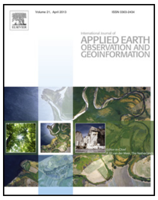
International Journal of Applied Earth Observation and Geoinformation 41 (2015) 46–55

Contents lists available at ScienceDirect

International Journal of Applied Earth Observation and Geoinformation

journal homepage: www.elsevier.com/locate/jag



Measures of spatio-temporal accuracy for time series land cover data

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ARTICLE INFO

Article history:
Received 17 February 2015
Accepted 22 April 2015
Available online 29 April 2015

Keywords:
Remotely sensed data
Spatio-temporal analysis
Accuracy assessment
Geographically weighted model
Principal component analysis

ABSTRACT

Remote sensing is a useful tool for monitoring changes in land cover over time. The accuracy of such time-series analyses has hitherto only been assessed using confusion matrices. The matrix allows global measures of user, producer and overall accuracies to be generated, but lacks consideration of any spatial aspects of accuracy. It is well known that land cover errors are typically spatially auto-correlated and can have a distinct spatial distribution. As yet little work has considered the temporal dimension and investigated the persistence or errors in both geographic and temporal dimensions. Spatio-temporal errors can have a profound impact on both change detection and on environmental monitoring and modelling activities using land cover data. This study investigated methods for describing the spatio-temporal characteristics of classification accuracy. Annual thematic maps were created using a random forest classification of MODIS data over the Jakarta metropolitan areas for the period of 2001–2013. A logistic geographically weighted model was used to estimate annual spatial measures of user, producer and overall accuracies. A principal component analysis was then used to extract summaries of the multi-temporal accuracy. The results showed how the spatial distribution of user and producer accuracy varied over space and time, and overall spatial variance was confirmed by the principal component analysis. The results indicated that areas of homogeneous land cover were mapped with relatively high accuracy and low variability, and areas of mixed land cover with the opposite characteristics. A multi-temporal spatial approach to accuracy is shown to provide more informative measures of accuracy, allowing map producers and users to evaluate time series thematic maps more comprehensively than a standard confusion matrix approach. The need to identify suitable properties for a temporal kernel are discussed.

1. Introduction

Land cover change is a spatially and temporally dynamic process which is known to affect the structure and function of global environments, such as climate (Rindfuss et al., 2004). Land cover changes, such as deforestation, desertification, urban expansion and agricultural land loss have been found to impact on global environmental conditions (Lambin et al., 2001; Turner et al., 2007), to be associated with biodiversity loss (Nagendra et al., 2013; Seto et al., 2012), climate changes (Feddema et al., 2013) and with human vulnerability (Foley et al., 2005; Verburg et al., 2009). Despite of the importance of understanding this dynamic process, it remains a challenge to describe reliably the accuracy of land cover and land cover changes over space and time.

Remote sensing has been an important tool for monitoring land cover and detecting change from local to global scales. The most common method is post-classification change detection in which thematic maps from different times are compared to identify changes (Tewkesbury et al., 2015). This approach has been often applied at fine spatial scales using data, such as IKONOS, Quickbird and Geoeye (Myint et al., 2011; Tsutsumida et al., 2015), and at medium scale, such as Landsat and Satellite Pour l'Observation de la Terre (SPOT) (Bayarsaikhan et al., 2009; Congalton, 1991; Yuan et al., 2005). Recently, the availability of coarse scale historical satellite imagery, such as Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Very High Resolution Radiometer (AVHRR) has increased (Clark et al., 2010, 2012; Lunetta et al., 2006; Sánchez-Cuervo et al., 2012; Tsutsumida et al., 2013; Verbesselt et al., 2012). Such data supports the temporal analysis of land cover changes, using for example, wave analysis (Lunetta et al., 2006), Breaks for Additive Seasonal and Trend (BFAST) method (Tsutsumida et al., 2013; Verbesselt et al., 2012) and random forest approaches (Clark et al., 2010, 2012; Sánchez-Cuervo et al., 2012). These studies have generated temporal sequences of thematic

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http://dx.doi.org/10.1016/j.jag.2015.04.018
0303-2434/

maps in order to understand the spatial and temporal dynamics of land cover. There is as yet little research that has considered changes in the spatial distribution of land cover accuracy over time. This paper addresses that gap.

2. Background

Land cover data are typically classified such that each pixel or object is labelled with a class as a result of classifying remotely sensed data. Land cover accuracy assessments quantify classification errors by comparing a sample of this estimated or predicted class with observed, validation data, usually on a pixel by pixel basis (Olofsson et al., 2014). The results are summarised in a contingency matrix, referred to as the confusion matrix, which cross-tabulates the allocated class against the reference data for the sample locations (Foody, 2002, 2004; Olofsson et al., 2014). The matrix can be used to calculate overall accuracy and class specific measures, such as user and producer accuracy. A description of the matrix and the measures that can be derived from it is found in Congalton (1991). In this way, accuracy assessments describe the appropriateness and quality of the data so that map users may evaluate the utility of a thematic map for their intended applications (Stehman and Czaplewski, 1998). However, the confusion matrix yields only static, global indicators of thematic classification accuracy and does not describe any spatial variations in accuracy (Comber et al., 2012; Comber, 2013; Foody, 2005). In order to overcome this issue, explicitly spatial measures of accuracy have been proposed (Comber et al., 2012; Comber, 2013; Foody, 2005).

Foody (2005) constructed local confusion matrices at discrete locations spaced at 50 pixel intervals using the closest 150 reference data points. The point accuracies were then interpolated over the test site to create an accuracy surface. Comber et al. (2012) extended Foody's work and developed a geographically weighted approach to estimate local accuracy. A logistic Geographically Weighted Regression (GWR) as proposed by Brunsdon et al. (1996) was used to estimate local accuracy measures at discrete locations on a grid using a moving kernel. At each location the data points used to calculate local accuracy were weighted by their distance to the kernel centre. The results describe the spatial variations in the relationships between the reference data and classified data (Comber et al., 2012). Comber (2013) further developed this approach and proposed a method for estimating overall, user and producer accuracies locally for generating maps of the spatial distribution of accuracies and any spatial autocorrelation of errors.

Little research has considered the spatial and temporal dimensions of accuracy of classified time series data together, using only the confusion matrix to assess accuracy (Clark et al., 2010, 2012; Lunetta et al., 2006; Sánchez-Cuervo et al., 2012) or a visual comparison of land cover changes with reference images (Tsutsumida et al., 2013). Approaches to systematically analyse when and where classifications are accurate or how and why accuracy varies over space and time are lacking despite the importance of understanding, monitoring and evaluating land cover spatio-temporal dynamics.

This study applied the spatial accuracy assessment methods proposed by Comber (2013) to a time series of land cover maps. The analysis of local measures of overall, user and producer accuracy determined using a geographically weighted kernel was extended into the temporal dimension. A principal component analysis (PCA) was then used to examine the temporal variations in spatial accuracy. Land cover data were created by applying a random forest classifier to the 16-day composite MODIS Enhanced Vegetation Index (EVI) at approximately 250-m spatial resolution during the period of 2001–2013. Each pixel was classified into one of three classes; *Agriculture*, *Urban* and *Forest*. Reference data for training and validation were collected at 1000 randomly selected locations and then sampled through time to generate approximately 4000 data points from historical very high spatial resolution (VHR) satellite imagery available in Google Earth. The accuracy analyses resulted in 91 maps (spatial distributions) of accuracy covering 13 years, with 7 accuracy layers generated for each year describing overall accuracy and user and producer accuracies for each class. The spatio-temporal variance in the class specific accuracy layers (user and producer accuracies) was extracted by applying a PCA.

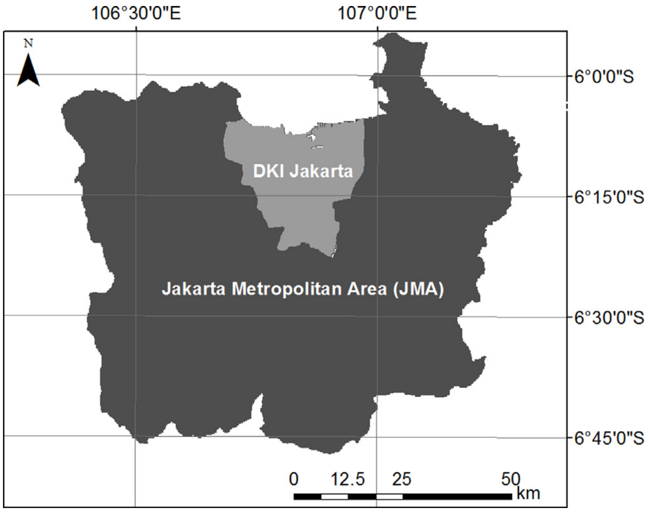

Fig. 1. Overview of a study area. DKI Jakarta is located as the urban core in the Jakarta metropolitan area.

3. Study area and data

3.1. Study area

The study area was the Jakarta Metropolitan Area (JMA) which covers DKI Jakarta, the capital of Indonesia, and its suburban area surrounded by agricultural land and forest, a total of 6659 km^2 (Fig. 1). The JMA has one of the highest population densities in south-east Asia, with approximately 27.2 million people in 2011. It has experienced rapid land cover changes due to urban expansion (Pravitasari et al., 2015). The urban core is located at DKI Jakarta, however, urban land cover conversion from agriculture to urban has occurred in surrounding areas driven by suburban population growth.

3.2. MODIS EVI data

In order to create annual thematic land cover maps, 299 MODIS EVI images from the MOD13Q1 product for the period of 2001–2013 (23 images in each year) were prepared. This dataset is a 16-day composite product at 231.7-m spatial resolution in the study area, composed of high quality pixels in terms of cloud-cover, view angle and residual atmospheric contamination over the period. The EVI time series can contain noise due to the atmospheric bias, surface anisotropic and sensor problems (Jönsson and Eklundh, 2004). To deal with these problems, only data flagged as *good* or *marginal* in the MOD13Q1 reliability layer were extracted from original EVI time series. This process results in a 36.3% loss of the total data in the study area during 2001–2013. Accordingly, the double logistic function in TIMESAT was utilised to interpolate missing values (Jönsson and Eklundh, 2004). This fits the time series image data to smooth continuous asymmetric curves and enhances the distribution of the data from original reliable pixel values (Eklundh and Jönsson, 2012). The processed data were split into 13 annual patterns (consisting 23 observations in each pattern) which were inputs to the random forest classification.