The Importance of Phytogenic Mounds (Nebkhas) for Restoration of Arid Degraded Rangelands in Northern Sinai

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Abstract

Natural accumulation of wind-borne sediments within or around the canopies of plants plays an important role in the ecological and evolutionary dynamics of many coastal and desert ecosystems. The formation of such phytogenic mounds (nebkhas) creates patches that can strongly influence the spatial distribution of plant and soil resources. In land restoration of arid and semiarid environments it is important to study the potential role of such biological patchiness that may provide sites for coexistence of species with different life and growth forms. Our main objective was to test whether the nebkhas of a leguminous shrub, *Retama raetam* (white broom), promote restoration of herbaceous vegetation and soil in the degraded rangelands of northern Sinai. Vegetation and microclimatic and edaphic characteristics within the nebkhas, as well as within internebkha spaces, were compared for ungrazed and grazed sites. Abundance and richness of herbaceous plants were positively related to nebkha area, which explained more of the variance of abundance and richness in the grazed site than in the ungrazed one. Protection from grazing, especially on nebkhas, was associated with an increase in abundance and richness of herbaceous plants, improved soil microclimate, and increased soil fine particles and nutrient concentrations. The results suggest that management (in casu protection from grazing) of nebkhas of woody perennial shrubs changes rangeland conditions and improves the resource regulatory processes. Furthermore, nebkhas of unpalatable plants have the potential to preserve plant diversity in overgrazed plant communities, because they are effective in capturing and retaining water, soil materials, and propagules within and from nearby areas, resources that would otherwise be lost.

Key words: **grazing, microclimate, phytogenic mounds, Ramsar, restoration, soil nutrients, wind erosion.**

Introduction

In arid and semiarid ecosystems, where variation in the spatial and temporal availability of water and nutrients is extreme, vegetated mounds, hummocks, or nebkhas cause local changes in microclimate and soil properties. These changes lead to complex local interaction between vegetation and soil (Batanouny & Batanouny 1968; Bendali et al. 1990; Danin 1996). The mounds are termed phytogenic hillocks or nebkhas (Batanouny & Batanouny 1968; Danin 1996; Bornkamm et al. 1999) because they are composed of wind-borne sediments that accumulate within or around the canopies of plants (Vasek & Lund 1980; Tengberg & Chen 1998; Batanouny 2001). Recent work has emphasized the role of nebkhas in combating land degradation through stabilizing soil surfaces and, by preventing soil erosion, in facilitating plant recruitment and survivorship (Brown & Porembski 1997; Blank et al. 1998; El-Bana et al. 2002b).

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Although many studies have focused on the geomorphological or pedological significance of nebkhas in arid and coastal areas (Khalaf 1989; Tengberg & Chen 1998; Hesp & McLachlan 2000; Langford 2000), lacking are studies that have evaluated how heterogeneity in microclimate and vegetation of nebkha patch are affected by overgrazing (Ayyad & El-Ghareeb 1982). The destruction of natural phytogenic mounds by animal overgrazing will lead to ecosystem degradation (Shachak & Lovett 1998). Therefore, monitoring the formation and resistance of nebkhas along a grazing gradient is crucial to restore the herbaceous plant communities that are the sources of productivity and diversity in arid and semiarid lands (Schlesinger et al. 1990).

In arid and semiarid rangelands of the Middle East detailed information on nebkhas is essential for several reasons. First, rangeland has been seriously degraded as a consequence of a long history of desertification, resulting from a combination of factors such as drought and overgrazing (Batanouny 2001). Second, nebkhas influence long-term vegetation dynamics and ecosystem processes, because they can survive for millennia (Danin 1996). Third, phytogenic mounds are loci for plant productivity and diversity (Brown & Porembski 1997; Shachak & Lovett 1998). Fourth, rehabilitation cannot easily be accomplished without a complete understanding of how nebkhas are affected by grazing.

Nebkhas formed around many psammophytes and halophytes are abundant throughout the Mediterranean desert of Sinai (Batanouny & Batanouny 1968; Danin 1996; El-Bana et al. 2002a). However, there have been no studies on the ecological significance of these nebkha patches. Large expanses of northern Sinai are occupied by the nebkhas of the leguminous shrub *Retama raetam* (white broom) (Gibali 1988; El-Bana et al. 2002b). Several morphological and biological characteristics of *R. raetam* (resistance to sand accumulation and deflation, shallow and deep root system, potential ability to fix nitrogen, dense litter accumulation) suggest that nebkhas in northern Sinai may have a strong localized effect on microclimate, soil properties, and vegetation structure.

The goal of this study was to understand how biological patchiness created by shrub nebkhas reduces the loss of natural resources and enhances plant diversity in degraded rangelands. The following specific questions were addressed: Does grazing influence abundance and richness of herbaceous species on nebkhas and internebkha spaces? What are the effects of nebkhas on soil microclimate and nutrients after the cessation of grazing? In overgrazed plant communities where soil deflation is severe, which role do nebkhas play in landscape resource regulatory processes?

METHODS

Study Sites

Field work was carried out during the growing season (April–May 2000) at Zaranik Nature Reserve located on the eastern part of Lake Bardawil (31°03′ N and 33°30′ E) on the Mediterranean coast of the Sinai Peninsula. Lake Zaranik was established as a Protected Area by the Egyptian Government in 1983 and was designated as a wetland nature reserve under the International Ramsar, Iran Wetland Convention in 1988 (Salama & Grieve 1996). The Lake Bardawil climate is arid; the Emberger's degree of aridity is about 13.6 (Shaheen 1998). Long-term average rainfall is about 82 mm with high variability and usually extends from October to May (Zahran & Willis 1992). The monthly relative humidity varies between 68 and 74% with an annual mean of 72%. Soils of the study islands are rich in lime with textural classes varying from sand to clayey and silty sand (Shaheen 1998).

A ground survey located *R. raetam* nebkhas in two comparable sandy islands, namely El Fusiyat and El Malty. El Fusiyat was heavily grazed by goats and sheep before 1983 but not after 1988 (W. Salama 1999, Zaranik Manager, personal communication). In contrast, El Malty is subjected to permanent heavy grazing by goats and sheep. The elevation of both islands is approximately 20 m above sea level. They are assumed to have similar levels of productivity because of their proximity, slope angles and exposure, soil, and flora (Shaheen 1998; El-Bana et al. 2002a). The density and cover of perennial vegetation on El Fusiyat island (ungrazed) is much greater than that on El Malty island (overgrazed) despite the physical similarity of the areas.

Sampling Methods

To determine possible vegetational and microenvironmental changes of *R. raetam* (white broom) nebkhas in response to protection for 12 years, we randomly selected 30 widely spaced nebkhas (the distance between neighboring nebkhas varied between 10 and 15 m) on the protected and 30 on the overgrazed island, hereafter called "ungrazed" and "grazed," respectively. We measured length (L), width (W), and height of each selected nebkha. Nebkha area was calculated using the formula for the area of an ellipse (i.e., $[\pi(L \times W)]/4$). The canopy diameter and height of *R. raetam* individuals inhabiting each nebkha were recorded. Mean canopy diameter was calculated as the average of maximum and minimum canopy diameter. The litter area on each nebkha was calculated from the mea-

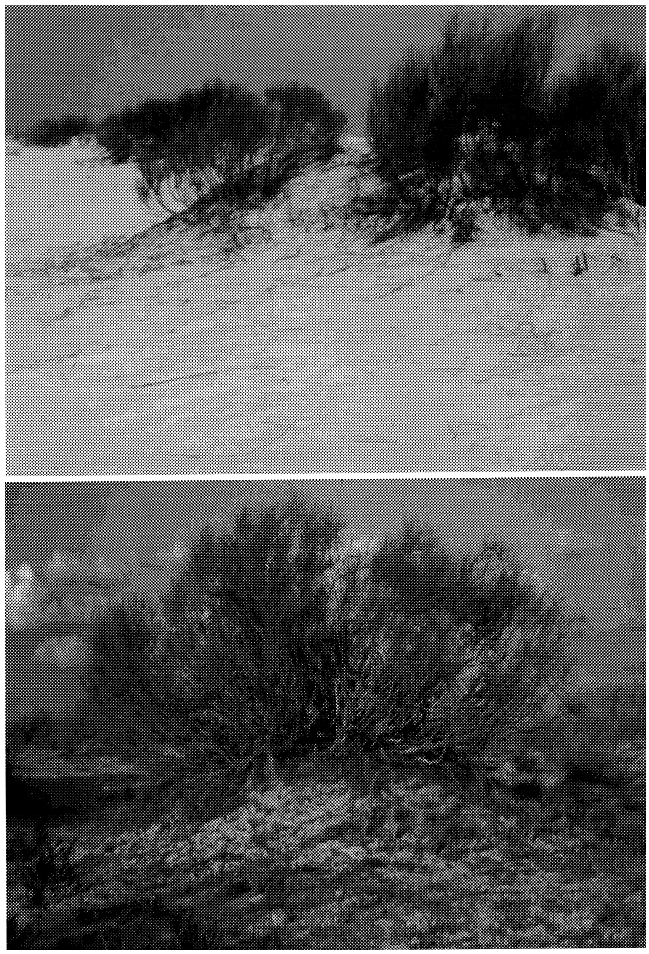

Figure 1. Top: Nebkhas of *Retama raetam* (white broom) in the grazed island of El Malty. Note the ripples and blowouts without litter cover. Bottom: Close-up view of a nebkha at the ungrazed island of El Fusiyat, showing natural regeneration. Note the dense herbaceous vegetation and litter cover.

surements of the major and minor axes through the center of each litter patch (De Soyza et al. 1997).

For each selected nebkha 8-m long transects were placed, radiating out in the four cardinal directions from the nebkha center to the internebkha spaces. Along each transect a series of four 1-m^2 quadrats were randomly placed to record the number of herbaceous plant species, two on the nebkha patches and the other two in the internebkha spaces. Because a previous study (El-Bana et al. 2002b) showed no effect of aspect on community structure, we pooled the data from the four cardinal directions into a single value and used that value in subsequent analysis. We calculated the mean abundance and frequency of presence per species in nebkha and internebkha patches. Nomenclature was according to Täckholm (1974) and Boulos (1995).

Species richness was calculated as total number of species occurring per unit area (1 m^2). This is a simple and easily interpretable indicator of biological diversity (Huston 1994). We further calculated the proportion of species recorded on the site that were found only on *R. raetam* nebkha patches and the proportion found only in internebkha spaces at both grazed and ungrazed sites.

To test whether the microclimate and soil properties of the grazed nebkha patches were different from those in the ungrazed patches, 10 nebkhas of comparable size (basal area ranged from 4.48 to 6.53 m^2) were selected at each site. We measured soil temperature and photosynthetically active radiation (PAR) at 0.5, 1.0, 1.5, 2.0, and 4.0 m from nebkha center to internebkha space between 12:00 and 14:00 hr local time during May 2000 under clear sky conditions. Incident PAR was registered at 30 cm above the ground using a gallium arsenide sensor (JYP-1000, SDEC France). Soil temperature was recorded at a depth of 2 cm below the soil surface using a thermistor probe (4 × 10 K, EC-95 thermistors in line). All sensors were interfaced to portable data loggers (DL2, Delta-T Devices, Burwell, U.K.) for data acquisition.

Three soil samples from the top 30 cm were collected and mixed from each of the 10 selected grazed and ungrazed nebkhas of comparable size. The same number of soil samples was taken in the internebkha spaces. Hence, 40 soil samples were collected and each treatment (microhabitat and grazing) had 10 replicates for all the subsequent analysis. Soil texture was determined with the hydrometer method, providing quantitative data on the percentage of sand, silt, and clay. Soil moisture content was calculated from the difference between weights before and after drying at 105°C for 48 hr. Organic matter was estimated by drying and then ignition at 600°C for 3 hr. Soil electrical conductivity was determined in an aqueous solution (20 g soil dissolved in 40 mL distilled water and manually shaken for 2 hr) using a digital conductivity meter (YSI Incorporated, OH, U.S.A.). Total nitrogen (N) was determined using the micro-Kjeldahl method and concentrations of the cations Na^+ and K^+ using a Corning 410 flame photometer.

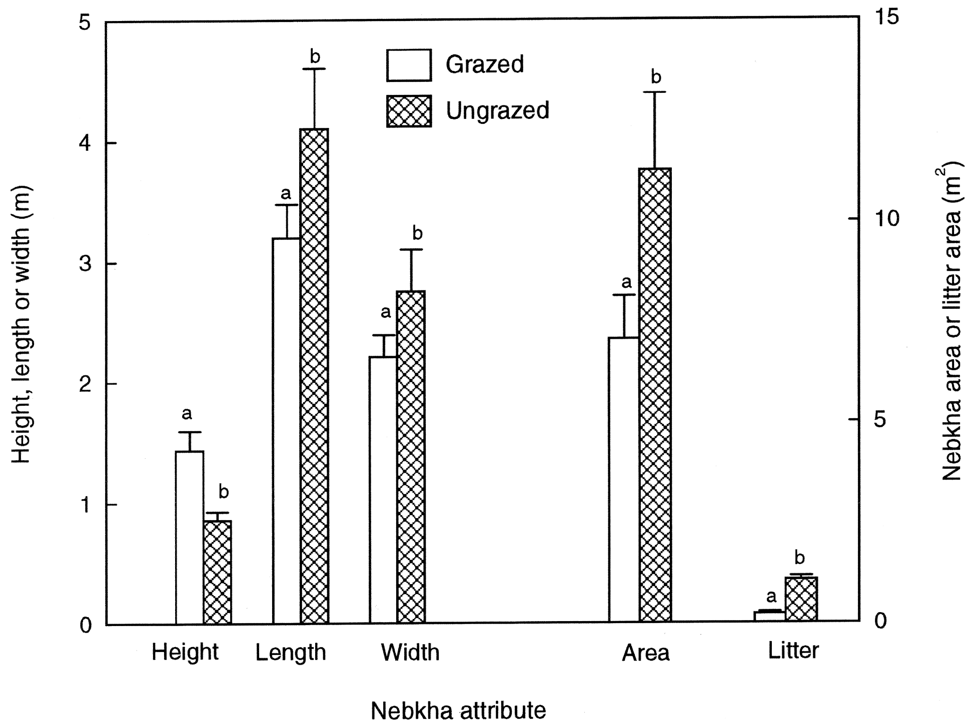

Figure 2. Height, length, width, area, and litter area of *Retama raetam* (white broom) nebkhas at the ungrazed and the grazed sites. Bars are averages ± 1 SE of 30 replicates; different letters indicate significant differences at $p < 0.05$ (Tukey's studentized range test).

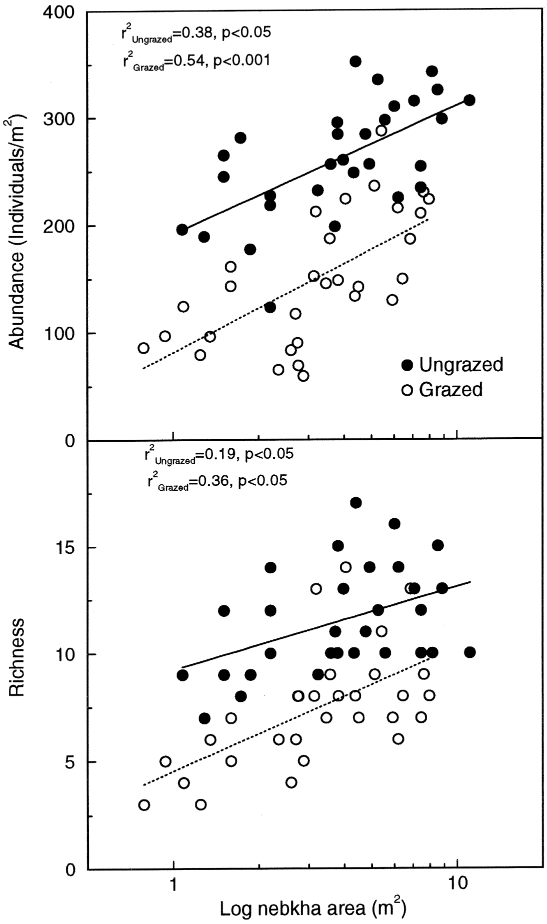

Figure 3. Relationships between abundance, richness of herbaceous species, and nebkha area at ungrazed and grazed sites.

Data Analysis

Regression analysis was performed to determine the relationship between nebkha area and abundance and richness of species found on each nebkha. One-way analysis of variance using SYSTAT 7.0 followed by Tukey's studentized test (Wilkinson 1997) was used to compare the microclimate and soil properties.

Results

Nebkha characteristics differed significantly between grazed and ungrazed sites (Figs. 1 & 2). Mean length, width, and area of ungrazed nebkhas were greater than their grazed counterparts. In contrast, grazed nebkhas were higher than ungrazed ones. Mean canopy diameter of the *Retama* plants for grazed nebkhas was 2.41 m (range of 1.1–3.8 m) and for ungrazed nebkhas was 3.23 m (range of 1.3–4.7 m). The average area of litter accumulation on ungrazed nebkhas was consequently much greater than on grazed ones.

At the grazed sites nebkha area explained 54 and 36% of the variance in species abundance and richness recorded on the nebkhas, respectively (Fig. 3), whereas only 38 and 19% were explained at the ungrazed sites. Grazing had a negative effect on the abundance and the richness of herbaceous species at both internebkha spaces and nebkha patches (Table 1 & Fig. 4a and b). The effect of grazing on both species richness and abundance was dependent on microhabitat (nebkha versus internebkha space) (Table 1 & Fig. 4c). At the grazed site an average of 42 and 7% of the species were restricted to nebkha and internebkha patches, respectively, whereas at the ungrazed

Table 1. Analysis of variance summary table showing F values and level of significance for the effects of microhabitat (nebkha vs. internebkha) and grazing on the abundance and richness of herbaceous plants.

Source	*df*	*Abundance*	*Richness*
Microhabitat	1	36.67***	29.39***
Grazing	1	92.66***	69.57***
Microhabitat by grazing	1	1.24*	1.78*

*** $p < 0.001$, * $p < 0.05$.

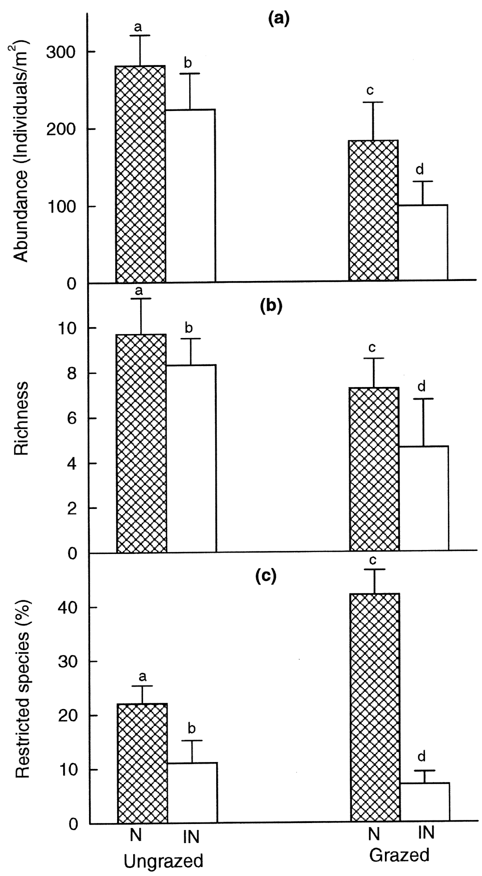

Figure 4. Abundance (a), richness (b), and the proportion of species in a site found exclusively on *Retama raetam* nebkhas (N) or in internebkha spaces (IN) (c) for ungrazed and grazed sites. Bars are averages ±1 SE of 30 replicates; different letters above bars indicate significant differences at $p < 0.05$ (Tukey's studentized range test).

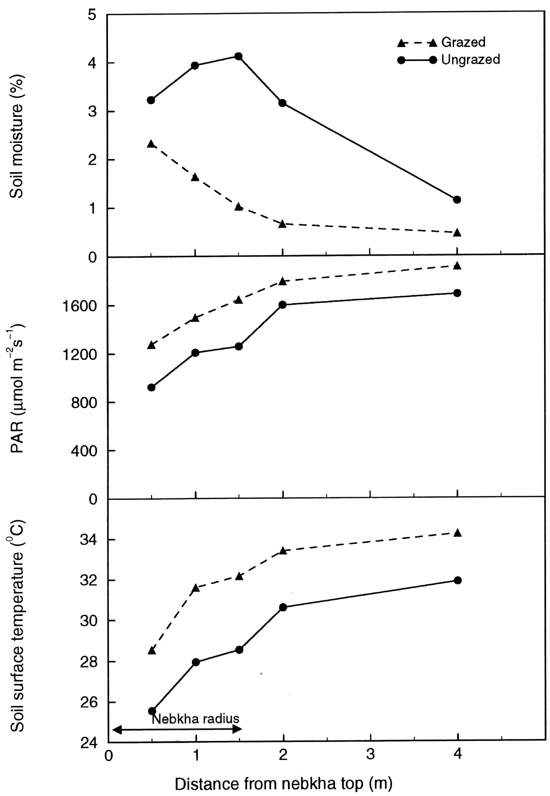

Figure 5. Spatial variation in microclimate as a function of distance from nebkha center. For each variable there was a significant differences at $p < 0.05$ (Tukey's studentized range test) between grazed and ungrazed positions.

sites 22 and 11% of the species were found only in nebkha and internebkha patches, respectively.

At the species level, in the grazed site the three palatable grasses (*Bromus rubens* [foxtail brome], *Panicum turgidum* [Sahara millet], and *Stipagrostis plumosa*) were recorded only at the nebkha patches (Appendix). The two short grasses (*Cutandia dichotoma* and *Schismus arabicus* [Arabian grass]) and the two forbs (*Lotus halophilus* [greater bird's foot trefoil] and *Senecio glaucus* [groundsel]) had a high frequency in the two microhabitats at both grazed and ungrazed sites. The short forbs (*Filago desertorum* [cudweed], *Herniaria hirsuta* [rupturewort], and *Ifloga spicata* [zenaymeh]) attained high values in the internebkha spaces at both sites.

The soil microclimate conditions differed between grazed and ungrazed locations and between nebkha and internebkha space (Fig. 5). At the ungrazed and grazed sites soil temperatures and PAR were lowest on nebkha centers and increased toward the internebkha space. Soil temperature and PAR were significantly higher at the grazed sampling positions than at the ungrazed ones. In contrast, soil moisture content decreased as a function of the distance to nebkha top, with higher values at the ungrazed locations.

The comparison of the soil variables by microhabitat and grazing is shown in Table 2. There were significant differences in soil texture and organic matter content related to grazing and microhabitat. The proportion of finest soil particles was higher on ungrazed nebkhas than on grazed ones and in the adjacent internebkha patches. The soils of ungrazed nebkhas had significantly higher organic matter content, total nitrogen, electrical conductivity, Na^+, and K^+ than of grazed ones. However, there was no significant difference in the total nitrogen between the soils of grazed nebkha and the adjacent internebkha spaces.

Discussion

The homeostatic environments of unpalatable *R. raetam* nebkha patches can have a strong effect on the structure of vegetation in northern Sinai, causing large increases in plant species abundance and richness in the degraded rangelands. This reveals that *R. raetam* nebkhas can be considered as "vegetation islands" in areas where soil is subject to severe deflation (El-Bana et al. 2002b). In previous studies phytogenic hillocks in desert regions have been regarded as "safe sites" for plants in sand-depleted and oil-polluted areas (Brown & Porembski 1997, 2000).

Land degradation resulting from heavy grazing in northern Sinai has been repeatedly identified as the main factor for albedo contrast in a satellite view between northern Sinai and western Negev (Tsoar 1995; Tsoar & Karnieli 1996). However, no field studies have yet tried to experi-

Table 2. Variation of soil properties between microhabitats (nebkha and internebkha) in the ungrazed and grazed sites.

	Ungrazed		*Grazed*	
Soil Factor	*Nebkha*	*Internebkha*	*Nebkha*	*Internebkha*
Sand (%)	86.2^a	94.1^b	89.1^c	95.5^d
Silt + clay (%)	13.8^a	6.5^b	10.3^c	4.4^d
Electrical conductivity (mS/cm)	0.82^a	0.63^b	0.58^c	0.38^d
Organic matter (%)	2.13^a	1.24^b	1.75^c	0.75^d
Total N (μg/g)	45.7^a	22.9^b	29.6^c	26.4^{bc}
Na (μg/g)	129.3^a	75.8^b	82.8^c	64.7^d
K (μg/g)	44.7^a	32.8^b	29.6^c	20.5^d

Values in a row with different letters are significantly different according to Tukey's studentized range test at $p < 0.05$.

mentally investigate land degradation in northern Sinai. Our data show that heavy grazing had a negative effect on nebkha attributes and on abundance and richness of herbaceous species in both nebkha and internebkha patches. The greater nebkha height in the grazed site suggests that soil erosion is more prevalent (i.e., with greater net losses) within internebkhas, but this soil can accumulate on nebkhas. This indicates that the cladodes of *R. raetam* shrub are effective in capturing and retaining soil. However, the reduction in the area of the grazed nebkhas implies that grazing led primarily to wind erosion on the circumference of the nebkhas, causing an increase in small scale soil redistribution on the nebkhas (i.e., increased height). Because *R. raetam* is poisonous and unpalatable (El Bahri et al. 1999), animals avoid walking or grazing on its cladodes, so that soil accumulates at the bases. Danin (1996) reported that *R. raetam* shrub can survive under cycles of accumulation and deflation of sand.

In both grazed and ungrazed sites the positive effect of *R. raetam* nebkhas on plant abundance and richness was dependent on nebkha area. However, the influence of area was greater in the grazed site, where grazing pressure was stronger in the internebkha spaces. In these areas heavy grazing and trampling enhance wind erosion and degradation. As a result fine soil particles, organic matter, nutrients, and seeds are transported from the internebkha spaces to the nebkha patches. In arid and semiarid environments the mound-plant patches can act as sinks for resources from the adjacent microphytic and bare patches (sources) (Ludwig & Tongway 1996; Tongway & Ludwig 1996; Shachak & Lovett 1998; Shachak et al. 1998; Bochet et al. 2000). We suggest that heavy grazing may intensify this source–sink relationship by increasing the proportion of sources. This effect was clear from the higher contribution of the plants that grew on the nebkhas to the site-level diversity at the grazed site. Therefore, as reported by Brown and Porembski (1997, 2000), nebkhas had a more positive effect on plant diversity when the environmental conditions were harshest.

The absence of several palatable species at both microsites in the grazed site indicates that direct consumption by grazing animals could contribute to lower abundance and richness of species. The restriction of other palatable species to the nebkha patches of the grazed site seems to occur for two reasons. First, the unpalatable cladodes of *R. raetam* may prevent grazing animals from gaining access to these species in the nebkha. Second, in addition to protection from animal grazing, the soil enrichment and moderate microclimate in the nebkha may enhance seed germination and seedling development.

The higher richness and abundance of plant species on the ungrazed nebkhas compared with the grazed ones could be related to greater nebkha area, higher organic matter accumulation, or the formation of fine-textured soil that increased soil moisture content and nutrient availability of nebkhas. Improved moisture conditions in nebkha soils (Brown & Porembski 1997) are well known to control plant diversity and vegetation dynamics. During the recovery of sand degraded habitats, plant diversity is strongly influenced by soil texture, particularly the fine soil particles that improve the moisture regime of soil, but only up to a point (Danin 1978, 1996).

Soil moisture, PAR, and soil temperature were all highly variable between grazed and ungrazed microsites. It has been shown that the grazed internebkha spaces had the highest mean soil temperature and PAR values and the lowest soil moisture. The topsoil in the grazed internebkha spaces is continuously being changed by trampling, which allows greater surface heating than the stabilized soil with litter accumulation of the ungrazed site. The highest soil moisture of the ungrazed nebkhas might be partly related to increased organic matter and fine texture accumulation (see below).

It has been shown that soil properties were strongly modified by grazing and microsite. Soils on the grazed and ungrazed nebkha patches had a significantly greater fraction of fine particles and nutrient concentrations than soils in the adjacent internebkha spaces. However, the higher proportion of these variables in soils of ungrazed nebkhas compared with grazed ones could be related to their larger canopy diameter and higher moisture content. These are the main factors for dry fine particle deposition in the arid and semiarid environments (Danin 1996; Moro et al. 1997; Shachak & Lovett 1998).

Following these arguments one would expect greater differences in soil nutrients between the ungrazed and grazed patches. Higher concentrations of total nitrogen and the essential ions Na^+ and K^+ were associated with changes in soil texture and higher organic matter concentration in soils of ungrazed nebkhas. It is probable that the greater canopy and litter cover on ungrazed nebkhas with their relatively high water content and lower temperature stimulate organic matter decomposition by soil microbial activity. Hesp and McLachlan (2000) found that litter production was the main factor affecting the abundances of amphipods and nematodes inhabiting nebkhas. The current study shows that soils in the grazed internebkha spaces had similar total nitrogen to soils in the adjacent nebkha patches. This is probably due to grazing animals, either through dung and urine deposition or by redistribution of organic matter from the nebkha patches to the surrounding internebkha spaces. Herbivores recycle about 75–85% of the nitrogen they remove from vegetation (Russelle 1992).

Conclusions and Implications

Our results indicate that *R. raetam* nebkhas are a unique microhabitat in degraded rangelands. Because of their specific soil properties, nebkhas represent patches of high water and nutrient availability for plants, which can deeply influence vegetation function and particularly plant diversity. Disturbance and destruction of these patches by overgrazing can reduce resource availability, negatively affecting natural biological functions in degraded rangelands of the Middle East (Brown & Porembski 1997). An important component of restoration programs in degraded ecosystems is to reduce the loss of resources by increasing the potential for sinks to develop (Shachak & Lovett 1998). Nebkhas and their host plants may be useful in this respect by increasing soil surface roughness and improving hydrologic and nutrient cycling processes through the capture of water, soil, nutrients, and organic materials. By managing this spatial heterogeneity, the system's productivity could be enhanced and degraded rangelands in arid and semiarid ecosystems rehabilitated.

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Appendix

List of herbaceous species with their presence percentage recorded in nebkha and internebkha microhabitats at both ungrazed and grazed islands of Lake Bardawil.

		Ungrazed		*Grazed*	
Family	*Species*	*Nebkha*	*Internebkha*	*Nebkha*	*Internebkha*
Alliaceae	*Allium papillare*	3*	0	0	0
Amaryllidaceae	*Pancratium maritimum*	86*	0	33*	0
	Pancratium sickenbergeri	27	20	86	100
Asteraceae	*Atractylis carduus*	20*	0	13*	0
	Centaurea calcitrapa	86*	0	33*	0
	Filago desertorum	0	100	47	93
	Ifloga spicata	7	86	33	100
	Launaea capitata	0	13	20	47
	Launaea nudicaulis	27*	0	6*	0
	Reichardia tingitana	0	20	7	0
	Senecio glaucus	20	47	86	100
Brassicaceae	*Eremobium aegyptiacum*	0	0	6	20
	Lobularia arabica	67	13	20*	0
Caryophyllaceae	*Herniaria hirsuta*	13	47	33	60
	Silene vilosa	20*	0	7*	0
Euphorbiaceae	*Euphorbia granulata*	7	20	0	13
Fabaceae	*Astragalus annularis*	7*	0	0	0
	Astragalus boeticus	3*	0	0	0
	Astragalus kahiricus	33	13	0	0
	Lotus halophilus	33	53	53	80
	Ononis serrata	33	100	7	20
	Trigonella stellata	13*	0	0	0
Lilaceae	*Asphodelus viscidulus*	0	13	0	20
Neuradaceae	*Neurada procumbens*	0	6	0	20
Orobanchaceae	*Orobanche cernua*	13*	0	6*	0
Plantaginaceae	*Plantago ovata*	27	86	13	93
Poaceae	*Avena sativa*	6*	0	3*	0
	Brachypodium distachyum	6*	0	2*	0
	Bromus rubens	67*	0	27*	0
	Cutandia dichotoma	47	67	86	100
	Panicum turgidum	33	47	13	0
	Poa annua	6*	0	0	0
	Schismus arabicus	67	80	93	73
	Stipagrostis plumose	60	47	20	0
Ranunculaceae	*Adonis dentata*	7	27	13	60

*Species restricted to nebkhas for ungrazed and grazed sites.