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Tracking annual cropland changes from 1984 to 2016 using time-series Landsat images with a change-detection and post-classification approach: Experiments from three sites in Africa

Yidi Xu[a], Le Yu[a,b,*], Feng R. Zhao[c], Xueliang Cai[d], Jiyao Zhao[a], Hui Lu[a,b], Peng Gong[a,b]

[a] Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University, Beijing 100084, China
[b] Joint Center for Global Change Studies, Beijing 100875, China
[c] Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA
[d] UNESCO-IHE, Westvest 7, Delft 2611, AX, the Netherlands

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ABSTRACT

Ensuring food security has been the top priority of many regions, particularly in developing countries in Africa. In recent decades, increasing population, together with growing food demands, have put great pressure on the world's food production. Long-term, up-to-date, annual cropland mapping at high resolution (i.e., at tens-of-metre levels) is in urgent demand for tracking spatial and temporal patterns of cropland change. However, because of the difficulty of capturing seasonality and flexible cropping systems, few studies have focused on understanding the dynamics of cropland using Landsat data in Africa. Here, we propose a new method of updating annual cropland mapping using a change-detection approach and post-classification to improve on traditional bi-temporal change vector analysis. Three Landsat footprints in Africa were selected (Egypt, Ethiopia and South Africa) as our study areas based on their different cropping systems and field sizes. The potential annual change areas were detected by employing multiple indices and thresholds in reference and long-term annual composite Landsat images. Next, map updates were conducted in the potential change pixels using random forest-based classification. Different training sample metrics were used (seasonal and annual samples) and compared in the classification step. The long-term cropland mapping accuracies for these three sites ranged from 88.04% to 94.30% (Egypt), 76.28% to 82.88% (Ethiopia) and 56.52% to 67.53% (South Africa). The results showed improvements in the accuracy and consistency of updating the annual cropland information using change-detection approaches, accounting for accuracy increases of 2.40%, 10.62% and 0.55% compared with a yearly cropland mapping approach in our previous research. The best results using annual samples extracted from the same season with the classified images supported the use of annual and growing samples in long-term annual mapping. Overall, a common trend of cropland expansion in all three sites was revealed, with an increase rate of 10.06, 3.73 and 1.35 kha/year in Egypt, Ethiopia and South Africa, respectively. The results indicated a rapid increasing pattern from bare land (desert) to irrigated systems (Egyptian site) but smaller and stable cropland changes in smallholder and farming-pastoral ecotones (Ethiopian and South African site), where limited land was still available for an expansion of agricultural area. This study highlights the potential application of time-series Landsat data in documenting and contributing missing cropland distribution information required for assessing and solving food security in Africa.

1. Introduction

Africa is one of the most food-insecure regions in the world. Rapid population growth and increasing food demand poses a major challenge to food security in this region. Furthermore, climate change (i.e., drought, higher temperatures or extreme rainfall) worsens existing conditions (Tubiello and Fischer, 2007). According to the Food and Agriculture Organization (FAO), sub-Saharan Africa accounts for 23.2% of global hunger today (FAO, 2015) and this is predicted to grow to 40%–50% by 2080 under most IPCC special report emissions scenarios (Fischer et al., 2005; Fischer et al., 2002; Schmidhuber and Tubiello, 2007). Thus, more effort needs be made to ensure food security in

* Corresponding author at: Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University, Beijing 100084, China.
E-mail address: leyu@tsinghua.edu.cn (L. Yu).

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Africa, in accordance with the Sustainable Development Goals of ending poverty and hunger by 2030.

Understanding the spatial and temporal dynamics of annual cropland, particularly in Africa, is critical in food security and agriculture-related studies (i.e., crop yield estimation, farming practices and water management). However, agricultural land cover changes are still poorly documented. Statistical records of agriculture from the FAO provide annual cropland area data for past decades. However, neither the spatial distribution of cropland extent nor the temporal consistency of inter-annual statistics is ensured (Xu et al., 2017). Some global (Finer Resolution Observation and Monitoring – Global Cropland [FROM-GC] (Yu et al., 2013a)) and regional (Africover) cropland maps provide spatial information on cropland distribution in Africa, but most are given at one time. These one-time-phase or multi-decadal products may not meet the global and national cropland monitoring (U.S. Climate Change Science Program, 2003) and production prediction objectives, by missing transient change (i.e., fallow land) between the time periods and not capturing the exact times of land use shifts (Broich et al., 2011). Therefore, monitoring of annual cropland change is in urgent demand in Africa, where there are rapid changes in agricultural land use.

Earth observation technology provides the only realistic approach to obtain annual cropland dynamics in detail at the continental level. The past decades have witnessed progress in cropland monitoring using remote sensing in several regards: (1) from distinguishing general agricultural land use to specific farming applications, i.e., irrigated/rainfed cropland (Portmann et al., 2010), fallow land (Estel et al., 2015; Tong et al., 2017) and specific crop mapping (Zhong et al., 2016); (2) from single satellite data to integrating multiple data sources (Gao et al., 2017; Yu et al., 2013b; Yu et al., 2014); and (3) from single- or multi-decadal monitoring to exploration of annual and even seasonal cropland dynamics (Waldner et al., 2015a; Zhang et al., 2017). Recently, some land use land cover (LULC) products including cropland types have been developed that show the spatial-temporal patterns of cropland changes at global (300 m—European Space Agency Climate Change Initiative (ESA-CCI) land cover products, from 1992 to 2014, http://maps.elie.ucl.ac.be/CCI/viewer/index.php) and regional (He et al., 2017) scales. Further, specific annual agricultural mapping at large scales—African annual cropland mapping from 2003 to 2014 (Xiong et al., 2017a, 2017b) and Australian crop mapping from 2000 to 2015 (Teluguntla et al., 2017)—have been created with multiple cropland products (i.e., cropland extent, cropland intensity and rainfed/irrigated cropland). The NDVI products with high temporal resolutions help to identify crop growing cycles and phenology within a year based on a quantitative spectral matching technique and rule-based specialized automated cropland classification algorithms (Thenkabail et al., 2009; Thenkabail and Wu, 2012). Time-series NDVI was also found to be useful for separating cropland and fallow land and quantifying its spatial and temporal distribution in the Fakara region, western Niger (Tong et al., 2017). Generally, these studies were conducted at coarse resolution (from 8 km to 250 m). Few studies have tried to track cropland annual dynamics in Africa using time-series Landsat images. However, small and very small field patches (0.64–2.56 ha and < 0.64 ha) (Fritz et al., 2015), flexible cropping systems and heterogeneous landscapes dominate agricultural land in Africa, making it a real challenge to accurately quantify annual cropland dynamics. Mosaics of cropland and natural vegetation also make it difficult to identify the exact cropland extent and limit the use of remote sensing in farming practice and land management (Yu et al., 2013a).

The availability of long-time-series 30-m Landsat images provides new opportunities for tracing cropland dynamics in Africa at higher spatial resolution and over longer periods than using MODIS. The China National Land Cover Datasets quantified the 30-m historical cropland changes at 5-year intervals from the 1980s to 2010 in China (Liu et al., 2014). However, the labour-intensive and time-consuming process prevents replication in other regions. In Africa, efforts have been made to capture cropland extent using time-series Landsat data (Xiong et al., 2017a, 2017b; Feng et al., 2016; Gong et al., 2013; Yu et al., 2013a) at a single time phase. However, few studies have adopted automated- and semi-automated algorithms to quantify the long-term annual cropland dynamics using Landsat images. Previous research along the Nile River Basin in Egypt used annual composite-based approaches in post-classification to derive the annual cropland mapping results (Xu et al., 2017). However, the unequal distribution of images within a year and false changes led to inter-annual inconsistency of cropland area. Other efforts in exploring detailed cropland dynamics i.e., mapping certain crop types based on phenological/phenology-related metrics extracted from vegetation indices (i.e., NDVI) (Dong et al., 2015; Zhong et al., 2014) or crop field identification based on weekly Web Enabled Landsat data using computer vision and geometric approach (Yan and Roy, 2016), were limited by local prior knowledge (i.e., accumulated temperature for certain crop types and transplant periods for rice paddy), a dense cloud-free Landsat time series and reliable cropland baseline products. As a result, tracking the annual cropland dynamics for regions like Africa during 1984 to 2016 through time-series Landsat images is needed, but has not been fully explored.

To mitigate inter-annual inconsistency and improve the robustness of the methodology, a shift from yearly cropland mapping to combining change-detection information with annual cropland updating is required. Recently, abundant change-detection algorithms have been developed for tracking LULC changes using time-series Landsat data (Brooks et al., 2014; Huang et al., 2010; Kennedy et al., 2010; Zhao et al., 2016; Zhu and Woodcock, 2014). However, most change-detection algorithms capable of capturing annual dynamics have been aimed at forest types (Hansen and Loveland, 2012; Zhu, 2017). In addition, the outputs of these algorithms are a binary result of change and no-change classifications with magnitude and direction (Hecheltjen et al., 2014; Ye et al., 2016). Only few can be used to label the from-to types (Zhu and Woodcock, 2014; Yin et al., 2018). In some two-time-phase studies, Multi-Index Integrated Change Analysis (MIICA) and other change-detection approaches, combined with post-classification have been successfully used in updating bi-decadal LULC products (Jin et al., 2017; Wessels et al., 2016; Xian et al., 2009). In this research, we propose a new method for monitoring long-term annual cropland dynamics by developing these traditional bi-temporal change vector analyses into a long-term cropland change monitoring algorithm. This approach combines the time efficiency and robustness of the previous bi-decadal studies and expands it to a time-series cropland monitoring algorithm. Here, the cropland is classed in accordance with the FROM-GC framework (Yu et al., 2013a), which includes arable land and permanent crops but excludes pastures.

Based on the necessity of capturing annual cropland dynamics in less-documented regions like Africa and the existing challenges in capturing annual cropland dynamics using Landsat data, we conducted annual cropland updating in three Landsat footprints in Egypt, Ethiopia and South Africa with different agri-systems. There were three objectives of this study: (1) to develop a robust and efficient long-term change-detection-based annual cropland updating system (CDB-ACUS) for agricultural areas in Africa, including the preparation of Landsat images, production of a base-year map, change-detection approach developed from bi-decadal MIICA and post-classification of the change areas; (2) to capture spatial and temporal cropland change patterns in different agri-systems in study regions in Africa over the past 33 years using satellite-based evidence at 30-m resolution; and (3) to reveal the potential impact of training sample selection in different seasons on cropland mapping.

2. Study area and methods

2.1. Study area

Long-term cropland mapping in Africa is a challenge because of