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Mapping patterns of urban development in Ouagadougou, Burkina Faso, using machine learning regression modeling with bi-seasonal Landsat time series

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ABSTRACT

Rapid urban population growth in Sub-Saharan Western Africa has important environmental, infrastructural and social impacts. Due to the low availability of reliable urbanization data, remote sensing techniques become increasingly popular for monitoring land use change processes in that region. This study aims to quantify land cover for the Ouagadougou metropolitan area between 2002 and 2013 using a Landsat-TM/ETM+/OLI time series. We use a support vector regression approach and synthetically mixed training data. Working with bi-seasonal image stacks, we account for spectral variability between dry and rainy season and incorporate a new class - *seasonal vegetation* - that describes surfaces that are *soil* and *vegetation* during parts of the year. We produce fraction images of *urban surfaces*, *soil*, *permanent vegetation* and *seasonal vegetation* for each time step. Statistical evaluation shows that a temporally generalized, bi-seasonal model over all time steps performs equally or better than yearly or mono-seasonal models and provides reliable cover fractions. *Urban* fractions can be used to visualize pixel-based spatial-temporal patterns of urban densification and expansion. A simple rule set based on a *seasonal vegetation* to *soil* ratio is appropriate to delineate areas of unplanned and planned settlements and, thus, contributes to monitoring urban development on a neighborhood scale.

1. Introduction

Within the last four decades, the number of city dwellers on the African continent increased from 24% to 45% of the total population. This constitutes the highest growth in urban population worldwide and the increase is likely to continue at a similar rate. It is projected that in 2030, 770 million people will be living in urban areas in Africa, compared to 83 million in 1970 (UNESDA, 2015).

This demographic development might have massive environmental, infrastructural and social impacts in and around a city. Decreased water availability and quality, extreme air pollution, densification of land usage, limited access to infrastructure such as health, schooling, electricity and sanitation as well as affected ecosystem balances and services are challenges that go along with a rapid population increase, particularly in Sub-Saharan Africa (Grimm et al., 2008; Myers, 2011; Goodfellow, 2013; Li et al., 2015a; Marlier et al., 2016).

Identifying urban expansion patterns and understanding the dynamics of urban settlements as well as associated consequences in Sub-Saharan Africa have accordingly emerged as important research topics (Murray and Myers, 2007; Myers, 2011; Parnell and Pieterse, 2014). A major challenge in this respect is a lack of data, in particular reliable census data (Beauchemin and Bocquier, 2004; Satterthwaite, 2010; Potts, 2012, 2017), that can add to the understanding of the above-mentioned processes and advise urban planning (Gandy, 2006; Goodfellow, 2013; Parnell et al., 2009). This is also true for this project's study site, Ouagadougou, Burkina Faso: Low availability of historic data, such as censuses, land cover maps or cadastral archives, along with a lack of urban growth governance structures and the high uncertainty of population projections in the area (Satterthwaite, 2010), makes in-situ methods of urban growth monitoring difficult. Thus, the analysis of urban densification and expansion processes in Sub-Saharan Africa is increasingly turning towards other data sources including remote sensing images (Potts, 2012; Harre et al., 2016). Multiple studies applied remote sensing techniques monitoring land use change processes in the studied area (e.g. de Jong et al., 2000; Mering et al., 2010; Gessner et al., 2015; Akintunde et al., 2016; Hou et al., 2016). Since the

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opening of the Landsat satellite archive (United States Geological Survey, 2008), the largest series of consistent space-borne earth observation data at high spatial resolution, it has been proven generally suitable for urban growth monitoring (Taubenböck et al., 2012; Sexton et al., 2013). Visually promising Very High Resolution (VHR) imagery is not sufficient for this purpose because of low and irregular image acquisition frequencies, short time series of technically consistent photographs, the lack of shortwave infrared sensors for urban surface detection and potentially large viewing angles from sensor pointing.

However, general and site-specific challenges for urban remote sensing monitoring remain also for the work with archived Landsat time series. For example, large urban areas experience highly dynamic land cover changes (Lambin et al., 2003; Taubenböck et al., 2012) with several land cover types showing spectral ambiguities (Small, 2004). Particularly in semi-arid areas with mud-made buildings and dust-coated objects, urban materials and open surfaces in the surrounding areas might resemble. The resulting confusion of land cover types is a limiting factor in the delineation of settlements in urban studies. The notably high dynamics and the level of detail of urban development pose a challenge to data selection and processing.

Another important challenge for the use of remote sensing approaches lies in the regional climatic conditions of Burkina Faso. Rainy seasons with heavy cloud coverage and, thus, fewer high-quality Landsat scenes lead to an unequal distribution of available imagery throughout the year. In addition, the high spectral variability of vegetated surfaces over the year with only smaller spectral variability for permanent soil and infrastructures implies seasonal differences in the spectral features of surfaces. Large areas of seasonal rain-fed vegetation and agriculture will be detected as vegetation in rainy seasons and as soil in dry seasons. That requires a general strategy of dealing with such variable spectral information and suggests the use of multi-seasonal data. In general, the use of multi-seasonal data in optical remote sensing land cover monitoring is not a new concept (e.g. Yuan et al., 2005). Performing a sensitivity analysis on Landsat imagery, Müller et al. (2015) find that seasonal information is particularly relevant for separating vegetation types in a savannah context. With regard to Burkina Faso in particular, Knauer et al. (2017) have recently shown the relevance of seasonal vegetation detection in studying agricultural processes and Zoungrana et al. (2015) suggest the use of image acquisitions from March, June, July and October for the purpose of vegetation cover analysis in Burkina Faso.

With regard to urban densification, a reliable distinction of permanent soil, seasonal vegetation and permanent vegetation appears important in addition to urban infrastructures maps. This is underpinned by the fact that temporary or permanent soil coverage during expansion phases might be an indicator for increasing settlement density and ongoing urbanization. Soil, seasonal and permanent vegetation might also contribute to the detection of the type of development, i.e. if it is planned or unplanned. Although the Landsat archive offers > 40 years of mostly multiple earth observations per year, only very few studies use multi-seasonal Landsat data for detailed urban land cover mapping in semi-arid regions. Furthermore, such studies usually target at discrete urban classification schemes (e.g. Taubenböck et al., 2012; Zhu and Woodcock, 2014). Reasons for this might be manifold. The intra-annual variability of land cover and a lack of quantitative mapping approaches that lead to reliable fractional cover maps from multispectral data are among the most prominent. But the identification of urban development patterns asks for a quantification of cover fractions instead of discrete classification and requires a methodology that provides information on gradual change (MacLachlan et al., 2017) and makes use of sub-pixel information.

A promising method to quantify land cover in heterogeneous urban areas is machine learning regression modeling. Machine learning algorithms generally turn out to be strong in describing multi-modal and spectrally similar classes in the urban space. Recently, it has been shown that an ensemble learning support vector regression (SVR) approach can be performed with highly generalized models in a spatial and temporal context using multi-site libraries (Okujeni et al., 2016). A requirement of regression modeling is the development of continuous training information consisting of pairs of reference signatures and land cover fractions. This data is conventionally generated by the manual definition of surface class polygon compositions in high resolution reference imagery (e.g. Sexton et al., 2013; Song et al., 2016). Okujeni et al. (2013) and Okujeni et al. (2016) demonstrate that SVR training data can also be based on synthetically mixed training spectra ($SVR_{synthmix}$) generated from pure library spectra, i.e. endmembers, obtained from the imagery without the need of high resolution reference imagery. This way, the availability of multi-temporal and retrospective reference information becomes possible.

In this study, we aim to quantify land cover for the city of Ouagadougou and its surroundings with Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+) and Operational Land Imager (OLI) data for the period from 2002 to 2013 using five time steps. We extend onto the concept of a generalized $SVR_{synthmix}$ model as suggested in Okujeni et al. (2016) by integrating series of bi-seasonal multi-spectral images. To do so, we work with stacked imagery from both phenological extremes at the end of rainy and dry season for each time step. The first study objective consists of the reliable identification of surface fractions for the study area, including seasonal vegetation into the classification scheme. Our second objective is to map urban development over time based on those fractions. Finally we wish to delineate areas with planned and unplanned development in order to better understand the spatial-temporal patterns of urban development.

2. Study area and data

2.1. Study area

Our study area comprises the greater Ouagadougou metropolitan region and adjacent landscapes (Fig. 1).

Counting about 1.3 million inhabitants in the last census in 2003, the capital of Burkina Faso has nearly tripled its population since 1985. With a current growth rate of 4 to 5% and a prospective population of 3.6 million in 2020 and 5.8 million in 2030 the city tends to extend its primacy in the national urban hierarchy (Harre et al., 2016; UNESDA, 2015). The reasons for this rapid urbanization are diverse, including demographic, economic and political factors (Ouédraogo, 2002; Fournet et al., 2008; Beauchemin, 2011; Nielsen and D'haen, 2015). An insufficient number of developed parcels, a lack of financial resources for their acquisition as well as land speculation have led to a massive growth of unplanned settlements in the outskirt areas. Many of these areas are marked by the establishment of uninhabited clay huts (Fournet et al., 2008), understood as an attempt to obtain registration and subsequently being attributed a parcel in case of future restructuration (Jaglin, 1995; Fourchard, 2001; Hauer et al., in press).

The spatial expansion of Burkina Faso's capital Ouagadougou is shaped by two major morphologically distinguishable kinds of settlements: Formally planned settlements stand out through highly systematic infrastructural networks under municipal supervision, defined architectural specifications and documented lot ownership (Fig. 2). Unplanned settlements, however, develop beyond official planning strategies and they feature more diverse lot and building layouts and suffer from limited access to water, electricity or roads. Predominant building materials are clay, corrugated iron, concrete and, rarely, asphalt for roads.

Burkina Faso is characterized by tropical summer-humid climate under the influences of a trade wind driven dry season from October to April and an Intertropical Convergence Zone driven rainy season from May to September. Whereas green vegetation largely disappears in the dry season, phenological peaks occur during the rainy season. Natural vegetation is largely shaped by rain-fed seasonal grasses, legumes and sedges as well as herbaceous woods. Cultivation encompasses maize,