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Scale Dependence of Soil Spatial Variation in a Temperate Desert*[1]

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ABSTRACT

Spatial variation is a ubiquitous feature of natural ecosystems, especially in arid regions, and is often present at various scales in these regions. To determine the scale dependence of the heterogeneity of soil chemical properties and the dominant scales (factors) for soil heterogeneity in arid regions, the spatial variability of soil resources was investigated in the Gurbantunggut Desert of Central Asia at the scales of 10^{-3}, 10^{-2}, 10^{-1}, 10^{0}, 10^{1}, 10^{2}, 10^{3} and 10^{4} m (from individual plant to population or community to ecosystem). Soil chemical properties including pH, electrical conductivity (EC), organic carbon, total nitrogen, available nitrogen, total phosphorus, and available phosphorus were considered in the investigation. At a scale of 10^{-1} m, which represented the scale of individual plant, significant enrichment of soil resources occurred under shrub canopy and "fertile islands" formed in the desert ecosystem. Soil EC exhibited the largest heterogeneity at this scale, indicating that individual plants exerted a great influence on soil salinity/alkalinity. Soil nutrients exhibited the greatest heterogeneity at a scale of 10^{2} m, which represented the scale of sand dune/interdune lowlands (between communities). The main important factors contributing to soil spatial heterogeneity in the Gurbantunggut Desert were individual plants and different topographic characteristics, namely, the appearance of vegetation, especially shrubs or small trees, and existing sand dunes. Soil salinity/alkalinity and soil nutrient status behaved differently in spatial heterogeneity, with an inverse distribution between them at the individual scale.

Key Words: chemical properties, nutrient status, plant, salinity/alkalinity, soil resources, topography

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Spatial heterogeneity is a property generally ascribed to a landscape or population or unit at a smaller scale. It refers to the uneven distribution of various soil or landscape properties within an area. A landscape with spatial heterogeneity has a mixture of concentrations of multiple species of plants or animals (biological), or of terrain formations (geological), or of environmental characteristics (*e.g.*, rainfall, temperature, and wind) covering its area. A population showing spatial heterogeneity is one where various concentrations of individuals of species are unevenly distributed across an area; it is nearly synonymous with "patchy distribution". Spatial heterogeneity of soil resources is recognized as a common feature in natural ecosystems (Robertson *et al.*, 1993; Schlesinger *et al.*, 1996; Gallardo, 2003; Palmer, 2003; Li, J. *et al.*, 2007). Indeed, spatial heterogeneity has long been considered to be a major driver of biological processes (Wang *et al.*, 2007; Zhou *et al.*, 2008) and a basic element of both competitive and facilitative biological interactions (Schlesinger and Pilmanis, 1998; Kumar*et al.*, 2006). Consequently, heterogeneity may determine the occurrence of plants, structure of vegetation, and pattern of landscape, and greatly affect biogeochemical cycles in many ecosystems (Schlesinger *et al.*, 1990; Robertson *et al.*, 1993; Burke *et al.*, 1999; Gallardo, 2003; Bekele and Hudnall, 2006; Zuo *et al.*, 2008).

Of special significance is the common acceptance that the spatial heterogeneity of soil resources is more significant in stressful environments such as arid or semi-arid regions (Schlesinger *et al.*, 1996; Whitford, 2002; Li, J. *et al.*, 2007). Schlesinger and Pilmanis (1998) and Cheng *et al.* (2004) reported that the spatial heterogeneity of soil nutrient distribution was much greater in shrub-dominated arid ecosystems than in grass-dominated vegetation or woody land. Such

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heterogeneity is particularly evident mostly because of the discontinuous distribution of vegetation, which forms "fertile islands" in these areas (Hook *et al.*, 1991; Schlesinger *et al.*, 1996). In addition to higher nutrient contents, physical properties, hydraulic characteristics and biotic activities of the island soils also differ from those in the interspaces between shrubs (Belsky *et al.*, 1989; Whitford *et al.*, 1997).

The scale and intensity at which spatial heterogeneity of soil resources is expressed have important consequences for plants or vegetation (Palmer, 1990; Levin, 1992; Robertson *et al.*, 1993; Schlesinger *et al.*, 1996; Perry, 2002; Kumar *et al.*, 2006; Hanan and Ross, 2010). Conversely, plant and vegetation feedbacks to the soil can also cause its heterogeneity at different scales (Schlesinger *et al.*, 1990; Perry, 2002; Mueller *et al.*, 2008). Hence, soil heterogeneity and its determinant factors are strongly scale-dependent. Specifically, it may exist across a broad range of scales, or be limited to a narrow range of scales (Levin, 1992; Ludwig *et al.*, 2000). The smallest level should be the rhizosphere, which is commonly regarded as the volume of a thin layer of soil immediately surrounding plant roots (Nye, 1981). Due to interactions between the microbial population (Marschner and Römheld, 1996) and root activity, the rhizosphere soil is usually significantly distinguishable from the bulk soil, which is not influenced directly by living roots (Bertin *et al.*, 2003). At the individual plant level, Schlesinger *et al.* (1990) found that shrubs in semi-arid and arid regions formed a self-sustaining system known as a "fertile island" through plant-soil feedback mechanisms, with soil resources accumulating significantly under shrub canopies *via* a combination of biotic and abiotic processes (Hook *et al.*, 1991; Li *et al.*, 2011). At the population or community scale, soil heterogeneity is strongly influenced by patterns of plant spacing and arrangement, which may in turn result in soil patchiness at this scale (Hutchings *et al.*, 2003; Gallardo *et al.*, 2005; Li *et al.*, 2010). There is a strong topographic influence on soil resource heterogeneity and vegetation distribution. The most common features are soil moisture and soil fertility gradients along a slope (Enoki *et al.*, 1996; Sebastiá, 2004; Zuo *et al.*, 2008), with minerals, organic matter and other nutrients accumulating in downslope or interdune areas as a result of wind erosion or soil water movement (Garten *et al.*, 1994; Enoki *et al.*, 1996; Li *et al.*, 2008). At the regional or landscape scale, which can also be recognized as an ecosystem scale, climatic and geomorphologic factors exert strong influences on the spatial heterogeneity of soil and vegetation (Delcourt and Delcourt, 1988). However, topography and vegetation should not be ignored because they are important factors in the formation of detailed landscape patterns (Enoki *et al.*, 1996; Ludwig *et al.*, 2000).

All the studies mentioned above have shown that the spatial heterogeneity of soil exists at scales ranging from the rhizosphere to the landscape or region. However, the scale at which this spatial heterogeneity is most significant and the most important factor to express this heterogeneity are still not known. Therefore, the current study investigated the spatial heterogeneity of soil chemical properties at scales from the rhizosphere to landscape in the Gurbantunggut Desert of Central Asia. Groundwater depth and precipitation are among the factors which influence soil spatial heterogeneity in the Gurbantunggut Desert (Qian *et al.*, 2007). The shrubs in the first few km of the southern edge of the desert can reach groundwater at 5–10 m below the soil surface, while the groundwater depth is much greater than 10 m further inside the desert, which prevents shrubs from reaching that water (Qian *et al.*, 2007). We investigated soil heterogeneity at several different scales, in order to analyze factor(s) or mechanism(s) controlling the soil spatial heterogeneity from the scale of rhizosphere to the scale of landscape in the Gurbantunggut Desert. We hypothesized that the largest heterogeneity might exist at 1) the rhizosphere scale (10^{-3} m), as in a stressful and resource-limited environment a plant root might be expected to do the utmost to modify its microenvironment; 2) the individual plant scale (10^{-1} m) due to the existence of "fertile islands"; 3) the scale of sand dunes or interdune lowlands (10^{2} m), which form a significant topographic wave landscape pattern which should result in physical soil movement and redistribution of soil resources; and 4) the landscape scale (10^{3}–10^{4} m), where the precipitation and groundwater depth gradient result in significant gradients in the vegetation cover and thus a spatial gradient in soil properties would also be expected.

MATERIALS AND METHODS

Study area

A field investigation was conducted from the southern periphery to the hinterland of the Gurbantunggut Desert (86°57′ E, 44°52′ N). The climate of the desert is temperate continental arid (Zhang and Chen, 2002). The mean annual precipitation is about 160 mm, while mean annual pan evaporation is about 1 000 mm, and the annual mean air temperature is about 6.6 °C (Xu and Li, 2006). Waves of sand dunes and interdune lowlands, orientated in an east-west direction, occur in