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Large-area settlement pattern recognition from Landsat-8 data

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ABSTRACT

The study presents an image processing and analysis pipeline that combines object-based image analysis with a Support Vector Machine to derive a multi-layered settlement product from Landsat-8 data over large areas. 43 image scenes are processed over large parts of Central Asia (Southern Kazakhstan, Kyrgyzstan, Tajikistan and Eastern Uzbekistan). The main tasks tackled by this work include built-up area identification, settlement type classification and urban structure types pattern recognition. Besides commonly used accuracy assessments of the resulting map products, thorough performance evaluations are carried out under varying conditions to tune algorithm parameters and assess their applicability for the given tasks. As part of this, several research questions are being addressed. In particular the influence of the improved spatial and spectral resolution of Landsat-8 on the SVM performance to identify built-up areas and urban structure types are evaluated. Also the influence of an extended feature space including digital elevation model features is tested for mountainous regions. Moreover, the spatial distribution of classification uncertainties is analyzed and compared to the heterogeneity of the building stock within the computational unit of the segments. The study concludes that the information content of Landsat-8 images is sufficient for the tested classification tasks and even detailed urban structures could be extracted with satisfying accuracy. Freely available ancillary settlement point location data could further improve the built-up area classification. Digital elevation features and pan-sharpening could, however, not significantly improve the classification results. The study highlights the importance of dynamically tuned classifier parameters, and underlines the use of Shannon entropy computed from the soft answers of the SVM as a valid measure of the spatial distribution of classification uncertainties.

1. Introduction

According to the United Nations' Vancouver Declaration on Human Settlements (1976), a settlement is defined as the totality of the human community with all the structural, organizational, social and cultural elements that sustain it (Salvatore et al., 2005). Commonly accepted definitions for the categorization of settlements are not existing, even though distinguishing different settlement types is recognized as being important (Principles and Recommendations for Population and Housing Censuses, 1998). Especially differencing between "urban" and "rural" settlements is a widely discussed topic and common approaches to categorize settlements include thresholding of the population size, density or the geographic area, the political, administrative and economic importance, the availability of services or the sphere of influence. Information on human settlements is crucial for a large range of applications including disaster risk reduction (Geiß and Taubenböck, 2013; Pittore et al., accepted for publication) and rapid emergency response (Pittore et al., 2014). A central issue in this context is the availability of up-to-date information on the extent, type and composition of human settlements. In particular in less developed countries such information is largely unavailable, due to rapid urbanization that often cannot be adequately mapped by local or regional authorities.

It is largely recognized that satellite remote sensing can provide the needed information in a time and cost-efficient manner over large areas. Despite the apparent potentials of remote sensing, there exist only few global and some regional settlement mapping approaches that include information beyond a simple binary classification of built-up/not built-up areas (Gamba and Herold, 2009). A majority of the global approaches are based on low-resolution earth-observation data (Potere et al., 2009). Due to their ground sampling distance (>100 m) they have the tendency to underrepresent small, scattered rural settlements. Efforts towards global high-resolution settlement products such as the Global Human Settlement Layer (Pesaresi et al., 2015) or the Global Urban Footprint

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(Esch et al., 2013) have been started recently to overcome these limitations. However, given the type of input data (very high resolution optical and SAR images), their time and cost-efficiency in producing regularly up-to-date settlement information may be rather limited. To this regard, the medium-resolution Landsat-8 satellite sensors show great potential for timely and cost-efficient settlement studies at regional scale (Bhatti and Tripathia, 2014; Poursanidisa et al., 2015; Roy et al., 2014). Previous Landsat sensors have already been exploited by several authors to conduct regional and global land-cover/land-use studies (Hansen and Loveland, 2012; Chena et al., 2015; Ban et al., 2015), but to the authors' knowledge, no study exists so far that uses Landsat-8 data for settlement pattern recognition at the regional scale.

A wide range of studies exists on built-up area extraction from medium resolution multi-spectral satellite images (Weng, 2012). Most of the studies use pixel-based approaches with unsupervised or supervised classification or regression. When further analyzing the built-environment from Landsat images, different built-up land-cover/land-use classes are mainly defined by the alignment of buildings, streets and open spaces and therefore cannot sufficiently be described by just the spectral values of a single pixel. In this context, object-based image analysis showed improvements over pixel-based approaches (Yan et al., 2006). In a previous study of the authors, the potential of combining object-based image analysis with machine learning for urban pattern recognition could be highlighted (Wieland and Pittore, 2014).

For the stratification of a settlement into meaningful spatially defined entities of similar building types and morphological structure, "urban structure types" can provide a valuable concept. Banzhaf and Hofer (2008) give a comprehensive overview of urban structure type studies, which shows their multiple applications in a variety of research fields. Classification schemes and analysis scales of urban structure types studies mainly depend on the particular area and structures of interest. Urban structure types mapping is usually carried out by means of a visual aerial or satellite image interpretation and field surveys. Taubenböck et al. (2008) use the urban structure types concept within the context of mega city mapping from satellite imagery. Herold et al. (2003) use a combination of remote sensing and landscape metrics to describe structures in urban land-use.

The aim of this study is to derive a multi-layered settlement product from Landsat-8 data covering a large area of Central Asia (Southern Kazakhstan, Kyrgyzstan, Tajikistan and Eastern Uzbekistan). The main tasks tackled by this work include:

- Built-up area identification;
- Settlement type classification;
- Urban structure types pattern recognition.

The study follows an object-based approach to image analysis and combines it with machine learning techniques. Besides commonly used accuracy assessments of the resulting map products, thorough performance evaluations are carried out under varying conditions to tune algorithm parameters and assess their applicability for the given tasks. As part of this, several research questions are being addressed in particular:

- Influence of the feature space on the classification performance: Is the Landsat-8 multi-spectral feature space sufficient for the classification tasks at hand? Which influence plays texture in the context of human settlement pattern recognition? Can features derived from digital elevation models improve the identification of built-up areas in mountainous regions?
- Influence of image pre-processing on the classification performance: Can pan-sharpening improve the accuracy of urban structure type pattern recognition?
- Spatial distribution of classification uncertainties: How are the classification uncertainties distributed in space and are they correlated with segment heterogeneity?

The paper is structured as follows. In Section 2 the study area, datasets and pre-processing steps are introduced. Section 3 outlines the method and describes the modules of the processing and analysis chain. Results are presented in Sections 4 and 5 with a particular focus of Section 4 being on performance evaluation of the learning machines under varying conditions. A comprehensive validation with in-situ and OpenStreetMap data is presented, before the study closes with a discussion and conclusion Section.

2. Study area and data

The study area covers 606,185 km^2 spanning large parts of Central Asia, namely Southern Kazakhstan (S-KZ), Kyrgyzstan (KG), Tajikistan (TJ) and Eastern Uzbekistan (E-UZ) (Fig. 1). The landscape of the study area can be divided into the flat steppes of Kazakhstan in the North, desert areas mainly in Uzbekistan and the mountainous regions of Kyrgyzstan and Tajikistan with the major mountain ranges being Tien Shan in Kyrgyzstan and Pamir in Tajikistan. Along the margins of the Amur Darya and Syr Darya rivers which flow in North-West direction through Kyrgyzstan, Tajikistan, and Eastern Uzbekistan vast agricultural areas can be found. Currently approximately 40% of the population in Central Asia live in urban areas while economies remain mostly agrarian-industrial. According to the Population Division of the UN Department of Economic and Social Affairs, the population living in urban areas will reach 45% by 2030 and exceed 55% by 2050 (Hashimov et al., 2013). Despite a rapidly changing built-environment, especially since the end of the Soviet-rule in 1990, no unified map of up-to-date settlement extents and compositions existed for the region at the time of writing this manuscript.

43 multi-spectral image scenes from Landsat-8 with a ground coverage of 185 $\times$ 180 km each were acquired over the study area between April and June 2013. The Landsat Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS) systems on board the satellite have a ground sampling distance of 30 m in the visible, near-infrared, short wave infrared and 100 m respectively in the thermal infrared with a spectral resolution of 10 bands plus an additional panchromatic band with 15 m spatial resolution. The images are delivered in processing Level 1 T-Terrain Corrected, which means they are orthorectified, radiometrically corrected and the TIRS bands are resampled to 30 m by using cubic convolution. A transformation of the images into the WGS84 coordinate reference system was performed. The images were converted to top-of-atmosphere reflectance, mosaicked and split into 494 regular tiles of 1500 $\times$ 1500 px. A Bayesian data fusion as implemented in OTB (Orfeo Toolbox Cookbook, 2015) and proposed by Fasbender et al. (2008) has been performed to pan-sharpen image tiles that intersect with reference datasets (see below for further explanation) in order to test the influence of the spatial resolution on the performance of classifying urban structures (Section 4.2). Moreover, the Shuttle Radar Topography Mission (SRTM) digital elevation model version 4 with 90 m horizontal resolution has been used for the area covered by these test image tiles in order to further evaluate the influence of features derived from elevation data on the classification performance.

3. Method

A processing pipeline has been developed, entirely based on free and open-source tools, in order to extract settlement patterns from multi-spectral satellite images (Fig. 2). The proposed