Journal of Geochemical Exploration 102 (2009) 137–141

Contents lists available at ScienceDirect

Journal of Geochemical Exploration

journal homepage: www.elsevier.com/locate/jgeoexp

Satellite prediction of soil $\delta^{13}C$ distributions in a southern African savanna

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ARTICLE INFO

Article history:
Received 17 June 2008
Accepted 27 October 2008
Available online 10 November 2008

Keywords:
Carbon
Isotope
Kalahari
Remote sensing
Soil

ABSTRACT

Stable carbon isotopes have been frequently used to indicate carbon pools and processes in soils, plants, and the atmosphere. Carbon isotope compositions are particularly useful in partitioning soil carbon sources between C_3 and C_4 vegetation because of the distinct $\delta^{13}C$ distributions for C_3 and C_4 vegetation. Remote sensing is a powerful tool used to identify ecosystem patterns and processes at larger scales. A union of these two approaches would hold promise for spatially continuous estimates of carbon isotope compositions. In the current study, a framework is presented for using high spatial resolution remote sensing to predict soil $\delta^{13}C$ distributions across a southern Africa savanna ecosystem. The results suggest that if the vegetation–soil $\delta^{13}C$ relationship can be established, soil $\delta^{13}C$ distributions can be estimated by high-resolution satellite images (e.g., IKONOS, Quickbird). Despite limitations remote sensing is a promising tool to expand estimates of terrestrial $\delta^{13}C$ spatial patterns and dynamics.

1. Introduction

Since the discovery of distinct carbon isotope signatures for C_3 and C_4 vegetation types in early 1970s (Smith and Epstein, 1971; O'Leary, 1981), $\delta^{13}C$ has been a powerful tool to reveal or constrain the ecological patterns and processes at scales from individual organisms to an entire ecosystem. $\delta^{13}C$ has been used indicate, for example, plant water use efficiency (Farquhar et al., 1989), sources of carbon in the soils (Balesdent et al., 1987; Bond et al., 1994; Biggs et al., 2002), vegetation distribution (Still et al., 2003), CO_2 exchange between biosphere and atmosphere (Fung et al., 1997), and long-term climatic variability (Wilson and Norris, 2001).

Soil organic matter (SOM) is one of the largest and most dynamic reservoirs of carbon in the global carbon cycle. The amount of carbon stored in SOM is about twice that stored in the biosphere and atmosphere combined (Schlesinger, 1997). Assessment of its stable isotope composition is probably one of the best ways to partition soil carbon sources between C_3 and C_4 vegetation because of the distinct $\delta^{13}C$ distributions for these plant types. To date, vegetation and soil $\delta^{13}C$ measurements are made through traditional Isotope Ratio Mass Spectrometry (IRMS) and are generally limited to spatially discrete and point-in-time sampling assessments. Continuous measurements of carbon isotopes at larger spatial scales, if applicable, could significantly improve the understanding in biogeochemical cycling and the related ecological processes across multiple spatial and temporal scales.

Remote sensing is a powerful tool to identify ecosystem patterns and processes at larger scales (e.g., from regional to global scales). Remote sensing techniques have been widely used to estimate plant biomass (Houghton, 2005), forest structure (Treuhaft et al., 2004; Hyde et al., 2006), and canopy chemistry (Curran et al., 1992; Asner and Vitousek, 2005). A union of point isotope measurements with remote sensing is one possible way to achieve continuous large-scale examination of isotope compositions and help to elucidate ecosystem processes at larger spatial scales with more detailed process information. The combination of these two techniques for use in ecological studies is, however, still at an exploratory stage, similar to the state of remotely-sensed canopy chemical composition in the late 1980s (Card et al., 1988; Peterson et al., 1988; Wessman et al., 1988). This is chiefly the result of a limitation in technology and the form of the samples on which measurements are made, e.g., remote sensing data do not yet have high enough spatial and spectral resolution to predict isotope composition. To our knowledge, there are no direct measurements of the vegetation or soil $\delta^{13}C$ values using remotely sensed data, although indirect relationships between remote sensing data and $\delta^{13}C$ values have been reported. For example, Guo and Xie (2006) correlated MODIS-derived NDVI data to field measured vegetation $\delta^{13}C$ data in the Tibetan plateau and observed that NDVI and precipitation had the same trend with foliar $\delta^{13}C$ values. Such use of remotely sensed data utilizes $\delta^{13}C$ values as proxies, and does not focus on estimating $\delta^{13}C$ itself. The purpose of this current study is to provide a framework for using high-spatial resolution satellite

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doi:10.1016/j.gexplo.2008.10.003

imagery to predict soil $\delta^{13}C$ distributions, using a case study from a southern African savanna ecosystem.

2. Materials and methods

2.1. Site description

The site employed in this study was a typical dry tropical savanna, located at southwestern Botswana near the town of Tshane (24.17°S, 21.89°E) (Fig. 1). The mean annual precipitation of this site is 365 mm and the precipitation is concentrated between November to April (Fig. 1). The mean soil temperatures measured in January–February 2006 in Tshane is 24.5 °C. The soil physical and hydraulic parameters and vegetation structure at this site have been well-documented (e.g., Caylor et al., 2003; Wang et al., 2007; Okin et al., 2008). The soil texture for this site is 98%–0%–2% for sand–silt–clay content, and bulk density is 1.41 and 1.47 g cm^{-3} for under canopy soil and open canopy soil, respectively (Wang et al., 2007). The woody cover of this site is around 14%. The vegetation in Tshane is open savanna dominated by *Acacia* species such as *A. luederizii* Engl. and *A. mellifera* Benth, the dominant grass species are *Eragrostis lehmanniana* and *Schmidtia pappophoroides*. The 16-year mean NDVI in Tshane (1983–1998) is between 0.2 and 0.3 (Scanlon et al., 2003). The mean soil $\delta^{13}C$ value in Tshane is −17.2‰ with range from −25.1‰ to −8.0%. The mean $\delta^{13}C$ values of C_3 and C_4 plants in Tshane are −25.9‰ and −14.2‰ (Wang et al., in press).

2.2. Methods

The spatial relationship of vegetation structure and soil $\delta^{13}C$ distributions at this site has been previously characterized (Table 1, Wang et al., in review); the current study focuses on a characterization of vegetation distribution from satellite images and on the predictions of soil $\delta^{13}C$ distributions based on the satellite vegetation distribution results. IKONOS satellite data was purchased and used for vegetation characterization. IKONOS has a spatial resolution for panchromatic data of 1 m. The 1 m spatial resolution is considerably finer than the observed tree crown size (~6–10 m at Tshane, Caylor, 2003) and soil $\delta^{13}C$ autocorrelation ranges (Wang et al., in review) in this ecosystem. The IKONOS image of Tshane site was classified using ENVI software (ITT Visual Information Solutions, Boulder, CO, USA). The unsupervised classification option was used to produce two classes of data, "trees" and "not trees". The "not trees" class consisted of bare soil and soil–grass mixtures in the tree interspaces.

Table 1
The spatial correlation range (indicates the distance of spatial autocorrelation between data pairs) of soil $\delta^{13}C$ and mean tree distance at Tshane.

Location	Soil $\delta^{13}C$ range (m)			Mean tree distance (m)
	Mean	Lower limit	Upper limit	
Tshane	9.66	9.42	9.90	~10

Note: The data are from Wang et al. (in review).

The classified image was resampled to different resolutions by first setting all pixels classified as "tree" to a value of one and all other pixels to a value of zero. Then, this reclassified image was averaged at different resolutions. In the first iteration, the entire image was averaged. In the second iteration, the image was divided into 2 ($=2^1$) blocks in each dimension and reclassified values were averaged within each block. In the third iteration, the image was divided into 4 ($=2^2$) blocks in each dimension and reclassified values were averaged within

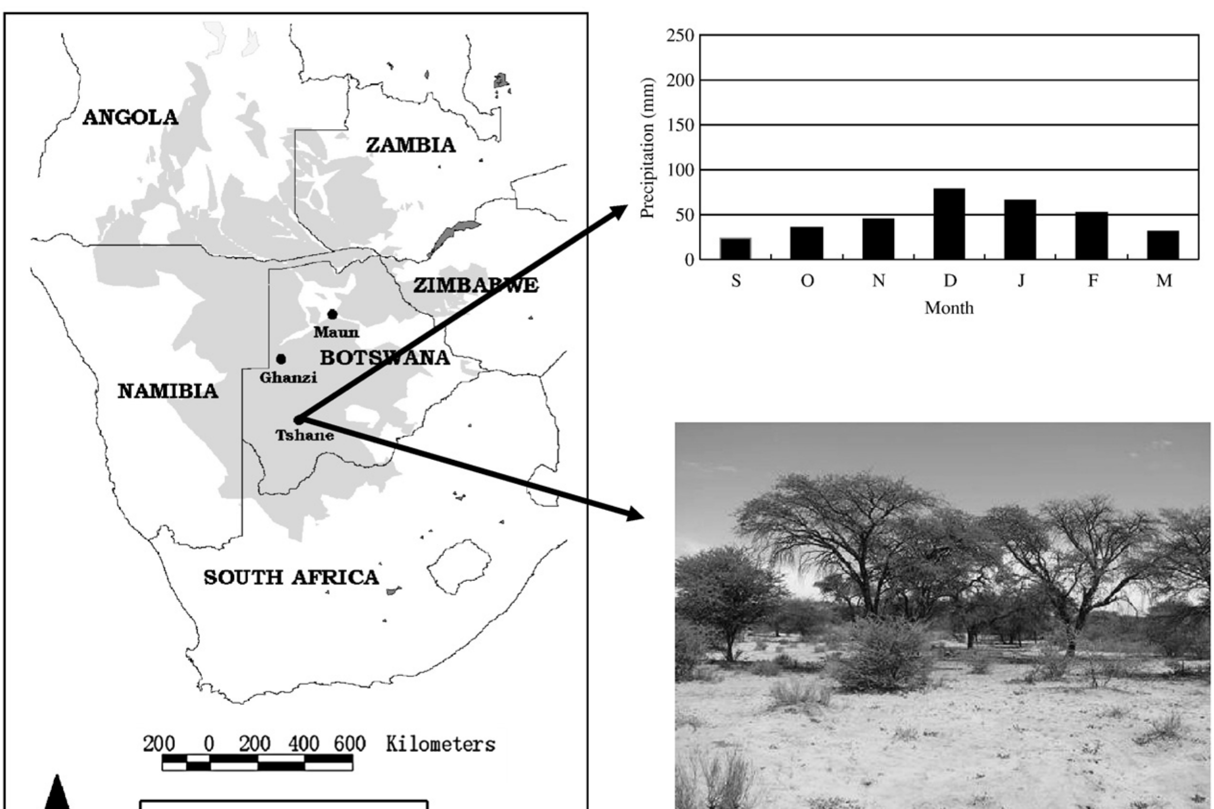

Fig. 1. The location, rainfall characteristic and field photo of the Tshane site. The column charts are the mean annual monthly precipitation data (1961–1990) of this site from Shugart et al. (2004).