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Evaluation of spectral unmixing techniques using MODIS in a structurally complex savanna environment for retrieval of green vegetation, nonphotosynthetic vegetation, and soil fractional cover

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ABSTRACT

This study tests the performance of spectral mixture analysis (SMA) and multiple endmember spectral mixture analysis (MESMA) for estimation of green vegetation (GV), nonphotosynthetic vegetation (NPV), and soil fractions in the heterogeneous, structurally complex savannas of the western Kalahari using the Moderate Resolution Imaging Spectroradiometer (MODIS) nadir-bidirectional reflectance distribution function (BRDF) adjusted reflectance (NBAR) product. Extensive fieldwork took place during the dry and wet seasons of 2009 to 2011 at 15 sites distributed along a 950 km long transect, stretching across western Botswana, each site was visited once during the wet season and once during the dry season. Data collection included a traditional line-intercept transect (LPIT) and a new spectral line point intercept transect method (SLPIT) were used to test the performance of a variety of unmixing procedures (MESMA vs. SMA) and endmember models. The results for this structurally complex landscape are consistent with results from similar studies undertaken in more homogeneous areas. GV cover was retrieved much more accurately than NPV or soil cover. MESMA also produced estimates of fractional cover with less error than simple SMA. However, the errors observed are greater than those observed for more homogeneous environments. Unlike the line-point intercept method, which requires user interpretation of vegetation greenness, the new method uses spectral data collected across the entire reflected solar spectrum to derive estimates of GV, NPV and soil fractional cover through spectral unmixing. Our results show that that the SLPIT fractions generally agree better with remotely-derived fractions than the LPIT-derived fractions. However, remote sensing of GV, NPV, and soil fractional cover, especially in heterogeneous landscapes and at the spatial resolution of MODIS, remains challenging. Nonetheless, the data do show that at this resolution various unmixing methods have the potential to inform our understanding of ecosystem dynamics in these environments.

1. Introduction

The ability to determine fractional cover of green vegetation (GV), nonphotosynthetic vegetation (NPV), and soil in savanna environments using coarse resolution satellite imagery could provide valuable information regarding general conditions of an ecosystem threatened by desertification and bush encroachment, information on fuel load, carbon storage, climate modeling, wildlife potential, and livestock stocking capacities (Ringrose, Matheson, Wolski, & Huntsman-Mapila, 2003; Sankaran, Ratnam, & Hanan, 2008; Wallgren et al., 2009). Over large areas, e.g. on national and regional scales, the determination of these fractions remains a challenge for land use managers due to the associated spatial extent and the difficulty collecting this information in the field. Previous studies have tried to determine vegetative cover using Normalized Difference Vegetation Index (NDVI) and other vegetation indices (Grist, Nicholson, & Mpolokang, 1997; Palmer & van Rooyen, 1998; Ringrose et al., 2003; Scanlon, Caylor, Levin, & Rodriguez-Iturbe, 2007). These indices are known to underperform in areas with vegetative cover less than 30% (Huete et al., 2002; Qi, Chehbouni, Huete, Kerr, & Sorooshian, 1994) and only provide information on one ground cover component, GV. Study and management of dryland ecosystems using remote sensing requires knowledge of surface dynamics that go beyond just the green fraction (Okin, 2010). At the spatial resolution of the Moderate Resolution Imaging Spectroradiometer (MODIS), unmixing techniques have been used for a variety of targets ranging from the extraction of information on snow cover (Vikhamar & Solberg, 2003), mapping of cropland distributions (Lobell & Asner, 2004), land cover mapping (Kumar, Kerle, & Ramachandra, 2008), and mapping of land forms (Ballantine, Okin, Prentiss, & Roberts, 2005). Despite the suitability and successful application of spectral unmixing

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techniques, the determination and validation of ground cover components with regard to GV, NPV, and soil remains challenging. At present spectral unmixing is a promising approach for determination of these ground cover components, and yet, to be useful, these methods need to be tested and successfully validated in heterogeneous dryland environments.

Spectral unmixing techniques are based on the assumption that the apparent surface reflectance can be modeled as a combination of the spectra of separable ground components, and that the coefficients of that mixture are equal to the actual fractional cover of those components on the ground (Ray & Murray, 1996; Settle & Drake, 1993). Studies of these techniques have indicated varying performances for different fractions and landscapes (Ballantine et al., 2005; Eckmann, Roberts, & Still, 2008; Guerschman et al., 2009; Okin, Clarke, & Lewis, 2013; Okin & Painter, 2004; Roberts, Smith, & Adams, 1993; Shreve, Okin, & Painter, 2009). While separating NPV and soil in all environments remains difficult due to their spectral similarity (Okin, 2007), this problem is likely to be exacerbated in structurally complex landscapes where multiple scattering and mutual shadowing complicate the signal and where spatial heterogeneity makes it difficult to connect remote measurements with validation sites on the ground (Ray & Murray, 1996).

The primary goal of this study is to test the performance of several approaches to spectral mixture analysis (SMA) to accurately retrieve fractions of GV, NPV, and soil in structurally complex savannas at MODIS (500-m) spatial resolution. However, in order to assess the accuracy of these techniques, reliable ground-reference data are required. This is complicated by the necessity separating GV from NPV when in truth tissue can be a mixture of both (Muir, 2011). There is no tried-and-true method to do this in the field, and therefore, we also investigated two methods for the collection of ground fractions: a traditional line point intercept transect (LPIT) and a spectral line point intercept transect method (SLPIT). The former method requires the subjective determination of ground cover type, whereas this is automated in the latter method.

2. Methods

2.1. Field sites

The Botswana part of the Kalahari Transect stretches 950 km from Shakawe in the northwest to Bokspits in the far south western corner of the country (Fig. 1). The transect follows a rainfall gradient, where precipitation ranges from 550 mm in the north in Shakawe to <250 mm in the south (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005). The rainfall pattern of the area is characterized by a distinct rain season starting in October and ending in March of the following year. However, rainfall events across the entire area and increasingly towards the southern end are characterized by sporadic, locally restricted convective thunderstorms events. The soils of the Kalahari are mainly of aeolian origin (Thomas, 1991). However, local differences can be observed in the form of active (site 15), inactive (sites 1, 2, 3, 4, 5, 7) or over washed (site 7) dune fields, riverbeds, or surfacing bedrock formations (site 8). Vegetation across the area can be best described as Kalahari thornveld (Thomas, 1991) with increasing canopy density and height from south to north (Caylor, Shugart, Dowty, & Smith, 2003; Sankaran et al., 2005). On a local scale vegetative composition varies with regards to species composition and structure.

To limit significant logistical problem with regard to site access and transportation, we decided to visit the 15 field sites twice each. Since the region is characterized by strong vegetation differences between the wet and dry seasons, visiting each site during each season significantly increased the size of the fractional cover data space we could use. In addition, there is a rough trend from high total cover to low total cover from north to south among our sites that is preserved regardless of season. By visiting each site during both the wet and dry seasons, we were able to fill the fractional cover data space along both the high soil cover–low soil cover axis and the high GV/NPV ratio–low GV/NPV ratio axis.

The sites are roughly evenly spaced sites along the 950-km transect. At each site, three 500-meter transects were laid out using measuring tapes. Each site was visited once in the wet season and once in the dry season. Table 1 indicates the center point at each site and the dates when the site was visited. A random number generator was used to establish the direction of the first transect at each site and each of the following transects were rotated clockwise at a spacing of 120°. The transect starts were located 30 m from the center point. The labor-intensive nature of the LPIT method often results in significant disturbance of biomass, especially NPV/senescent grass. It was decided that this disturbance would also potentially be a source of spatial variation that could be avoided by offsetting the transect during the second visit by 60°. Our analyses do not involve direct comparisons between dates, but rather comparisons between transects and remote sensing data, making remeasurement along the same transect unnecessary for our purposes here. Error resulting from spatial variation is a result of the unavoidable mismatch in size between transects and pixels coupled with real landscape heterogeneity, and therefore is included as a source of variability in our results.

2.2. Endmember collection, processing, and selection

Spectral endmembers for GV, NPV and soil were collected near or directly on the vegetation transect (maximum distance 2 m) utilizing an ASD Fieldspec Pro with a contact probe with a leaf-clip attachment (PANalytical, Inc., Boulder, CO) for GV endmembers. For NPV and soil endmembers, the leaf clip was removed and spectra were collected by direct contact between the object (a piece of NPV or a patch of soil) and the contact probe. A separate white reference was taken for each object. Reflectance spectra were obtained by division of endmembers' radiance spectra by the measured radiance of a Spectralon™ panel. Each endmember was visually inspected before its integration into a mixture model. All resulting reflectance spectra were convolved to MODIS wavebands (see example in Fig. 2).

2.3. Line point intercept transect (LPIT)

Measurements of in situ fractional cover were conducted over 100 m at the center of each 500 meter transect (ranging from the 200 to the 300 meter mark). Data capture and interpretation follows the procedures and methods described for line point intercept transect (LPIT) by Krebs (1999). The LPIT is therefore a subset of the SLPIT and as with most transects, we assume similarity. For each line, all woody vegetation taller than 25 cm was identified following the nomenclature provided by Palgrave (1977). Average height, distance covered over the line, and distance and direction of the stem(s) were recorded to calculate total transect woody canopy cover exceeding 25 cm in height. Time spent at each transect depended heavily on number of individuals encountered and took between one and four hours. In order to calculate the total vegetation cover, herbaceous and litter layers were also recorded along the same line. Cover for each clump was categorized by visual inspection based on the 'greenness', with each clump classified as either GV or NPV based on the preponderance of green or non-photosynthetic tissue. Trees (woody vegetation > 2 m) were classed as GV in the wet season (due to a preponderance of green tissue) or NPV during the dry season (due to the lack of green leaves during this time). Total lengths of GV, NPV, and soil readings along the transects were divided by 100 m to yield fractional cover estimates.

2.4. Spectral line point intercept transect (SLPIT)

The LPIT method uses a binary GV/NPV categorization to produce endmember fractions. The SLPIT method is similar to the method applied by Numata et al. (2008) and is designed to produce spectral data