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Effects of *Caragana microphylla* patch and its canopy size on "islands of fertility" in a Mongolian grassland ecosystem

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Abstract In arid and semiarid regions, variations in "islands of fertility" accompanied by discontinuous vegetation is frequently observed. However, the effects of vegetation patches on soil, including the influence of canopy size, are not fully understood, particularly under conditions of severe grazing. We examined the effects of patches of mound-forming shrub, *Caragana microphylla*, and the plant's canopy size on these islands of fertility in a heavily grazed Mongolian grassland. In 11 patches with various canopy sizes (32.5–180 cm in diameter), we compared the chemical properties of soils among three microsites: Mound, Below, and Around, which were inside, below, and outside of *C. microphylla* mounds, respectively. Total carbon (C) and most essential elements for the plants were more concentrated in Mound, but total nitrogen (N) and nonlimiting elements, such as exchangeable sodium (Na), did not significantly differ among microsites. Larger canopies more strongly affected the enrichment of total C and most essential elements, including total N, in Mound. These results suggest that *C. microphylla* patches substantially enrich total C and most essential elements and that the extent of enrichment was intensified with canopy size. However, under severe grazing, total N may be relatively more affected by the redistribution of resources through grazing, particularly when the canopy size is small.

Keywords Livestock grazing · Microsite · Semiarid · Shrub · Soil nutrient · Vegetation mound

Introduction

In arid and semiarid regions, the vegetation is often discontinuous because qualitative and quantitative restrictions occur via plant competition for soil water and nutrients (Noy-Meir 1973; Wedin and Tilman 1990; Frelich et al. 1993; Augustine 2003). Within such vegetation patches, "islands of fertility" are often observed (Charley and West 1975; Garner and Steinberger 1989; Hook et al. 1991). These islands of fertility are created by nutrients gathered from surrounding areas by expanded roots, as well as nutrients accumulated beneath the canopies by litterfall (e.g., Garner and Steinberger 1989; Schlesinger et al. 1990; Hook et al. 1991). In the case of shrubs, mounds often accompany these vegetation patches, especially in windy regions (Burke et al. 1999). Mounds are structures that are microtopographically swollen compared with the surrounding soil surface. The mechanisms of mound formation include the trapping of flowing particles, accumulation of plant litter, and prevention of wind erosion (e.g., Burke et al. 1999; El-Bana et al. 2002; Facelli and

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Temby 2002). These mechanisms can intensify islands of fertility because flowing particles and plant litter contain nutrients (Szott et al. 1991; Scholes and Archer 1997). For example, Burke et al. (1999) demonstrated that the soil in mounds of *Bouteloua gracilis* had higher total soil carbon (C) and nitrogen (N), higher C and N in coarse particulate organic matter, and higher rates of C and N potential mineralization. Similarly, El-Bana et al. (2002) reported that the soil of *Retama raetam* mounds had higher soil moisture, larger pools of organic C and total N, and higher concentrations of phosphorus (P), sodium (Na^+), and potassium (K^+) compared with surrounding soils. Several previous studies have demonstrated that for soil nutrients under tree canopies, the extent of enrichment is correlated with canopy size or tree age (Barth 1980; Bernhard-Reversat 1982; Klemmedson and Tiedemann 2000; Ludwig et al. 2004). Because enrichment of soil nutrients in mounds is expected to intensify under larger canopies, the effects of canopy size should be considered when examining the effects of vegetation mounds on local soil properties.

Caragana microphylla, a dominant plant species in Mongolian grasslands, is a leguminous deciduous shrub that forms various-sized mounds. This species is a typical C_3 shrub that fixes atmospheric N (Liu et al. 2004) and can grow under poor nutrient conditions (Su et al. 2005). Due to its N_2-fixing abilities, *C. microphylla* plays an ecologically important role in N cycling in arid ecosystems (Virginia 1986; Bernhard-Reversat 1988; Scholes and Archer 1997). This shrub has been used in plantations as a sand barrier and/or windbreak in sandy Chinese lands that suffer from severe wind erosion (Su et al. 2005). Whereas *C. microphylla* strongly resists grazing because of the spines on its stems (Xiong et al. 2003; Zhang et al. 2006), it often serves as supplemental livestock forage due to its high nutrient value (Liu et al. 2004). Thus, *C. microphylla* is an ecologically key species in northeast Asian grasslands. Previous studies in Chinese plantations under nongrazed conditions demonstrated the erosion-control abilities of *C. microphylla*, as well as higher C and N concentrations in soil under its canopy (e.g., Su and Zhao 2003; Su et al. 2005; Zhao et al. 2007). However, Mongolian grasslands are characterized by severe livestock grazing that can alter the redistribution processes of organic resources on the soil surface (e.g., Garner and Steinberger 1989; Hook et al. 1991), and the effects of *C. microphylla* mounds on local soil properties under such conditions are not yet fully understood.

The objectives of this study were to determine soil chemical properties, including inorganic N availability, of mounds formed by *C. microphylla* and to examine the effects of canopy size on the extent of islands of fertility in a Mongolian grassland ecosystem.

Materials and methods

Study site

The study site is located on a gently sloped hill (45°48′N, 106°11′E, about 1,560 m in elevation) near Mandalgobi Town, Dundgobi Province, Mongolia. This area is a steppe ecological zone where the vegetation is generally dominated by perennial grasses, forbs, or shrubs, depending on the landscape position and climatic conditions (Sasaki et al. 2008b). The Mongolian grassland has a long grazing history by domestic livestock under nomadic or seminomadic land use (Sasaki et al. 2008b). The main livestock in this region are sheep, goats, and cattle; the most grazed livestock are sheep (Sasaki et al. 2008b). Near our study site, there is a livestock camp where nomads keep their livestock at night during winter. The camp is about 400 m away from our study site and kept ∼500 head of livestock (Sasaki et al. 2007). The climate is characterized by strong winds, with an annual mean wind velocity of 4.7 m s^{-1} (National Climate Data Center 2008). The mean annual precipitation was 156.2 mm from 1998 to 2007, and about 80% of the precipitation fell as rain during July and August (National Climate Data Center 2008). The mean annual air temperature was 3.0°C, ranging from −17.3°C in January to 21.1°C in July (National Climate Data Center 2008). The climatic conditions were measured at a weather station in Mandalgobi Town about 10 km from our study site. The soils of the region are classified as Aridisols based on US Department of Agriculture (USDA) Soil Taxonomy (Soil Survey Staff 2006), and the texture is sandy loam or sandy silt loam with abundant gravel. The discontinuous vegetation on the hill slope is dominated by *C. microphylla* and *Artemisia adamsii*. Patches of *C. microphylla* form mounds, the diameters of which are typically smaller than the shrub canopy.

Soil sampling

At the study site, 11 *C. microphylla* patches (canopy diameters of 32.5–180 cm) were selected within 4 ha to examine soil chemical properties. For each patch, we recorded heights and diameters of their mound and canopy (Table 1). The height was the difference from the surrounding soil surface. The diameter was the average length for the longest and its orthogonal diameters. On 14 August 2007, soils were collected from three microsites of each patch using a 100-ml soil core. For each microsite, soils were sampled from three directions (north, southwest, and southeast) and then combined to avoid bias based on the prevailing wind direction. The first microsite was located horizontally 30 cm inside of the edge of the mound. When the radius of a mound was <30 cm, the first microsite was

located around the center. Soil samples were collected from 5 to 10 cm from the surface of the mound (hereafter Mound) (Fig. 1). The second microsite was below Mound, and soil samples were taken at 5–10 cm from the surrounding soil surface (hereafter Below) (Fig. 1). The third microsite was horizontally located 50 cm outside of the edge of the mound, and soil samples were collected 5–10 cm from the soil surface (hereafter Around) (Fig. 1).

Laboratory analysis

Soil samples were air-dried and passed through a 2-mm sieve to remove debris and gravel. These samples were used for analyses of soil electrical conductivity (EC), pH [water (H_2O)], inorganic N pools, total C and N pools, available P pool, exchangeable cation pools [Na, K, calcium (Ca) and magnesium (Mg)], and net N transformation

rates. Soil EC and pH (H_2O) were measured using electrodes in 1:5 and 1:2.5 soil–water suspensions, respectively. For ammonia (NH_4^+–N) and nitrogen nitrate (NO_3^-–N) pools, a 4.5-g soil sample was extracted with 45 ml of 2 M potassium chloride (KCl), and the concentrations of NH_4^+–N and NO_3^-–N in the extracts were determined colorimetrically using the Indo-phenol blue method and diazotitation after reduction to NO_2^-–N by zinc powder (Keeny and Nelson 1982). For net soil N transformation rates, a 4.5-g soil sample was incubated in the dark at 25°C for 28 days, with moisture held constant at 60% of the water-holding capacity. After incubation, NH_4^+–N and NO_3^-–N pools were determined using the methods described above. The net N mineralization rate was calculated as the difference in total inorganic N (NH_4^+–N + NO_3^-–N) pool before and after incubation, and the net nitrification rate was calculated as the difference in the NO_3^-–N pool before and after incubation. For total C and N pools, soil samples were powdered and analyzed using a CN coder (MT-700; Yanaco, Kyoto, Japan). For the available P pool, a 1.25-g soil sample was extracted, with 25 ml of 0.5 M sodium bicarbonate ($NaHCO_3$), adjusted to pH 8.5, and the concentration of inorganic P in the extracts was determined colorimetrically using a molybdate–ascorbic acid method (Olsen and Sommers 1982). For exchangeable cations, a 3-g soil sample was extracted with 30 ml 1 M ammonium acetate (CH_3COONH_4) at pH 7. Concentrations of exchangeable K and Na in the extracts were measured using flame emission, and concentrations of exchangeable Ca and Mg in extracts were determined using atomic absorption spectrophotometry (AA660; Shimadzu, Kyoto, Japan).

Statistical analysis

Mean values of the soil chemical properties were compared among the three microsites (Mound, Below, and

Table 1 The size of mounds and canopies in patches of *Caragana microphylla*

Individual numbers	Mounds		Canopies	
	Diameter (cm)	Height (cm)	Diameter (cm)	Height (cm)
1	70.0	14	90.0	27
2	30.0	6	32.5	9
3	50.0	11	67.5	25
4	45.0	10	50.0	12
5	32.5	8	52.5	29
6	175.0	39	180.0	33
7	55.0	18	115.0	48
8	45.0	11	77.5	39
9	60.0	12	95.0	36
10	77.5	24	115.0	36
11	32.5	10	70.0	32

Fig. 1 Location of each microsite (Mound, Below, Around)
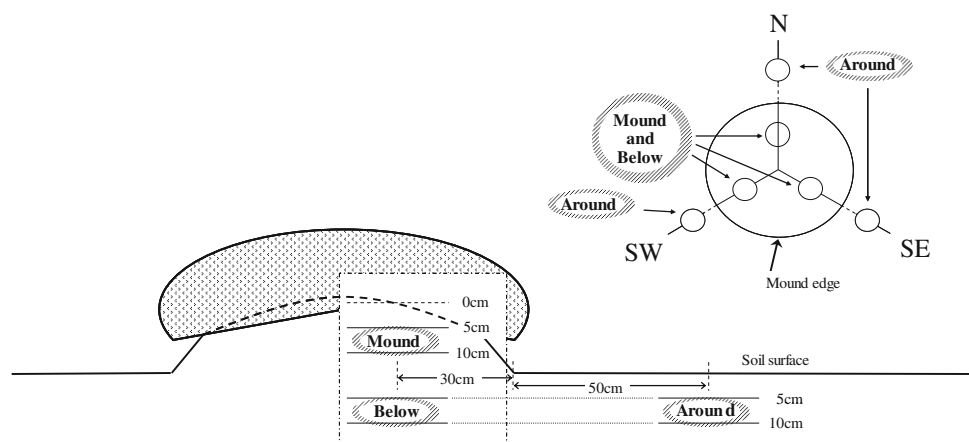
Table 2 Values of soil properties at three microsites of *Caragana microphylla* patches in a Mongolian grassland [mean ± standard error (SE)] ($n = 11$)

Soil properties	Mean value (±SE)		
	Mound	Below	Around
EC (mS m^{-1})	31.8 (±4.72)[a]	27.2 (±2.52)[a]	13.3 (±2.52)[b]
pH (H$_2$O)	7.34 (±0.08)[a]	6.46 (±0.12)[b]	6.77 (±0.10)[b]
Inorganic N pools (g-N m^{-2})	3.46 (±0.51)[a]	1.89 (±0.19)[b]	1.03 (±0.25)[b]
Net N mineralization rate (g-N m^{-2} 28 days^{-1})	2.07 (±0.28)[a]	0.77 (±0.05)[b]	0.68 (±0.08)[b]
Net nitrification rate (g-N m^{-2} 28 days^{-1})	4.15 (±0.35)[a]	1.22 (±0.05)[b]	1.12 (±0.16)[b]
Available P pool (g-N m^{-2})	6.09 (±0.61)[a]	2.68 (±0.11)[b]	2.31 (±0.19)[b]
Total C pool (g-C m^{-2})	483.7 (±22.2)[a]	425.4 (±8.27)[b]	393.2 (±13.4)[c]
Total N pool (g-N m^{-2})	62.3 (±1.16)[a]	59.9 (±0.78)[a]	60.4 (±0.99)[a]
Exchangeable Na pool (g-Na m^{-2})	5.26 (±0.30)[a]	4.15 (±0.23)[b]	4.63 (±0.20)[ab]
Exchangeable K pool (g-K m^{-2})	100.0 (±4.17)[a]	79.4 (±5.99)[b]	83.1 (±5.23)[b]
Exchangeable Ca pool (g-Ca m^{-2})	263.9 (±19.5)[b]	343.7 (±22.0)[a]	322.9 (±22.6)[a]
Exchangeable Mg pool (g-Mg m^{-2})	46.6 (±2.40)[a]	53.6 (±3.22)[a]	54.2 (±2.92)[a]

EC electrical conductivity, *N* nitrogen, *P* phosphorus, *C* carbon, *Na* sodium, *K* potassium, *Ca* calcium, *Mg* magnesium

Values denoted by the same letter are not significantly different from each other at $P < 0.05$ (Tukey's honesty significant difference test)

Around) using one-way analysis of variance (ANOVA). The multiple comparisons of mean values among three microsites were performed by Tukey's honestly significant difference (HSD) test. To examine the effect of *C. microphylla* canopy size on the extent of the islands of fertility, canopy size was regressed against differences in soil properties between Mound and Around. All statistical analysis was performed using the STATISTICA 06J software (StatSoft Inc. 2005).

Results

Soil chemical properties varied significantly among the three microsites ($P < 0.05$; Table 2), with the exceptions of pools of total N and exchangeable Mg ($P > 0.05$).

Soil EC was significantly higher in Mound and Below than in Around, and soil pH (H$_2$O) was significantly higher in Mound than in Below or Around (Table 2). Pools of total inorganic N and total C were significantly larger in Mound and significantly smaller in Around compared with Below (Table 2). Both types of net N transformation rates were significantly higher in Mound than in Below or Around (Table 2). Similarly, the available P pool was significantly larger in Mound than in Below or Around (Table 2). In contrast, the total N pool did not differ significantly among microsites (Table 2). The exchangeable Na pool was significantly larger in Mound than in Below but did not differ significantly between Mound and Around or between Below and Around (Table 2). The exchangeable K pool was significantly larger in Mound than in Below or Around, whereas the exchangeable Ca pool was significantly smaller in Mound than in Below or Around (Table 2). The exchangeable Mg pool did not differ significantly among microsites (Table 2).

A linear regression analysis indicated that the differences in soil properties (soil EC, inorganic N pool, available P pool, and total C and N pools) between Mound and Around were significantly positively ($P < 0.05$) related to canopy size (Fig. 2a, c, f, g, h). For soil pH, the net N mineralization and nitrification rates, and exchangeable Na, K, Ca, and Mg pools, regressions with canopy size were not significant (Fig. 2b, d, e, i–l).

Consequently, we observed four patterns of differences in soil chemical properties among the three microsites (Table 2; Fig. 2). First, values of soil EC and pools of total inorganic N, available P, and total C (Table 2; Fig. 2a, c, f, g) were higher in Mound and/or Below compared with Around; larger canopy sizes more strongly affected differences between Mound and Around. Second, soil pH (H$_2$O), net N transformation rates, and the exchangeable K pool (Table 2; Fig. 2b, d, e, j) were higher in Mound than in Below or Around, but canopy size did not explain differences between Mound and Around. Third, pools of exchangeable Na, Ca, and Mg (Table 2; Fig. 2i, k, l) did not differ significantly among microsites or were higher in Around compared with Mound; canopy size did not account for differences between Mound and Around. Lastly, the total N pool (Table 2; Fig. 2h) did not differ significantly among microsites, but larger canopy sizes at least partially explained differences between Mound and Around.

Discussion

This study demonstrated clear differences in soil chemical properties and the effects of canopy size among three microsites of mounds formed by *C. microphylla* in a Mongolian grassland (Table 2; Fig. 2). Previous studies have shown that soil beneath plants contains more nutrients
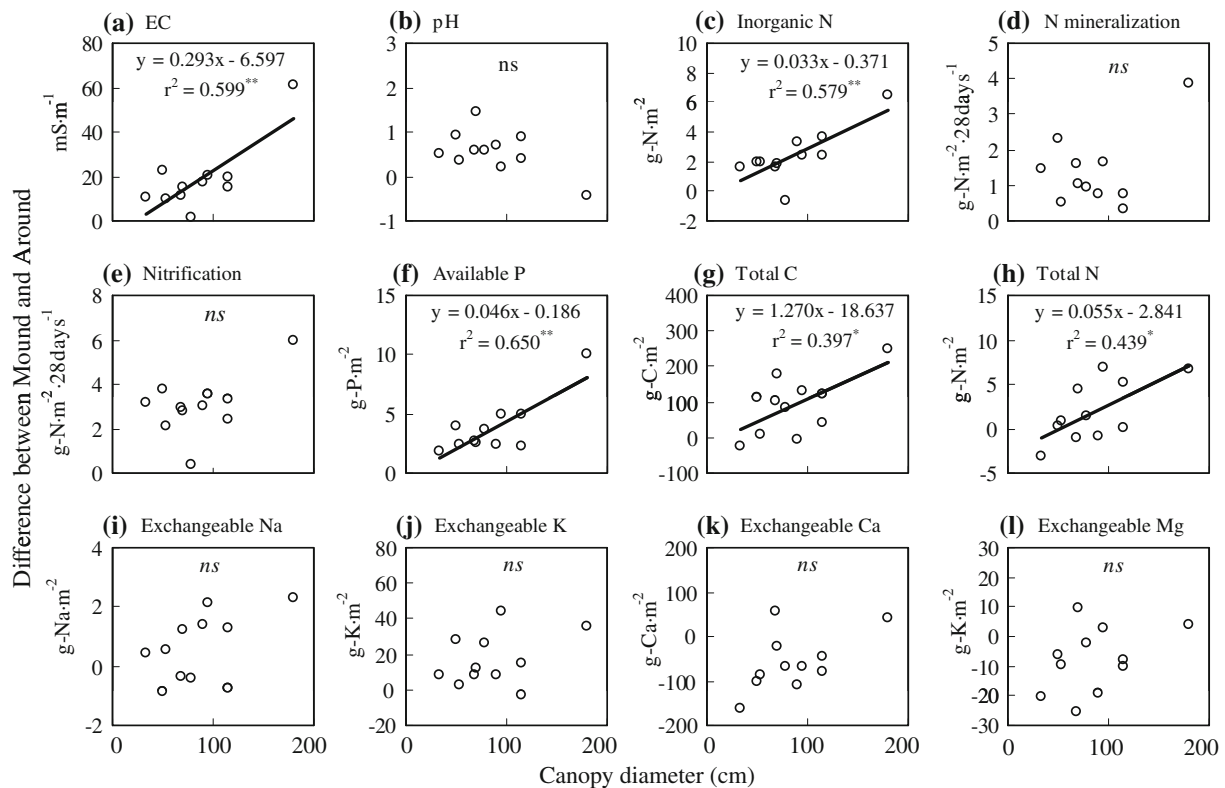
Fig. 2 Canopy size and differences in soil properties between two microsites (Mound and Around). **a** Soil electrical conductivity (EC), **b** pH [water (H₂O)], **c** total inorganic nitrogen (N) pool, **d** net N mineralization rate, **e** net nitrification rate, **f** available phosphorus (P) pool, **g** total carbon (C) pool, **h** total N pool, **i** exchangeable sodium (Na) pool, **j** exchangeable potassium (K) pool, **k** exchangeable calcium (Ca) pool, and **l** exchangeable magnesium (Mg) pool. The *lines* and *equations* show significant regressions. *$P < 0.05$, **$P < 0.01$, *ns* not significant

and/or higher nutrient availabilities (Kelly et al. 1996; Schlesinger et al. 1996; Burke et al. 1999; Wezel et al. 2000; El-Bana et al. 2002; Tompson et al. 2006). For example, the soil in mounds formed by shrubs had higher amounts of total soil C and N, higher rates of potential C and N mineralization, or higher concentrations of P and K compared with bare soil in the shrub interspace (Burke et al. 1999; Wezel et al. 2000; El-Bana et al. 2002; Li et al. 2007). Schlesinger et al. (1996) and Wezel et al. (2000) also demonstrated that available N, P, and K were significantly more concentrated under shrubs than in shrub interspaces, whereas concentrations of Ca, Mg, and Na under shrubs were less than or equal to those in shrub interspaces. Similarly, for *C. microphylla*, total C and N were more concentrated in soil under the canopy than in shrub interspaces (Su and Zhao 2003; Su et al. 2005; Zhao et al. 2007).

Our results were generally consistent with those of previous studies (Kelly et al. 1996; Schlesinger et al. 1996; Burke et al. 1999; Wezel et al. 2000; El-Bana et al. 2002; Tompson et al. 2006). Under discontinuous vegetation cover, different patterns of soil properties among microsites can be caused by shifts in the relative importance of biological and physical processes for a particular soil property (Schlesinger et al. 1996). Soil properties that were higher in Mound compared with the other two microsites (the first and second patterns described above) would likely be more affected by biological processes. Vegetation patches concentrate the biogeochemical cycles of C, N, P, and K in the islands of fertility localized beneath their canopies, whereas adjacent intershrub spaces are comparatively devoid of such biotic activity (Schlesinger and Pilmanis 1998). Carbon and other essential elements for plants (especially limiting nutrients) can accumulate in mounds via one or more of three processes: accumulation of nutrients in plant biomass from adjacent areas via roots, accumulation of litter beneath individual plants, or physical redistribution of litter on the soil surface to prevent loss of deposits by wind (Hook et al. 1991; Szott et al. 1991; Burke et al. 1999; Ludwig et al. 2004; Zhao et al. 2007).

With regard to the effectiveness of canopy cover on local soil properties, previous studies have reported that the extent of enrichment of soil C and nutrients under tree canopies increased with tree age or size (Barth 1980; Bernhard-Reversat 1982; Klemmedson and Tiedemann 2000; Tiedemann and Klemmedson 2000; Ludwig et al. 2004). Higher enrichment of C and nutrients beneath the

canopy with increased tree size was probably due to increased primary production or litter supply per unit area (Bernhard-Reversat 1982; Hook et al. 1991; Tiedemann and Klemmedson 2000) and longer occupancy of a particular area (Hirobe et al. 2001).

The higher values of certain soil properties in Mound (Table 2) could have been caused by the litter supply (e.g., Garner and Steinberger 1989; Hook et al. 1991; Burke et al. 1999) and the trapping of flowing particles (e.g., Szott et al. 1991; Scholes and Archer 1997). Because the extent of enrichment was significantly related to canopy size for soil EC and pools of total inorganic N, available P, and total C (Fig. 2a, c, f, g), biological processes were indeed important for enrichment of these properties in mounds. Canopy size was not related to the enrichment of soil pH (H_2O), net N transformation rates, or exchangeable K pool (Fig. 2b, d, e, j), perhaps suggesting that the enrichment of these properties was more strongly affected by trapping flowing particles than by direct biological processes (i.e., litter supply). Flowing particles are usually composed of surface soil eroded by wind, and the essential elements for the plants are generally more concentrated in surface soil by biological cycling (Jobbágy and Jackson 2001).

Nonlimiting or nonessential elements for plants are often more strongly affected by physical and geochemical processes, such as wind or water movement (Abrahams and Parsons 1994; Schlesinger et al. 1996; Cross and Schlesinger 1999; Jobbágy and Jackson 2001; Housman et al. 2007) For example, Ca, Mg, and Na are often slightly more concentrated in the soil between shrubs in arid regions (e.g., Schlesinger et al. 1996). We observed a similar trend for pools of exchangeable Na, Ca, and Mg (Table 2), and the absence of a significant relationship with canopy size was consistent with the importance of physical processes for the spatial distribution of these properties. However, the trends of Ca and Na among microsites were inconsistent (Table 2). In this region, the surface soil of shrub interspace was eroded by wind, whereas shrubs could protect the surface soil (Sasaki et al. 2008a). This may expose subsurface soil in shrub interspace (Schlesinger et al. 1996) and redistribution of eroded materials onto Mound may cause higher concentration of Ca in Around (Table 2). Na might not be affected by this process because Na is the cation that is most easily leached into deeper soil (Jobbágy and Jackson 2001).

Although previous studies have reported higher pools of total N in mound soils (Burke et al. 1999; El-Bana et al. 2002; Li et al. 2007) or in the soil beneath *C. microphylla* canopies in plantation sites (Su and Zhao 2003; Su et al. 2005; Zhao et al. 2007), the total N pool did not differ significantly among our microsites (Table 2; Fig. 2h). This result may be attributable to the quality of total N differing among microsites, or the soil in Mound may contain a higher proportion of easily mineralizable organic N (Kelly

et al. 1996; Hook and Burke 2000), although data for the constituents of total N were not available. The redistribution process of N by grazers (Garner and Steinberger 1989; Hook et al. 1991; Russelle 1992; El-Bana et al. 2003) may be partially responsible for the observed patterns in total N. Grazers can redistribute 75–85% of N in grazed plant material (Russelle 1992), and our study site has been heavily grazed by sheep, goats, and cattle (Sasaki et al. 2008b). Thus, grazers are likely to have redistributed organic N via their excreta to the shrub interspace. This redistribution process by livestock may more strongly affect the spatial distribution of total N when the canopy size is small, as suggested by the significant relationship with canopy size (Fig. 2h). Under the same grazing condition, a larger proportion of primary production might be redistributed by livestock grazing, especially for the smaller patch with lower primary production. Additionally, the relative importance of biological and physical factors might be changed with canopy size. Further investigation is still needed to clarify the relationship between *C. microphylla* mounds and spatial distribution of total N.

In this study, we demonstrated that *C. microphylla* enriched soil nutrients in their mound, and the extent of enrichment was intensified with canopy size. *C. microphylla* is supposed to be an important livestock forage, especially in spring in Mongolian steppe ecosystem, as *C. microphylla* starts to grow soon after snow melt, whereas herbaceous plants start to grow after a significant rain in early summer (Yamada et al. 2009, Fujita personal communication). In addition, *C. microphylla* provides a nutrient-rich habitat for herbaceous species in summer. Thus, it can be concluded that *C. microphylla* plays a key role in maintaining this ecosystem. In Mongolia, the number of livestock has continued to increase rapidly since the change in the political system in 1991. *C. microphylla* may be disappear if grazing intensity becomes more severe (Sasaki et al. 2008b). *C. microphylla* concervation is considered one of the most important matters for sustainability of this ecosystem.

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