets five times more than predicted by their availability, as measured by relative percentage cover (Fig. 3). Native perennial grasses that burros selectively consumed included *Achnatherum hymenoides* (11 times more represented in diets than expected based on availability), *Pleuraphis jamesii* (2 times), and *Elymus multisetus* (6 times). In contrast, shrubs were consumed 37% less than expected. *Artemisia nova* (black sagebrush) was the least preferred, with 18% availability but
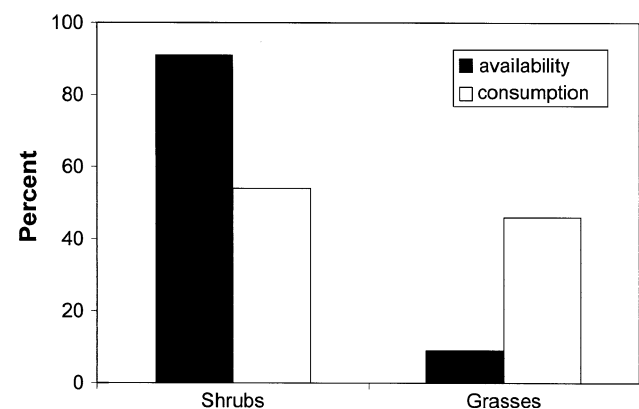

Fig. 3 Comparison of field availability of shrubs and grasses to their actual consumption by burros in the Cottonwood Mountains, Death Valley National Park, northwestern Mojave Desert, USA. Data from Ginnett (1982)

constituting only 0.3% of diets. *Ephedra nevadensis* (Nevada jointfir), *Ambrosia dumosa*, *Hymenoclea salsola* (cheesebush), and *Larrea tridentata* also were shrub species appearing in diets less than expected based on field availability. Another study (Jordan and others 1979) measured only summer burro diets but corroborated Ginnett's (1982) finding that burros preferentially consumed perennial grasses. For example, Jordan and others (1979) found that *Muhlenbergia porteri* comprised 24% of July burro diets in Grand Canyon National Park but was only a minor component of plant communities. These studies support observations (Smith 1969, Douglas and Hiatt 1987) that while burros can forage on a variety of plant species, they forage selectively when given the opportunity.

Several techniques in combination might be useful for more closely linking burro diet research with plant availability and actual effects on plant communities. One difficulty with fecal analysis, for example, is that the "study area" from which burros obtained their diet is seldom precisely known. Results depend on where burros were before eating the vegetation reflected in their fecal samples. Tracking sample burros might help elucidate where they are foraging, such as Woodward and Ohmart's (1976) observation that summer diets dominated by plants of mesic affinities (e.g., *Prosopis* spp. [mesquite] and *Pluchea sericea* [arrowweed]) corresponded with observed occurrences of burros within riparian areas. Techniques such as McMichael's (1964a, b) use of binoculars to directly observe burro feeding may also complement fecal or stomach analyses. Although this direct observation technique has several limitations (e.g., if observer presence alters burro behavior), it may have potential for evaluating plant consumption and preference by burros at specific locations.

Utilization

Findings of the six utilization studies (Table 1) often were contradictory, making it difficult to draw generalizations. For example, Douglas and Norment (1977) found that *Ambrosia dumosa* was the second most utilized species (96% of individuals in intermediate or heavily browsed categories) of 10 shrub species monitored in the Panamint Mountains of Death Valley National Park. Conversely, O'Farrell (1978) found that *A. dumosa* was the least browsed (only 0.7% of plants showed browsing evidence) of 10 shrubs studied in Lake Mead National Recreation Area in the eastern Mojave Desert. Similarly, *Acamptopappus shockleyi* (Shockley's goldenhead) was the most heavily utilized of 10 shrubs in one study (Douglas and Norment 1977), but among the least in another (Yancey and Douglas 1983). *Ephedra nevadensis*, however, consistently showed little utilization, representing the least utilized shrub species in all three studies where it was

monitored (Douglas and Norment 1977, White 1980, Yancey and Douglas 1983). Collectively, utilization studies suggest that, similar to selective grazing on different plant growth forms (e.g., graminoids versus shrubs), burros selectively browse within the shrub category in a given study area. It is difficult to generalize on preferred species, however, because they varied among studies. Furthermore, utilization may vary temporally (Yancey and Douglas 1983) and spatially, such as increasing closer to water sources (Hanley and Brady 1977b, White 1980).

Utilization monitoring could be improved by establishing control (grazing excluded) plants, better differentiating grazing among herbivores, and including plants other than just shrubs (Table 3). Many types of herbivores (e.g., jackrabbits [*Lepus californicus*]) also occupy areas inhabited by burros, making it important to carefully distinguish burro grazing from that of other herbivores (Leslie and Douglas 1979; Hunter and others 1980). The absence of monitoring any plants except for shrubs limits inference because this review suggests that shrubs are the least preferred plant growth form among graminoids, forbs, and shrubs (Ginnett 1982) (Fig. 3). Effects of utilization of annual plants could depend on the timing of utilization (e.g., before or after plants set seed) and on the abundance of annuals relative to burros. Including annuals and other forbs or grasses in utilization assessments might be useful for determining the relative sensitivities of shrubs and these plant groups in wet compared to dry years (Fisher 1974).

Control-Impact Comparison

Inference is weak in two of three studies that attempted to measure burro effects by comparing areas not thought to contain burros with areas considered to be impacted by burros (Table 3). The two studies (Carothers and others 1976, O'Farrell 1978) were not replicated and did not compare control-impact sites that were environmentally equivalent, a premise for this type of study (Beever and Brussard 2000). Nevertheless, an unreplicated study (Carothers and others 1976) was consistent with the replicated study (Bennett and others 1981) that found that plant species richness (determined by equal numbers of point-intercept transects) differed by only one or two species in control and impact areas. While control-impact monitoring may be useful in conjunction with other research approaches, it is difficult to locate sufficient sites that are environmentally equivalent and differ only in the presence or absence of burros (Bennett and others 1981).

Exclosure Studies

Similar to control-impact comparisons, a lack of replication limited inference in exclosure studies, exacerbated by

no pretreatment data collection in four of the five studies (Table 3). The most striking trend in a replicated study (Longshore and Douglas 1988) was that perennial grasses were three to nine times more dense inside than outside exclosures averaged for 2–3 years of measurements (Fig. 4). This result is consistent with Ginnett's (1982) finding that grasses occurred in burro diets five times more than predicted by their availability (Fig. 3). However, similarly to the utilization studies, it may be important to isolate grazing by burros from that of other herbivores, which was not addressed in any of the exclosure studies. Since exclosures measure vegetation change in the absence of grazing, expanding their use may improve our ability to predict communities arising if grazing is removed (Potter and Hansen 1979). Some species potentially reduced by grazing may have limited dispersal capabilities, so actively seeding or planting species inside and outside of exclosures may also improve and speed inferences about plant community development when protected from grazing (Valone and others 2002). Since burro grazing varies spatially, establishing a strategically located network of exclosures would be important to increase the generality of results.

Forage Analysis

Analyzing plant characteristics, such as chemical composition or digestibility, could allow predictions about preferred and nonpreferred forage species. Four studies noted only weak relationships between forage protein content and utilization or burro diet composition. For example, Douglas and Hiatt (1987) found that the correlation (Pearson r) between protein and fecal percentage was only –0.22 in an analysis of four species in Death Valley National Park. Similarly, Norment and Douglas (1977) and White (1980) concluded that energy content

and shrub utilization were not strongly related. Douglas and Norment (1977) found that Ca:P ratios were most closely related to utilization, although fat content and Mg or K also were correlated (maximum $r = 0.75$) with one or more utilization classes. By matching Woodward and Ohmart's (1976) fecal analysis to Watkins' (1976) chemical analysis in the Havasu Resource Area, lignin ($r = -0.79$), silica (0.69), and in vitro digestibility (0.68) were most strongly correlated for nine analyzed plant species. Hanley and Brady (1977a) concluded that the annual forb *Plantago ovata*, the most consumed species according to diet analyses (Table 2), exhibited several characteristics that make it desirable forage. This species is rich in protein, P, beta-carotene, is highly digestible, and can still be consumed after senescence. Hanley and Brady's (1977a) study suggests that predicting forage preference from plant characteristics requires a multivariate approach including plant chemical composition, digestibility, phenology, and morphology.

Forage analysis studies could be improved by more frequently relating plant characteristics to actual consumption by burros and by upgrading species selection procedures (Table 3). For example, actual burro consumption of no more than nine species could be matched to forage analyses in the six studies, with half of the studies allowing comparisons for only four species each. All species able to be matched, except for the forb *Plantago ovata*, were shrub species. Including more species, preferably anticipated preferred and nonpreferred species, would strengthen these analyses. As with diet analyses, sharp seasonal variation in plant chemical characteristics should be accounted for (Hanley and Brady 1977a, White 1980).

General Grazing Theories

Some general theories about grazing effects on plant communities include (i) grazing increases species richness due to reduction of competitive dominants, (ii) grazing results in increases in nonpreferred species, and (iii) grazing increases exotic plant species (Stohlgren and others 1999, Milchunas 2006). These theories, primarily developed from studies in mesic regions, have been little evaluated for grazing in arid lands. The two Mojave Desert studies (both of which were control-impact) uncovered in this review that evaluated burro effects on plant species richness found that richness differed by only one or two species between grazed and ungrazed areas (Carothers and others 1976, Bennett and others 1981). For the grazing-increasing richness theory to hold under current conditions in the Mojave, grazing would need to result in decreases in dominant shrubs like *Larrea tridentata*. This seems unlikely, because *Larrea* and most other dominant shrubs are not preferred burro forage. This is more difficult to
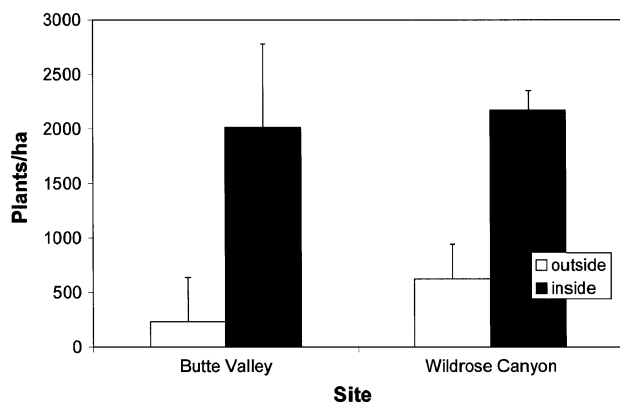

Fig. 4 Perennial grass density averaged across 3 years (1985–1987; Butte Valley) or 2 years (1986–1987; Wildrose Canyon) inside or outside of exclosures in Death Valley National Park, Mojave Desert, USA. Data from Longshore and Douglas (1988)

evaluate for annuals, because *Plantago ovata* is a dominant annual and a major forage species, yet it is unclear if burro grazing increases or decreases this species. Similarly, burros consume *Bromus rubens*, but this exotic annual has increased to become the most abundant annual in many areas (Hunter 1991).

This review suggests that burros preferentially graze some species, particularly forbs and grasses, which may have decreased due to grazing. It is not clear whether nonpreferred species, such as many shrubs, have concomitantly increased. This is hard to assess because in many of the heavily grazed canyons of utilization studies in Death Valley, burros may already have eaten and reduced preferred forbs and grasses before needing to heavily utilize less preferred shrubs (Yancey and Douglas 1983). Thus, it is possible that cessation of burro grazing could actually increase nonpreferred species in some areas, because these are the species that persisted through the grazing period.

Burros could decrease exotic plants by grazing them or increase exotics by eating competitive native plants, dispersing seed, or disturbing soil. Exotic annual grasses, such as *Bromus rubens*, are concerns in the Mojave Desert because they fuel desert wildfires thought to often further increase invasion of these grasses (Brooks 1999). Although burros may graze *B. rubens* (Douglas and Hiatt 1987), many burro-inhabited areas have experienced desert wildfires fueled by exotic annual grasses in the Mojave Desert (US-BLM 2006). Since all but one of the reviewed studies were published before 1988 (Table 1), little documentation is available on burro foraging or effects on exotic plant populations thought to be on recent upsurges (Hunter 1991). For example, burros have been observed consuming the exotic forb *Brassica tournefortii* (Sahara mustard; J.E. Spencer, Lake Mead National Recreation Area, unpublished data), which was not recorded in any of the diet analysis studies. Sufficient evidence to assess the hypothesis that burro grazing increases exotic species, however, is not available.

Conclusion and Future Research

Findings of studies in this review should be considered in their temporal context. Most studies of burro grazing effects on vegetation in the Mojave Desert occurred in a 12-year period, from 1972 to 1983, and in ecosystems that had been grazed by burros and other livestock for potentially 100 years prior to these studies. Several studies suggested that burro grazing reduced native perennial grasses during the study period (e.g., Jordan and others 1979, Ginnett 1982, Longshore and Douglas 1988), although it less clear if these grasses were already at reduced quantities due to historical grazing. Based on the current status of knowledge, giving special attention to

restoring native perennial grasses on existing or formerly burro-inhabited areas seems reasonable during revegetation efforts. Perennial grasses, and other preferred forage species, likely require protection from grazing in burro-inhabited areas if revegetation efforts are to be successful.

No documents on burro grazing effects on Mojave vegetation uncovered by this review have been produced in the last 20 years (Table 1). Understanding both past and present burro effects remains an important research need. Two examples illustrate the complexity and interrelated effects of burros on desert ecosystems and how understanding past effects may enhance management decision-making. Bowers (1997) reported that burro grazing in Grand Canyon National Park had reduced populations of *Ambrosia dumosa* that serve as nurse plants for cactus regeneration. This reduction in nurse plants was suspected to have resulted in an observed lack of recruitment of *Ferocactus cylindraceus* (barrel cactus), a unique species of management concern. In another example, Bradford and others (2004) theorized that burro grazing kept vegetation open and suitable as habitat for endangered relict leopard frogs (*Rana onca*) at springs in the eastern Mojave Desert. These authors were concerned that vegetation encroachment following active burro removals were causing habitat to become unsuitable for this rare amphibian, and called for surrogate management treatments to mimic the functional role that burros had come to serve.

While burro effects may seem visually clear in some areas, many anecdotal observations about effects (e.g., fouling of water supplies) have been called in to question by more systematic studies (e.g., Sumner 1959, Welles and Welles 1961, Seegmiller and Ohmart 1981). This observation, combined with emerging management issues that burro grazing may interact with (e.g., succession and revegetation on widespread desert burns), underscores the importance of rejuvenating grazing research and monitoring in the Mojave Desert using methodological approaches providing reliable inferences. Burro grazing and its effects may be a function of many factors, including burro population density, topography and soils, resident plant communities, spatial and temporal scale, other disturbances, year-year and longer-term climatic variation, and animal behavior. Research and monitoring approaches that assess the relative importance of these factors in regulating actual burro effects on ecosystem structure and function would be particularly timely. As long as burro protection and management continues to be mandated by law on many western U.S. public lands, effects monitoring information that remains current with changing climates and other factors could be useful for making informed policy and management decisions.

of a grazing management strategy at Lake Mead National Recreation Area and by an invitation to present at the symposium entitled "Ecology and Management of Wild and Non-native Equids," organized by Tracey Jean Wolfe (Natural Resources Conservation Service) and Linda Coates-Markle (Bureau of Land Management), at the Society for Range Management 2007 annual meeting. I thank Sharon Altman (Public Lands Institute, University of Nevada Las Vegas) for creating Figs. 1 and 2; Michele Slaton (National Park Service) for providing unpublished documents on file at Death Valley National Park; and Sharon Altman, Thomas Hanley, and three anonymous reviewers for providing helpful comments on the manuscript. Funding was provided by the National Park Service through a cooperative agreement with the University of Nevada Las Vegas.

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