Multi-level monitoring of subtle urban changes for the megacities of China using high-resolution multi-view satellite imagery

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ABSTRACT

Megacities have evolved at an unprecedented rate under the pressure of urban population growth and economic development, particularly in the developing countries. For instance, many cities in China are experiencing a large number of rapid but subtle changes resulting from urban infrastructure construction. Information concerning such small changes is imperative for understanding the local environment and human activity, and can also provide key insights for urban planners. Undoubtedly, high-resolution remotely sensed data should play an essential role for the monitoring of such subtle changes, due to the improved observation capacity of the spatial details. However, few studies have investigated high-resolution data for change detection at a large geographic scale, due to the multi-temporal heterogeneity of the data, e.g., spatial mis-registration, parallax distortion for high architectures, and the different viewing angles. In this study, we attempted to fill this gap and resolve these problems by the use of multi-view ZY-3 satellite data, which are used to generate multi-temporal orthographic images through photogrammetric derivation. In the meantime, we present a general framework for precise urban change analysis in a multi-level (pixel, grid, and city block) approach. Two typical Chinese megacities—Beijing and Wuhan—are chosen in the experiments. The results confirm the accuracy of the proposed multi-level method for monitoring subtle urban changes, achieving Kappa coefficients of ~0.8 at the pixel level and a correctness of 93–95% at the grid level. The landscape analysis further indicates that the rapid urban construction led to greater fragmentation and spatial heterogeneity of buildings and decreased minimum distance between building patches (by ~1.0 m between 2012 and 2013). Moreover, the performances of ZY-3 and Landsat for the monitoring of subtle urban changes are compared, revealing that the high-resolution sensor—ZY-3 (2.5 m)—is essential for precisely detecting subtle urban changes, whereas the Landsat data (30 m) are not sensitive to most of the subtle changes that occur in the urban areas.

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1. Introduction

Urban areas, which cover only 0.5% of the Earth's land surface (Schneider et al., 2009), host more than half of the world's population, and the urban population is projected to continually increase, particularly in developing countries (UN, 2014). As human-dominated habitants, the megacities have experienced a rapid process of urban development, resulting in a series of negative effects, e.g., resource depletion, land degradation, traffic congestion, environmental and ecological problems, and urban heat island effects (Lasanta and Vicente-Serrano, 2012; Ma et al., 2012; Susaki et al., 2014; Zhou et al.,

2014). In-depth studies of urban changes are essential to promote sustainable urbanization (Dewan and Yamaguchi, 2009; He et al., 2006).

China, as the largest developing country, has been undergoing rapid and frequent changes (Fig. 1) due to the "reform and opening-up" policy (Lu et al., 2007). In addition, the pace of urbanization in a lot of Chinese cities has been further accelerated due to the great reliance on the revenue from land transactions and real estate construction (Bai et al., 2011). Specifically, land-related incomes can account for 30–70% of a city's financial revenue (Bai et al., 2014; Lin, 2007). China's macro-control policy, i.e., the central government on behalf of the Chinese public controls and empowers local governments to make land-use decisions, was implemented in order to standardize the land market (Long, 2014). However, authorities uncovered and investigated a total of 53,000 cases of illegal land use across the country in 2010 alone (ChinaDaily, 2011). Moreover, large areas of land (up to 113 km²), which could provide housing for 1 million households, were found idle nationwide after land developers purchased land-use rights (People'sDaily, 2010).

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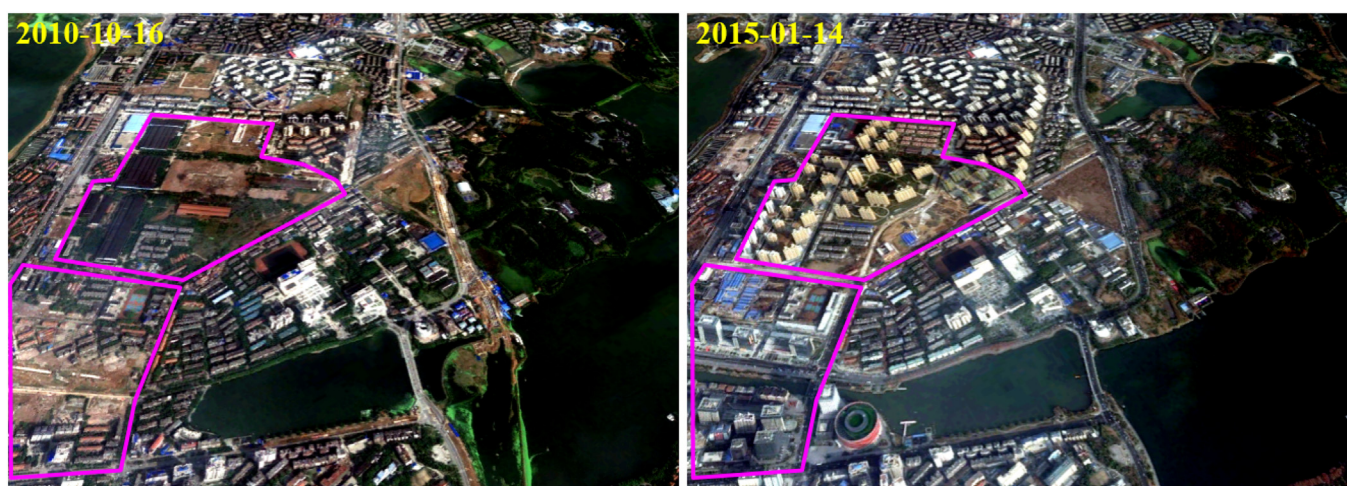
Fig. 1. An example from Wuhan, China, showing the subtle changes of urban land cover and landscapes. (Source of images: Google Maps.)

Generally speaking, a large number of land parcels have either been illegally occupied or remain idle due to the lack of public participation and the unclear demarcation for land development projects, leading to ineffective use of land resources and challenges to land-use management (Koroso et al., 2013; Li, 2016).

Recently, remote sensing techniques have shown their notable advantages in monitoring urban change, as a result of the large geographic coverage, rich spatial details, and high temporal frequency (Baus et al., 2014). A number of studies concerning urban development have been carried out using remote sensing data, such as the Advanced Very High Resolution Radiometer (AVHRR) data of the National Oceanic Atmospheric Administration (NOAA) (Kressler and Steinnocher, 1999; Stow and Chen, 2002), the Moderate Resolution Imaging Spectroradiometer (MODIS) data (Lunetta et al., 2006; Mertes et al., 2015), Landsat data (Schneider, 2012; Shalaby and Tateishi, 2007), and the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) nighttime light data (Liu et al., 2012; Ma et al., 2012). It should be noted that these studies have largely focused on the use of coarse- or moderate-resolution data, which are effective for monitoring the macro changes in a large-scale area, but can miss subtle urban changes (Yu et al., 2016).

Therefore, precise urban monitoring, which can detect subtle changes at a very fine scale, is of vital importance for regulating urban land cover/ use and landscapes. The availability of high spatial resolution remote sensing data can support such detailed urban monitoring, e.g., the demolition and construction of urban infrastructure, and hence allow in-depth change analysis for landscapes. However, high-resolution change detection has rarely been studied in the existing literature, due to the heterogeneity existing in the multi-temporal high-resolution imagery (e.g., spatial mis-registration, parallax distortion for high architectures, illumination conditions, and different viewing angles) (Stumpf et al., 2014). These problems make it difficult to accurately detect micro changes from high-resolution imagery, leading to a large number of false alarms, especially for pixel-based processing. In this regard, the ZiYuan-3 (ZY-3) satellite, which is China's first civilian high-resolution three-line array stereo satellite (launched in January 2012), has the ability to provide multi-temporal orthographic images, so as to minimize the spatial inconsistency as much as possible using the multi-view mode. In this way, it becomes possible to perform change detection from the high-resolution and multi-temporal orthographic images, courtesy of the merits of the multi-view images.

With respect to the change detection methods, although much progress has been achieved in recent years (Du et al., 2013; Tewkesbury et al., 2015), it is a big challenge for accurate multi-temporal classification

and change detection using high-resolution images, especially in the complex urban scenes. Most of the current change detection algorithms employ pixel-based methods (Song et al., 2016). However, it is widely agreed that pixel-based approaches do not exploit spatial or contextual information, and can be subject to the "salt and pepper" effect (Hussain et al., 2013; Yu et al., 2016). Therefore, in this study, a multi-level framework (i.e., pixel, grid, and block) for change detection is presented, in order to make full use of spatial details in high-resolution images and analyze urban changes at various scales.

In the meantime, how to perform accurate multi-temporal classification in an effective way, is also an essential issue, which provides underlying basis for the subsequent change analysis. For the high-resolution image classification, it is not sufficient to only consider spectral bands. In order to improve separability among spectrally similar objects (e.g., soil, roofs, and roads), researchers have proposed a series of spatial and structural features (e.g., pixel shape index (Zhang et al., 2006), morphological profiles (Mura et al., 2010), and textural metrics (Pacifici et al., 2009)). However, in most cases, it seems impossible to select one optimal feature set for different objects and scenes (Huang and Zhang, 2013). In addition, different spatial features can compensate each other in classifying different land covers by characterizing image properties from different perspectives. Consequently, multi-feature image classification is attempted in this paper, in order to improve interpretation efficacy of high-resolution imagery. On the other hand, conducting classification in each time series separately is the most ad hoc way in current literature (El-Kawy et al., 2011; Tarantino et al., 2016). In this way, sample collection is required for each separated classification process, which is time-consuming and labor-intensive, especially at a large geographic scale. Furthermore, it hampers the possibility of classifying time series of images accurately and consistently in a more automated fashion. Considering this, we aim to propose a sample migration strategy to reduce work in sample collection.

In summary, the objective of this study is to address the key research questions for change detection using high-resolution multi-view and multi-temporal satellite imagery, concerning how to

(1) minimize the spatial heterogeneity existing in the multi-temporal high-resolution imagery;
(2) conduct a multi-temporal classification in an efficient way; and
(3) analyze multi-level urban changes.

The proposed methodology is conducted in two representative Chinese cities—Beijing and Wuhan—over a short time period (2012–2013),