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Spatial variation of soil $\delta^{13}C$ and its relation to carbon input and soil texture in a subtropical lowland woodland

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ABSTRACT

Spatial patterns of soil $\delta^{13}C$ were quantified in a subtropical C_3 woodland in the Rio Grande Plains of southern Texas, USA that developed during the past 100 yrs on a lowland site that was once C_4 grassland. A 50 × 30 m plot and two transects were established, and soil cores (0–15 cm, $n = 207$) were collected, spatially referenced, and analyzed for $\delta^{13}C$, soil organic carbon (SOC), and soil particle size distribution. Cross-variogram analysis indicated that SOC remaining from the past C_4 grassland community co-varied with soil texture over a distance of 23.7 m. In contrast, newer SOC derived from C_3 woody plants was spatially correlated with root biomass within a range of 7.1 m. Although mesquite trees initiate grassland-to-woodland succession and create well-defined islands of soil modification in adjoining upland areas at this site, direct gradient and proximity analyses accounting for the number, size, and distance of mesquite plants in the vicinity of soil sample points failed to reveal any relationship between mesquite tree abundance and soil properties. Variogram analysis further indicated soil $\delta^{13}C$, texture and organic carbon content were spatially autocorrelated over distances (ranges = 15.6, 16.2 and 18.7 m, respectively) far greater than that of individual tree canopy diameters in these lowland communities. Cross-variogram analysis also revealed that $\delta^{13}C$ – SOC and $\delta^{13}C$-texture relationships were spatially structured at distances much greater than that of mesquite canopies (range = 17.6 and 16.5 m, respectively). These results suggest fundamental differences in the functional nature and consequences of shrub encroachment between upland and lowland landscapes and challenge us to identify the earth system processes and ecosystem structures that are driving carbon cycling at these contrasting scales. Improvements in our understanding how controls over soil carbon cycling change with spatial scale will enhance our ability to design vegetation and soil sampling schemes; and to more effectively use soil $\delta^{13}C$ as a tool to infer vegetation and soil organic carbon dynamics in ecosystems where C_3–C_4 transitions and changes in structure and function are occurring.

1. Introduction

Natural stable isotope ratios are widely used in ecological research as intrinsic tracers to investigate structural and functional characteristics of ecosystems and their responses to environmental changes and human activities (Amundson et al., 1998; Boutton et al., 1999; Ehleringer et al., 2000; Pataki et al., 2003, 2007; West et al., 2010). Soil carbon isotopic signatures ($\delta^{13}C$) are commonly used to reconstruct plant community history, determine sources of soil organic carbon (SOC), and quantify SOC turnover rates (Balesdent et al., 1987; Choi et al., 2001; Sanaiotti et al., 2002; Krull et al., 2007; Boutton et al., 2009a). Soil $\delta^{13}C$ values correspond closely to the $\delta^{13}C$ of plant residues entering the system through litterfall and root turnover (Nissenbaum and Schallinger, 1974; Ludlow et al., 1976; van Kessel et al., 1994). After plant residues enter the soil, their $\delta^{13}C$ values may be modified slightly from their initial value by isotope fractionation associated with microbial decay processes, and by differential decay of isotopically unique biochemical compounds that comprise soil organic matter (Blair et al., 1985; Agren et al., 1996; Santruckova et al., 2000; Fernandez et al., 2003; Crow et al., 2006). Therefore, variation in soil $\delta^{13}C$ values and their evolution over time are controlled primarily by carbon inputs from vegetation and secondarily by biological decay processes (Nadelhoffer and Fry, 1988; Garten et al.,

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2000). Here we examined the influence of these two processes on the spatial pattern of soil $\delta^{13}C$ on a site transformed from grasslands dominated by C_4 plants to woodlands dominated by a C_3 plants.

At ecosystem to global scales the relative abundance of C_3 and C_4 plants exerts the strongest control over soil $\delta^{13}C$. $\delta^{13}C$ values of C_3 plants range from −32 to −22‰, while those with C_4 photosynthesis range from −17 to −9‰ (Farquhar et al., 1989), with the $\delta^{13}C$ of SOC usually reflecting the magnitude of C_3 and C_4 plant inputs to community net primary productivity (Troughton et al., 1974; Balesdent and Mariotti, 1996; Suits et al., 2005). In areas where vegetation has changed from one photosynthetic pathway type to another (e.g., $C_4 \rightarrow C_3$, or vice versa), SOC reflects a combination of inputs from both the past vegetation and the current vegetation, the isotopic signal from the original vegetation persisting in the SOC pool for a duration dependent on the turnover rate of SOC in that ecosystem. Soil $\delta^{13}C$ values have thus been utilized to document vegetation changes in a variety of ecosystem types around the world where plant cover has changed from C_4 to C_3 or vice versa (Boutton, 1996; Krull et al., 2005; Dümig et al., 2008; Silva et al., 2008; Wittmer et al., 2009). In this study a geostatistical analysis of spatial patterns of soil $\delta^{13}C$ was undertaken as a means of assessing how the development of C_3 woodland communities on C_4 grasslands has influenced soil carbon pools.

Organic matter inputs from C_3 vs. C_4 plants are modified during the decomposition process to influence soil $\delta^{13}C$ (Boutton et al., 1998; Liao et al., 2006a; Wynn and Bird, 2007; Diochon and Kellman, 2008). For example, soil factors that retard decomposition rates will favor the persistence of carbon derived from the original C_4 vegetation and hence affect soil $\delta^{13}C$ values (Balesdent et al., 1987; Desjardins et al., 1994; Balesdent and Mariotti, 1996; Bird et al., 2003; Liao et al., 2006a). Under similar climatic conditions, the dominant factor controlling decomposition processes is soil texture (Schimel et al., 1994; Jobbagy and Jackson, 2000), with slower rates of SOC turnover in fine-textured soils where clay micelles protect organic matter from mineralization (Anderson and Paul, 1984; Feller and Beare, 1997; Hassink, 1997). It is therefore important to understand and account for the influences of soil texture on soil $\delta^{13}C$ to effectively use soil carbon isotope techniques to study vegetation change and soil carbon cycling processes. Here, we use omnidirectional variogram analyses to quantify the spatial scale of variation in soil $\delta^{13}C$, SOC and texture; and cross-variogram analyses to determine the spatial scale over which variation in soil $\delta^{13}C$ values are correlated with SOC pools and soil texture. We then relate the scales of spatial variation in soil $\delta^{13}C$, SOC and texture to present-day patterns in vegetation distribution.

The simultaneous application of geostatistical approaches with isotopic analyses of the plant-soil system promises to be a powerful approach for interpreting ecosystem and ecological processes at landscape and regional scales (e.g., van Kessel et al., 1994; Marriott et al., 1997; Biggs et al., 2002; Boeckx et al., 2006; Powers, 2006; West et al., 2010). Despite the potential for understanding and quantifying ecosystem processes such as soil carbon dynamics and vegetation change at the landscape scale, the union of these methodologies remains largely unexplored. Here we combined these approaches to quantify the spatial scaling of soil isotopic values and identify the factors controlling it.

In the Rio Grande Plains of southern Texas, subtropical thorn woodlands dominated by C_3 honey mesquite (*Prosopis glandulosa*) trees have become significant components of landscapes once dominated almost exclusively by C_4 grasslands (Archer et al., 1988; Boutton et al., 1998). In the sandy loam upland portions of the landscape, this grassland-to-woodland conversion is initiated when a mesquite tree establishes within the grassland and then facilitates the establishment of other woody species beneath its canopy (Archer et al., 1988), resulting in the formation of discrete shrub islands within a grassland matrix. Recent studies have confirmed this pattern of woody patch development, and showed that the scale of variation in soil $\delta^{13}C$ in the upland were tightly coupled to discrete patterns of shrub distribution but not to scales of soil clay distribution (Bai et al., 2009). With this study we sought to extend our isotopic assessment of upland successional processes to adjoining lowlands characterized by a woodland physiognomy.

Given that these lowland woodlands are characterized by a mesquite overstory with an understory shrub species composition generally similar to that of upland woody patches, our working hypothesis is that grassland-to-shrubland successional processes similar to those operating in uplands have also occurred in these low-lying portions of the landscape (Archer, 1995). If this hypothesis is correct, then we would expect to see patterns of soil $\delta^{13}C$ that vary in accordance with patterns of mesquite distribution. To test this hypothesis, we sought to: (1) determine spatial scale of variation of soil $\delta^{13}C$ in a C_3 woodland formerly dominated by C_4 grasses; (2) examine spatial relationships between soil $\delta^{13}C$, SOC pools and soil texture; and (3) investigate spatial correlations between soil $\delta^{13}C$ and the relative proportions of SOC derived from C_3 vs. C_4 plant sources. In contrast to uplands, we found that the scale of pattern in soil $\delta^{13}C$ in lowlands substantially exceeded that of mesquite plant canopies. These results suggest the mesquite overstory is no longer the dominant source of SOC; that translocation of surface litter and sediments by intermittent flooding has obscured local plant-induced gradients; or that grassland-to-woodland succession has occurred via different mechanisms on this landform.

2. Materials and methods

2.1. Study area

Research was conducted at the Texas AgriLife La Copita Research Area in Jim Wells County, 15 km SW of Alice, TX (27° 40′ N; 98° 12′ W) in the eastern Rio Grande Plains of the Tamaulipan Biotic Province. The climate is subtropical with a mean annual temperature of 22.4 °C. Mean annual precipitation is 680 mm with bimodal maxima in May–June and September.

La Copita landscapes grade (1–3% slopes) from sandy loam uplands (approximately 85–90 m asl) to clay loam lowlands (approximately 84–85 m asl) that receive runoff from the uplands (Wu and Archer, 2005) and have intermittent water flow during high rainfall periods. This study was conducted in the lowland portion of the landscape, characterized by closed-canopy woodlands dominated by honey mesquite and lime prickly ash (*Zanthoxylum fagara* (L.) Sarg.). Soils in the lowlands are finer-textured clay loams (Pachic Argiustolls), with pH ranging from 4.4 to 7.7. Woody plant encroachment in the study area over the past 75–100 years due to the interaction of livestock grazing and reduced fire frequency has been well documented (Archer, 1995; Archer et al., 2001).

2.2. Study design and field sampling

A 50 × 30 m plot consisting of 5 × 5 m grid cells was established in 2004 (Fig. 1). This specific location was chosen because it allowed us to install a plot with relatively large dimensions entirely within a drainage woodland landscape that has been free from human disturbance (except for low to moderate levels of livestock grazing) since at least 1930. The corners of the plot were georeferenced using a high resolution GPS (Trimble Pathfinder Pro XRS, Trimble Navigation Ltd, Sunnyvale, CA). The locations of cell corners and transect points within the grid were calculated based on measured distances to the georeferenced points. Locations of all mature