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Multi-faceted land cover and land use change analyses in the Yellow River Basin based on dense Landsat time series: Exemplary analysis in mining, agriculture, forest, and urban areas

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A B S T R A C T

The Yellow River Basin is one of China's most dynamic regions, where past and recent anthropogenic land use activities and polices have had a remarkably impact on the basin's surface. Over the past decades, the rapid socio-economic development has increased the pressure on the prevailing water and land resources with various repercussions on the environment and society. Counteracting ecological degradation in the basin, large-scale conservation and restoration plans have been initiated to expand vegetation coverage on deteriorated land, simultaneously fostering rural sustainable agriculture production. In this context, we derived precise spatial thematic products from long-term satellite time-series about high-frequency temporal dynamics. This information, available in a consistent and repeatable fashion is rare and relevant for many regional and local stakeholders and must be monitored annually to capture the rapid rate of change. Such information serves as a valuable base for decision-making processes. In this study, we used all the archived Landsat images between 2000 and 2015 (4520 scenes) to computed annually the spatially continuous spectral-temporal and textual metrics based on dense Landsat time-series to derive annual maps showing the most prominent land-cover change types related to mining, agriculture, forestry, and urbanization in four sub-regions spread over the Yellow River Basin. These novel land cover/use products provide new insights into recent regional and local dynamics. For final classification, we employed random forest classifiers for each thematic focus-region, trained and tested based on a stable-pixels data set. The resulting maps achieved high accuracies and show afforestation on the Loess Plateau and urbanization as the most prominent drivers of land use/cover dynamics. Agricultural land remained stable, showing local small-scale dynamics. Our study highlights the great potential of using consistent spectral-temporal metrics derived from dense Landsat time-series data together with a stable pixels reference set, allowing for local and regional land surface dynamics mapping at high spatial resolution and the prediction of implications of future change for effective and sustainable basin management.

1. Introduction

The strong interrelations between natural and human-induced land cover variability have a long and complex history spanning millennia. Over the last 50 years, these changes have intensified and humans have profoundly altered the Earth's biosphere at an unprecedented scale compared to any other period in the entirely of human history (Millennium Ecosystem Assessment, 2005). The numerical human population has increased remarkably and more than doubled since the 1970s (NBS, 2015; World Bank, 2014). Concomitant with population growth, the increasing demand and extraction of natural resources puts extra pressures on the Earth's

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ecosystem, including anthropogenic induced climate change, increasing UVB radiation from declining stratospheric ozone, changes in water and nutrition cycles, eutrophication of coastal and continental aquatic systems, land use and land cover dynamics, loss of biodiversity, and an overall decline in environmental quality (air, water, soil). This creates, in turn, feedback processes affecting human well-being at all spatial scales (Boden, Marland, & Andres, 2016; Hansen et al., 2013; IEO, 2016; IPCC, 2013; IUCN, 2015; Vitousek, 1994).

Worldwide, China ranks amongst the most populous countries, has risen to be the second largest economy, and continues to be one of the fastest growing economies (World Bank, 2016). As one of China's most vital regions for economic development, the heterogeneous Yellow River Basin, with a total area of around 750,000 km^2, is a blueprint region for contemporary dynamic Global Change processes occurring throughout the country, which is currently transitioning from an agrarian dominated society into a modern society characterized by massive urbanization and the strong growth of the tertiary and quaternary sectors (Webber, Barnett, Wang, Finlayson, & Dickinson, 2008; Wen, Zhang, Zhang, Gao, & Han, 2009; Wohlfart, Kuenzer, Chen, & Liu, 2016). The basin has undergone tremendous changes in land cover dynamics during the past decade mainly stemming from urbanization, agricultural expansion and intensification, and mining encroachment, as well as environmental and ecological restoration. Urban areas boomed due to the near-doubling of the population since the 2000s (from 60 to 100 million), agricultural fields expanded, crop output increased by 25% from 2000 to 2015 to sustain food security and energy consumption grew annually by more than 10% (NBS, 2015). Hence, the high demand for (and increasing consumption of) the prevailing water and land resources that have tremendously impacted on the basin with serious adverse effects on the environment and society (Cai, 2008; Miao, Yang, Chen, & Gao, 2012; Ringler et al., 2010). To counteract environmental deterioration, many land use reforms and afforestation management plans, partially supported with international aid, have been launched to restore vegetation coverage to impede soil and vegetation degradation, thus simultaneously fostering sustainable agriculture production (Bennett, 2008; Liu et al., 2013; Xu, Yin, Li, & Liu, 2006; Zhou, Van Rompaey, & Wang, 2009).

For extensive and dynamic areas, such as the Yellow River Basin, the delineation of spatially, temporally, and categorially systematic and synoptic land-cover information is crucial and is a required input for sustainable land and water management (Lambin et al., 2001; Pettorelli et al., 2016; Roy et al., 2014). Earth observation tools play an important role in monitoring the Earth's surface in a consistent fashion. The scale and pace of all aforementioned dynamic processes must be monitored at annual time steps to capture the rapid rate of change. Multi-temporal information at a sufficient temporal resolution is pivotal to understand the underlying complex drivers of change. Further, intra-annual time-series information significantly enhances the capabilities for mapping annual land-cover using the inherent phenology trajectories across varies land entities, proven by several studies for e.g. agriculture (Eisfelder & Kuenzer, 2015; Müller, Rufin, Griffiths, Barros Siqueira, & Hostert, 2015), forest (Hansen et al., 2014; Kennedy, Cohen, & Schroeder, 2007), or urban environments (Schneider, 2012). Aside from the temporal aspect, adequate spatial detail is necessary to delineate the heterogeneous landscape types that are present in the Yellow River Basin. Spatially high resolution datasets (30 m), such as Landsat, balance the trade-offs involving spatial and temporal resolution, areal coverage, and availability of long-term historical data (Griffiths et al., 2014; Kuenzer, Dech, & Wagner, 2015; Kuenzer et al., 2014; Schneider, 2012; Wulder, White, Masek, Dwyer, & Roy, 2011). The opening of the United States Geological Survey (USGS) Landsat archive for free, included automatically orthorectified imagery data (L1T-product), has tremendously increased the opportunity for regional delineations of land surface entities at higher temporal frequencies and more spatial details (Hansen & Loveland, 2012; Woodcock et al., 2008). So far, a number of multi-temporal Landsat based remote sensing studies have been conducted within the Yellow River Basin to provide diverse regional spatial dynamics (Dong, Wang, Ma, Kong, & Veroustraete, 2009; Guo & Gong, 2016; Kuenzer et al., 2014; Ottinger, Kuenzer, Liu, Wang, & Dech, 2013; Schneider, 2012; Wang, Liu, & Liu, 2013; Yue, Liu, Jørgensen, & Ye, 2003), but comparatively little scientific work has analyzed long-term annual land cover change processes for the basin and regional detailed investigations are rare (Wohlfart, Liu, Huang, & Kuenzer, 2016).

The objective of this paper was to provide a detailed multi-faceted land cover change analysis by delineating and analyzing the most prominent land cover dynamics across four selected focus regions located in the Yellow River Basin in China in a semi-automated fashion. Such a comprehensive and complex land cover change analyses is novel and provides new insights into recent regional dynamics. We computed annually spatially continuous spectral-temporal and textual metrics based on dense Landsat time-series to derive annual maps to (1) assess the dynamics of mining activities on the Qinghai-Tibet Plateau; (2) appraise agricultural dynamics in the largest irrigation district located in Inner Mongolia; (3) quantify ecological restoration on the degraded Loess Plateau; and (4) depict urban encroachment in the largest metropolitan region. A total number of 4520 Landsat (TM, ETM+, OLI) scenes between 2000 and 2015 were acquired and processed. Further, we determined a comprehensive stable pixel reference data set to keep manual sampling requirements to a minimum level, which served as training and validation set for Random Forest classifiers.

2. Study area

This study was conducted across the Yellow River Basin in northern China, which is the sixth largest river basin worldwide, spanning an area of around 750,000 km^2 and provides a livelihood for 190 million people (NBS, 2015). Originating on the vast Qinghai-Tibet Plateau at an elevation of 5200 m, the sediment-laden river crosses various ecoregions, such as the Ordos and Loess Plateau and empties after 5450 km into the Bohai Sea (Fig. 1) (Olson et al., 2001). On account of the large geographical coverage, the basin is characterized by various climatic conditions and transits from cold alpine climate (ET) and arid desert (Bw) climate, to temperate climates (Cw), according to the Köppen climate classification (Peel, Finlayson, & McMahon, 2007). The average annual precipitation for the river basin averages around 480 mm but and is unevenly distributed in space and time. Generally, rainfall decreases from southeast to northeast and is strongly seasonal, accumulating mainly between June and September (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005).

The Yellow River basin contains a wide range of land cover types, which were shaped by humans for centuries. Large areas, particularly the Loess Plateau, were turned into vast degraded landscapes (Fig. 2). Today, China's tremendous economic development make the basin one of the most dynamic regions in China and is associated with profound land use activities, such as urbanization, intensification and encroachment of agricultural areas, as well as extraction of natural resources with associated adverse environmental and social repercussions (Kuenzer, 2007; Ringler et al., 2010; Song & Kuenzer, 2014; Wohlfart, Kuenzer, et al., 2016; Zhu, Giordano, Cai, & Molden, 2004) (Fig. 2). To counteract degradation and restore the ecosystem functions, diverse land use policies