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Assessing land use and land cover dynamics using composites of spectral indices and principal component analysis: A case study in middle Awash subbasin, Ethiopia

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1. Introduction

Fulfilling demands of the rapidly growing population without affecting the sustainability of ecosystem services are the main interest and concern of the current world (Galvani, Bauch, Anand, Singer, & Levin, 2016). Poverty is a severe challenge of developing nations where African countries, particularly East African countries including Ethiopia, have still remained suffering from food and nutrition security problems at most (Gebrehiwot & van der Veen, 2014). To cope with food shortage problems and to fulfill daily demands, people continuously interact with their environment inducing pressure beyond ecosystem carrying capacity. A number of developmental sectors, which intensively require ecosystem services have been emerged constraining and challenging sustainability of ecosystem services. Irrigation development is among the rapidly growing sectors with positive impact in terms of ensuring food security, stabilizing crop prices and contributing its share towards minimizing terrestrial carbon emission. Nonetheless, it challenges the sustainability of future water security unless appropriate policy is set for efficient water utilization (Liu et al., 2017b).

Moreover, degradation of environmental resources is further aggravated by climate change resulting in socio-economic instability and population displacement (Warner, Hamza, Oliver-Smith, Renaud, & Julca, 2009). The joint effect of anthropogenic activity and climate change alters the natural state of the environment and shapes the traditional landscapes (Brunori, Salvati, Mancinelli, Smiraglia, & Biasi, 2016). Agricultural expansion, land use policies and environmental calamities like drought and flooding are always exerting pressure on the environment resulting in land use and land cover (LULC) changes. There are a number of disturbance sensitive ecosystem setups like wetlands, flood plains, wildlife habitats, desert fringes, recreational sites, world heritage sites, energy development and production areas, residential and industrial development areas, which need accurate information for timely policy adjustments and remedial measures (Abdulaziz, Hurtado and Al-Douri, 2009; Anderson, Hardy, Roach, & Witmer, 2001; Michel et al., 2013; Zhou et al., 2010). In order to curb these interrelated problems and to support evaluation of the status and transition of ecosystems, monitoring and mapping land cover changes with reliable information are extremely important (Jin, Yang, Zhu, & Homer, 2017; Mushore, Mutanga, Odindi, & Dube, 2016). Simulating future changes is also important to understand the degree of interaction between human beings and their environment and to devise appropriate counteractive remedial measures (Pathak, 2014). Studies have shown that some developing countries could wisely reconcile environmental degradation: for example minimizing deforestation while improving agricultural production by establishing sound policy and problem solving innovations (Lambin & Meyfroidt, 2011). Ecological water diversion project in China has proved the feasibility of restoring degraded vegetation, improving soil condition and raising groundwater level (Bao, Huang, Ma, Guo, & Wang, 2017). The role of protected areas in conserving biodiversity and maintaining the integrity of an ecosystem was well represented by the work of Sieber et al. (Sieber et al., 2013). These facts generally depict that monitoring ecosystem disturbances using accurately retrieved data is important to develop change predictive models, devise appropriate corrective measures and secure environmental, social and economic sustainability of the entire ecosystem (Alphan, Doygun, & Unlukaplan, 2009; Hilker et al., 2009).

Monitoring environmental status and analyzing LULC change trends using remote sensing techniques have become popular these days owing to the technological advances in the earth observation system and their availability at different costs depending on data quality and mission of data providers (Feng et al., 2017; Kamh, Ashmawy, Kilias, & Christaras, 2012; Li et al., 2017; Roy et al., 2016; Vogelmann, Gallant, Shi, & Zhu, 2016). Opportunities have been created by institutions dedicated to earth resource studies like the United States Geological Survey (USGS), which started releasing moderate and medium resolution multispectral imagery dataset free of charge from their over forty years Landsat archives on regular basis. Landsat imageries are of special interest for their historical time series data and their suitability for large catchments LULC change detection studies (Wulder et al., 2008) and

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also for analyzing effects of natural disasters and recovery rates through the use of different image processing algorithms (Wagner, Myint, & Cerveny, 2012). Developing countries, which cannot afford allocating adequate financial resources for ground survey and monitoring programs are taking full advantage of accessing and utilizing these freely available imagery datasets, particularly for studies related to rapidly changing large catchments like that of Middle Awash subbasin of Ethiopia.

Despite the freely available moderate and medium resolution imageries, there are still challenges of converting the embedded data to useful information. The first challenge is associated with problems of acquiring cloud free imageries at the satellite's revisit times. This restricts the analyses of land surface change trends in reflectance over time to cloud-free imageries (Goodwin, Collett, Denham, Flood, & Tindall, 2013). Fortunately, a good opportunity of acquiring Landsat imageries in 8 days interval was created during the periods between the launch of Landsat-7 in April 15, 1999 and official decommissioning of Landsat-5 in June 05, 2013. The continuity has been again maintained after the launch of Landsat-8 in 2013, which offers 16-day repetitive earth coverage, an 8-day repeat with Landsat-7 offset. However, Landsat-7 data quality has been degraded since May 31, 2003 after the sensor permanently lost its scan line corrector (SLC) that resulted in loss of about 20% of the data from each scene (Abd El-Kawy, Rød, Ismail, & Suliman, 2011; Gao et al., 2017). The missing data could, however, be filled by data gap filling algorithms with acceptable errors. The other major challenge is to spectrally distinguish land features having similar signatures in heterogeneous landscapes. Under this condition image classification accuracy could likely be diminished and subsequently change detection capacity would greatly be hampered due to errors induced while training a machine for classification.

In order to overcome these two big challenges a number of research works have been carried out and different techniques have been proposed in the literature. Data fusion technique was among the proposed techniques to improve temporal and spatial resolutions by blending two images with varying temporal and spatial resolutions (Gao et al., 2017; Qu, Li, & Dong, 2018). The method explores the possibility of extracting better information (either temporally or spatially) from different sensors with varying resolutions. This technique worked well in landscapes covered by well clustered homogenous land feature (Hilker et al., 2009). The challenge, however, persisted in areas covered by heterogeneous land features because of the fact that the images were again of coarse spatial resolution. Studies have also been conducted on image segmentation, which have yielded satisfactory result in areas covered by clusters of homogenous land covers: for example in the study of mapping desert buffelgrass (Brenner, Christman, & Rogan, 2012). This method, however, is still challenged by heterogeneity of land covers that degrades its applicability outside the spatial domain. Maxwell and Warner (Maxwell & Warner, 2015) have alternatively attempted combining of ancillary data from historical records and digital elevation models with image data and as a result they have obtained a better classification accuracy.

Alternatively, several studies have demonstrated the possibility of utilizing spectral indices developed from remotely sensed data as a proxy for biophysical representations of an ecosystem. In this regard, a number of research works have been carried out on vegetation related studies and a wide range of vegetation indices have been developed including the normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), normalized difference greenness index (NDGI), radar vegetation index (RVI), leaf area index (LAI), coupled vegetative urban index (CVUI), soil-adjusted vegetation index (SAVI) and fractional vegetation coverage (FVC) (Bao et al., 2017; Gao, 1996; Wagner et al., 2012; Zhu et al., 2016). NDVI has received greater popularity and widely used not only for vegetation detection, but also for analysis of climate variation, human activities, and environmental events (Chen et al., 2004). NDVI is especially useful in identifying crops in irrigated fields by considering the phonological information based on cropping calendar (Akhtar, Awan, Tischbein, & Liaqat, 2017). Normalized difference water index (NDWI) and modified normalized difference water index (MNDWI) are indices proposed primarily for the analysis of water resources data and estimation of turbidity level on water bodies (Gao, 1996; McFeeters, 1996; Xu, 2006). Besides water resources study, Gao (Gao, 1996) has also demonstrated the applicability of NDWI for analysis of liquid water content of vegetation canopies.

In the indices-based multispectral image classification approach classification of built-ups and bare lands are extremely difficult due to heterogeneity and spectral similarity of both land features (Li et al., 2017). In order to minimize this challenge a lot of spectral indices have been developed, among which the following can be listed as an example: normalized difference built-up index (NDBI), enhanced built-up and bareness index (EBBI), urban index (UI), normalized difference bareness index (NDBaI), and bare soil index (BI) (As-syakur, Adnyana, Arthana, & Nuarsa, 2012; Chen, Zhao, Li, & Yin, 2006; He, Shi, Xie, & Zhao, 2010; Rikimaru & Miyatake, 1997; Zha, Gao, & Ni, 2003).

As it can be clearly noted from the above explanations each spectral index gives more emphasis towards separation of the particular land feature under consideration. In fact, all indices give clue about the presence of other land features based on cautiously classified threshold values. What matters in any classification attempt is that how much accurate the classification output is and its implication on LULC change detection analysis, especially vital for classifications performed based on digitally complex remotely sensed data (Congalton, 1991). Performance of any classification technique is judged based on results of accuracy assessment. Kamh et al. (2012) have evaluated the performances of five change detection techniques: image differencing, image rationing, image overlay, multi-date principal component analysis (PCA) and post-classification comparison where the last method yielded the most satisfactory classification accuracy. This entails that caution has to be taken before applying any image classification technique and change detection method. The good thing of course is that there is an uninterrupted academic research effort to improve image classification accuracy along with the advances in acquiring remotely sensed data. Complementary to the above-mentioned single spectral index-based classification accuracy improvement efforts, the use of tasseled cap, PCA, fuzzy c-means clustering (FCMC), possibilistic C-Means (PCM) and artificial neural networks, which employ synthetic bands have been tested by many researchers (Ganbold & Chasia, 2017; Novelli et al., 2016; Sun, Huang, Cheung, Liu, & Huang, 2005). The role of the synthetic bands is to maximize dimensions in addition to the raw spectral bands for better image extraction and pattern recognition. Novelli et al. (2016) have for example proposed artificial neural network based on Landsat image to extract impervious pixels with improved classification accuracy using synthetic bands generated from PC, Tasseled Cap (TC), Brightness Temperature (BT) and vegetation indices. The work by Mello et al. (2013) was unique in effect that the proposed technique, Spectral–Temporal Analysis by Response Surface (STARS), utilized all the spectral and temporal information to represent the spectral variation over time. Unlike other applications such as PCA, whose performance depends on the nature of data distribution (requiring normal distribution), STARS performs well in any type of distribution (Mello et al., 2013). In this regard, improving pattern recognition by adding a suitable dimension without computational complexity is an ongoing research area and was also our prime motive for this research.

In Ethiopia several studies on image classification methodologies and LULC dynamics have been carried out linking with social, economic, and climatological drivers (Ariti, van Vliet, & Verburg, 2015; Biazin & Sterk, 2013; Kindu, Schneider, Teketay, & Knoke, 2015; Wondie, Schneider, Melesse, & Teketay, 2011). In this particular study we have intensively explored the possibility of improving multispectral satellite image classification accuracy by compositing selected spectral indices and applying PCA in the process of investigating LULC change dynamics from year 1995 up to 2017 and future trends in Middle Awash subbasin, Ethiopia. This particular subbasin was chosen for its representativeness to complex geomorphological setup, intense