Remote Sensing of Environment 156 (2015) 182–195

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Detecting changes in vegetation trends using time series segmentation

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ARTICLE INFO

Article history:
Received 3 December 2013
Received in revised form 8 September 2014
Accepted 8 September 2014
Available online 16 October 2014

Keywords:
Vegetation dynamics
Change detection
Satellite imagery
Trend analysis
Time series
Segmentation
DBEST
GIMMS
NDVI

ABSTRACT

Although satellite-based sensors have made vegetation data series available for several decades, the detection of vegetation trend and change is not yet straightforward. This is partly due to the scarcity of available change detection algorithms suitable for identifying and characterizing both abrupt and non-abrupt changes, without sacrificing accuracy or computational speed. We propose a user-friendly program for analysing vegetation time series, with two main application domains: generalising vegetation trends to main features, and characterizing vegetation trend changes. This program, Detecting Breakpoints and Estimating Segments in Trend (DBEST) uses a novel segmentation algorithm which simplifies the trend into linear segments using one of three user-defined parameters: a generalisation-threshold parameter δ, the m largest changes, or a threshold β for the magnitude of changes of interest for detection. The outputs of DBEST are the simplified trend, the change type (abrupt or non-abrupt), and estimates for the characteristics (time and magnitude) of the change. DBEST was tested and evaluated using simulated Normalized Difference Vegetation Index (NDVI) data at two sites, which included different types of changes. Evaluation results demonstrate that DBEST quickly and robustly detects both abrupt and non-abrupt changes, and accurately estimates change time and magnitude.

DBEST was also tested using data from the Global Inventory Modeling and Mapping Studies (GIMMS) NDVI image time series for Iraq for the period 1982–2006, and was able to detect and quantify major change over the area. This showed that DBEST is able to detect and characterize changes over large areas. We conclude that DBEST is a fast, accurate and flexible tool for trend detection, and is applicable to global change studies using time series of remotely sensed data sets.

1. Introduction

Vegetation is an important component of terrestrial ecosystems (e.g. Prentice et al., 2000; Sitch et al., 2003). It is now widely recognized that vegetation can respond to climate and disturbance in a complex, non-linear fashion (e.g. Lambin and Ehrlich, 1997). External disturbances to ecosystems, including insect outbreaks, fires, forest clear-cutting, and conversion of natural grasslands to cultivated crops, increase the complexity of vegetation variations across a wide range of spatio-temporal resolutions and scales (e.g. Higgins et al., 2002; Lambin et al., 2003). There is a corresponding need for data and tools which can properly capture and represent such complex dynamics, at a level of detail which is appropriate to the question under consideration. One flexible and simplifying idea is to allow the user to define the boundary between signal and noise. Developing analysis tools that embody this idea can help us to characterize and understand vegetation dynamics with much greater efficiency.

Vegetation dynamics are often monitored at different spatial and temporal scales through vegetation index data series, such as GIMMS (Global Inventory Modeling and Mapping Studies), MODIS (Moderate Resolution Imaging Spectroradiometer), and SPOT/Vegetation (System Pour l'Observation de la Terre) data sets. One widely used index is the Normalized Difference Vegetation Index (NDVI), which is an indicator of the vegetation's greenness (Rouse et al., 1973). Temporal trend analysis of NDVI has proved particularly useful for monitoring and characterizing the response of land cover to phenomena with a range of time scales, from abrupt natural or anthropogenic events (Verbesselt et al., 2009), to seasonal variability of plant phenology caused by changes in temperature and rainfall regimes (Heumann et al., 2007), through to gradual inter-annual climate changes (Jacquin et al., 2010). Similar analyses of NDVI trends have also been used to investigate the relationship between NDVI and Leaf Area Index (LAI), a key variable which is functionally related to plant biomass production. Studies have indicated that this relationship is not completely linear, particularly for high LAI values (e.g. Carlson and Ripley, 1997; Fan et al., 2009).

Non-linear temporal trends in NDVI can be studied by a number of techniques, including time series segmentation (Keogh et al., 2004). Series segmentation refers to approximating a time series by a set of piecewise straight-line segments, in the process eliminating noise but

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http://dx.doi.org/10.1016/j.rse.2014.09.010
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preserving the salient details of the trend. Two significant merits of segmentation are that first, it approximates complex signatures to extract their basic features (Zeileis et al., 2003) and second, it increases the efficiency of data storage and further computation (Keogh et al., 2004). The size of the output set can vary between one and the size of the original time series, and is a key parameter in determining the type of information available to the user, from most generalised/compressed information (one segment) to all possible details (all data points).

A particular type of segmentation technique, which always outputs one segment, is the ordinary least-squares (OLS) technique. It has been widely used for assessing long-duration changes in vegetation greenness using NDVI time series (Eklundh and Olsson, 2003; Fensholt et al., 2009; Fuller, 1998; Nemani et al., 2003; Peng et al., 2012). However, the implicit assumption that vegetation always changes gradually and constantly over the entire study period is a critical drawback of this method (e.g. Jamali et al., 2014). Consequently, it is impossible using OLS to identify periods in which the rate of change, or even the sign of the rate of change, varies within a given time period: for example, the existence of short-duration nonlinearities such as ‘greening’ or ‘browning’ patterns may be completely obscured because they have been averaged out altogether (de Jong et al., 2012). On the other hand, using the original time series in further analysis is not cost effective and may also, in cases when only the main features of the vegetation change are of interest, carry unused detailed information and noise.

Fortunately, to date at least two alternative approaches between the two mentioned extreme cases have been introduced for detecting trends and estimating changes in vegetation time series. The first approach, Landsat-based detection of Trends in Disturbance and Recovery (LandTrendR), uses arbitrary temporal segmentation to divide long-term trends into piecewise linear segments for the representation of spectral change in forested ecosystems (Cohen et al., 2010; Kennedy et al., 2010). LandTrendR focuses solely on Landsat derived data, and requires several complex control parameters to be specified. Moreover, different signal-to-noise ratios and spectral properties of different instruments may require alteration of the algorithms and parameters used in LandTrendR, and its generalisation for use with time series of other sensors in other ecosystems has not yet been implemented.

The second approach, Breaks For Additive and Seasonal Trend (BFAST), was one of the first general methods for detecting changes in time series data, focusing on the trend and seasonal components in long-term NDVI data series, at spatial scales ranging from continental to global (e.g. de Jong et al., 2013; de Jong et al., 2012; Verbesselt et al., 2010a; Verbesselt et al., 2010b). It employs a generic approach by assuming that a time series can be modelled in terms of its trend, seasonal, and remainder components, including breaks in the trend and seasonal components. In BFAST, nonlinearity in the trend component is also simplified into a number of individual trend segments, in order to identify sudden structural shifts. The simplified trend is therefore composed of segments with gradual changes, separated from each other by relatively brief, abrupt changes (de Jong et al., 2012; de Jong et al., 2013; Verbesselt et al., 2010a). Our experience using BFAST (most recent version 1.4.4) shows that although the user can control the number of breaks to be detected, they do not have full control over the level of trend generalisation (whether basic features or detailed information will be extracted), or over the change magnitude that is detected. More importantly, the discontinuities may not be instantaneous for which modelling them as one time-step shifts can be seen as a limitation.

Thus, to the best of our knowledge, no attention has yet been paid to segmenting time series of vegetation indices to generalise trends and detect both abrupt and non-abrupt changes, in a way which allows the user to control the segmentation. Ideally the user should be able to choose the generalisation scheme and extract information about both the main feature and details. The user should also be able to detect and characterize changes of interest, including realistic abrupt and non-abrupt changes of different durations and in any order within a particular sequence of occurrences.

The overall aim of this paper is to propose a novel approach for segmenting and analysing trend changes in time series of vegetation indices (VI). The method, called Detecting Breakpoints and Estimating Segments in Trend (DBEST), provides both generalised trend segments and estimates of the characteristics of both abrupt events and long-term processes. DBEST has been tested and evaluated using simulated NDVI data series. We also applied DBEST to a GIMMS–NDVI dataset (1982–2006) for Iraq, to detect major changes, determine change type (abrupt or non-abrupt) and estimate the characteristics (time, magnitude) of the changes in a spatio-temporal framework. The method allows for fast, flexible and accurate estimations of trends, essential from a global change perspective.

2. Data and study area

We have developed our method using a commonly used time-series data source: the NASA GIMMS data set. Then, we applied the methods to selected study areas that highlight certain temporal features. The methods are not specific to either the data type or the sites, which merely represent commonly used data and illustrative cases.

2.1. GIMMS data

The GIMMS data set is a twice-monthly composite NDVI product with global coverage at an 8-km spatial resolution, which is available for the 25.5 year period from July 1981 to December 2006 (Tucker et al., 2004; Tucker et al., 2005). The GIMMS data were derived from the output of the AVHRR (Advanced Very High Resolution Radiometer) instrument on board NOAA (National Oceanographic and Atmospheric Administration) satellite series 7, 9, 11, 14, 16 and 17. The NDVI is computed from the red and near infrared bands of the AVHRR sensor, and is correlated with photosynthetic activity and the LAI of green vegetation. The GIMMS data have been corrected for variations arising from calibration, view geometry, volcanic aerosols, and other factors not related to actual vegetation change (Tucker et al., 2005). The GIMMS data have also been validated against the well-calibrated and atmospherically-corrected MODIS data set for the period 2000–2007 for the Earth's semi-arid regions (Fensholt et al., 2012). Despite the corrections, the GIMMS data may contain residual invalid measurements, but these are well indicated using quality flags (de Jong et al., 2012). Based on the quality flags, we only considered pixels with at least 75% valid data points (i.e., flag value zero) through the whole time span.

2.2. Study area

The case study was Iraq, selected due to the fact that large parts of the country's land surface have undergone major changes in the recent past. Iraq's geography consists of four main zones: desert in the west and southwest, rolling upland between the upper Tigris and Euphrates rivers in north central Iraq, highlands in the north and northeast with mountains, and alluvial plain through which the Tigris and Euphrates flow from northwest to southeast. About 77.7% of Iraq's land area is not viable for agriculture. 0.3% is forest and woodlands situated along the extreme northern border with Turkey and Iran. The remaining 22% are used for a range of agricultural activities (Schnepf, 2004).

Over the last two to three decades, the landscape of Iraq has witnessed many changes (UNEP, 2001). These have been caused by frequent natural hazards, such as sand storms (Draxler et al., 2001) and floods (Hamdan et al., 2010), and human activities, such as forced migration, social conflicts, and wars (especially in south-eastern and northern