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Forest cover change in Miombo Woodlands: modeling land cover of African dry tropical forests with linear spectral mixture analysis

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ABSTRACT

Dry tropical forests are experiencing some of the highest rates of change among the globe's forests. In sub-Saharan Africa, gross (loss, gain) and net changes in dry tropical forest areas are difficult to quantify at sub-national scales because of high spatio-temporal variability in land cover conditions due to vegetation phenology and land use practices. In this project, we developed new, field-validated remote sensing characterizations of dry season surface components to separate forest from non-forest land cover, and assessed forest changes from the 1990s–2010s in a Tanzanian Miombo Woodland landscape. Using a linear spectral mixture analysis (LSMA) approach with Landsat 5–8 data, we examined the hypothesis that higher proportions of substrate and non-photosynthetic vegetation (NPV) at non-forest regions distinguished them from forest cover against seasonally variable land cover conditions. Subsequently we evaluated the efficacy of multi-temporal classification and single-date image thresholding for identifying forest from non-forest cover. We found significantly greater proportions of substrate and NPV over non-forest compared to forest areas that enabled identification of forest cover across dry season images. Single-date, forest/non-forest maps based on an LSMA-derived metric attained overall accuracies of 81.0–85.3%, which approached multi-temporal unsupervised classifications (86.5% for forest/non-forest maps). Applying the LSMA-derived metric to study forest changes, our study region experienced a net 15.0% loss of 1995 forest area, and a 7.0% overall reduction in the total forest-occupied land cover from 1995–2011. Areas of gross forest gain were substantial, totaling 13.6% of the 1995 forest area. We found differing patterns in gross forest losses and gains among sub-regions and through time in our Tabora study area, which provide bases for testable hypotheses in future research on regional and localized drivers affecting forest cover. Our finding that non-green surface components distinguished forest from non-forest via an LSMA approach may be widely applicable to studying forest conversions in Miombo Woodlands and other dry tropical forests. This approach may also be useful for evaluating how land cover conditions change in response to potential land use or climate driving variables, or the impact of land changes for carbon balance and other ecosystem processes.

1. Introduction

Forest losses, gains and agricultural land changes in seasonally dry tropical ecosystems are among the least well quantified and understood land cover changes globally (Lambin, Geist, & Lepers, 2003; Lepers et al., 2005). These ecosystems, including tropical deciduous forests and savannas, occupy about 14% of Earth's terrestrial area (18.6×10^6 km^2) and comprise 15% of global vegetation carbon stocks (137.5 Pg) at the third-highest biomass carbon (C) density (200 g C m^{-2} (Aber & Melillo, 2001)). They have among the largest reserves of the globe's arable land that is not yet cultivated (Lambin & Meyfroidt, 2011). Among nations with the highest deforestation rates, significant proportions of their forest losses come from dry tropical forests, which have few areas under legal protected status (FAO, 2010; Green et al., 2013). Satellite remote sensing assessments of forest conversions (deforestation, forest regrowth or afforestation) in the dry tropics have been limited by the high temporal and spatial variability in land cover conditions, which stem from complex regional vegetation ecology, land use practices and disturbance regimes. Currently, poor knowledge of land cover variability across land cover types, which includes characterization of land cover components such as green vegetation or substrate (i.e. soil) at landscape scales, hinders differentiation of forest and non-forest areas and evaluation of forest change in a "wall-to-wall" fashion (Bodart et al., 2013; Grainger, 2008).

This study develops a model to quantitatively characterize and differentiate dry tropical forest cover from non-forest areas using analyses of Landsat satellite data, and assesses forest conversions in the Miombo

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Woodlands of western Tanzania. The Miombo Woodlands span 2.8 million km^2 across sub-Saharan Africa, and contain the largest contiguous dry tropical forests globally (Campbell, Frost, & N. B., 1996). Many Miombo regions are home to small land-holding agricultural communities with high population growth rates and increasing land change pressures. Since the 1990s, cultivation of resource-intensive cash crops such as tobacco, and natural resource demands of urbanization such as fuel wood are contributing to high rates of forest changes (Geist, Chang, Etges, & Abdallah, 2009; Kutsch et al., 2011; Yanda, 2010). Recent studies have shown that large net loss of Miombo woodland has been almost 40% in eastern Tanzania since 1975. This rate of loss has far exceeded that of Africa's humid tropical forests (5.1% of 1975 area) (Green et al., 2013). In western Tanzania, rates of woodland habitat loss to agriculture have been documented at 4.7% from 1984–1995 and 11.2% from 1995–2000 (Yanda, 2010). Regional and plot-scale studies have also observed forest regrowth (Chidumayo, 2013; Prins & Kikula, 1996; Yanda, 2010). Beyond documented net forest cover losses, little data exists on the patterns of gross forest loss and regrowth that are resulting in the net changes.

Past assessments of regional forest change in the Miombo have relied on supervised classification or image-interpretation approaches with remotely sensed data (Cabral, Vasconcelos, Oom, & Sardinha, 2011; Green et al., 2013; Yanda, 2010). While locally informative, these are difficult to repeat for regular, long-term monitoring over large areas. These local approaches have been necessary because remote sensing-derived land cover datasets produced at global scales often fail to distinguish forest cover or lack calibration in dry tropical ecosystems and particularly in the Miombo (Lepers et al., 2005; Sedano, Gong, & Ferrao, 2005).

Forest cover in the Miombo includes areas with tree cover as low as 30%, with many trees between 3 and 5 m tall (Chidumayo, 2013; Eamus & Prior, 2001; Frost, 1996). An accuracy assessment of the MODIS Global Land Cover Product (MOD12Q1) in a Miombo region of Mozambique found that nearly all forest and agriculture training sites were inaccurately described as Savanna or Woody Savanna (Sedano et al., 2005). The global land cover product did not distinguish tree-dominated from grass-dominated areas, limiting their usefulness for forest monitoring for purposes such as carbon accounting. More recent products, such as the global forest-change maps of Hansen et al. (2013), evaluate forest conversion only in areas with greater than 50% canopy cover and with trees greater than 5 m height (Hansen et al., 2013). Such definitions may exclude many chronically disturbed and re-growing Miombo forest regions (Chidumayo, 2013; Prins & Kikula, 1996). Physically-based, regionally-calibrated measures are needed to identify forest cover and conversions in the Miombo using satellite data.

Satellite-based, quantitative characterizations of forest cover and conversions in the Miombo face two challenges. First, inter-annual variability in precipitation and fire confounds the temporal variability of land cover components among forest and non-forest land cover (Serneels, Linderman, & Lambin, 2007). Precipitation drives vegetation production and 85% of annual rainfall falls in a single wet season in Miombo regions (Fuller, 1999; Zhang, Friedl, Schaaf, Strahler, & Liu, 2005). As forests in the Miombo are comprised of 85% deciduous species and agriculture is rain-fed, forest and non-forest areas have similar phenologies (Frost, 1996). In the dry season, fires occur on 15% or more of the landscape as part of either forest clearing, or other land-use activities such as understory burning to drive game animals or to spur growth of forage for livestock (Frost, 1996; Williams et al., 2008). The spectral properties of burned vegetation in satellite data are the same across different land cover categories. Thus, in burned areas, there is limited ability to differentiate whether the burn constitutes land conversion (e.g. forest cleared for agriculture) or variability in land cover conditions without conversion.

The second challenge is the high spatial variability of land cover conditions. Field sizes in the Miombo are small (0.5–2.0 ha) and irregularly shaped (Palm et al., 2010). Long-term shifting cultivation and chronic ecological disturbances have created patchy forest structures. Non-forest areas often have some degree of tree cover (Frost, 1996) (Fig. 2b). Forest clearing is done largely by hand; the largest trees are left standing due to limited labor and for their use as sources of fruit, medicine or other products (Campbell et al., 1996).

Though complex, the seasonal variability of Miombo landscape components presents a physical basis for differentiating forest and non-forest areas. Forest and non-forest surface components change with different patterns during transitions between wet and dry seasons. From the late wet–mid-dry season, forest areas retain green vegetation cover and have lower albedo than non-forest areas; senescence occurs over many weeks, and so canopy cover remains and shades underlying areas (Frost, 1996). Meanwhile, in non-forest areas such as agriculture or grassland regions, harvest and grazing of herbaceous forage occurs rapidly at the start of the dry season. These processes remove green vegetation material, leaving behind crop residues and other non-photosynthetic vegetation (NPV) and exposing substrate. On the ground, the physical differences in land-cover components between forest and non-forest areas are largest in the early to mid-dry season, though there are large variations due to the patchiness of forest cover and distribution of cultivated fields, homesteads and low-lying grassland regions. Past studies of forest change using satellite imagery in the Miombo have targeted the early to mid-dry season as an optimal time for forest change detection using measures of greenness such as NDVI (Prins & Kikula, 1996). However, no prior studies have attempted to physically model a broader suite of surface components, or develop and test metrics to distinguish forest cover that account for the seasonal variability of land cover conditions.

With this project, we develop and assess quantitative methods for distinguishing forest from non-forest land cover in the Tanzanian Miombo and apply them to study regional-scale forest changes. We use field data, multi-temporal and single-date analyses of 30 m Landsat data in the 2008 dry season to test how satellite observations of land cover correspond with surface components of forest and non-forest land cover. We examine the hypothesis, based on ground observations, that higher senesced/non-photosynthetic vegetation and substrate exposure at non-forest sites will distinguish non-forest from forest during the early–mid-dry season at scales of Landsat observations. We compare the accuracies of a multi-date classification and single date approaches to distinguish forest and non-forest areas, and qualitatively relate analyses to 250 m MODIS-scale observations. Subsequently we assess forest change patterns from 1995–2011 at regional scales and their variability across sub-regions with different land use pressures.

2. Methods

2.1. Study area and field data

Our study region is in central Tabora province, Tanzania (Fig. 1a). The landscape is dominated by a complex dry Miombo woodland ecosystem with locally diverse land uses (Fig. 1b–e) (Palm et al., 2010). Mean annual temperature is 23.9 °C and mean annual precipitation (2000–2009) is 770 mm with 90% falling between mid-November and early May. Agro-pastoral communities have lived in Tabora for centuries; political changes have strongly affected land use since the mid-19th century (Kjekshus, 1977). Since the 1990s, land change pressures have accelerated. Major drivers of land changes include population change (both migration and local growth), resource demands from urbanization including timber and charcoal, economic reforms leading to increased demand for land for cash crops such as tobacco, and road building (Chidumayo & Gumbo, 2013; Geist et al., 2009; Lambin et al., 2003; Yanda, 2010). In local sub-regions (Fig. 1d), Tabora includes the provincial capital Tabora Town (Fig. 5a), which has a