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Satellite monitoring of urbanization and environmental impacts—A comparison of Stockholm and Shanghai

Jan Haas*, Dorothy Furberg, Yifang Ban

Division of Geoinformatics, Department of Urban Planning and Environment, KTH Royal Institute of Technology, SE-10044 Stockholm, Sweden

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ABSTRACT

This study investigates urbanization and its potential environmental consequences in Shanghai and Stockholm metropolitan areas over two decades. Changes in land use/land cover are estimated from support vector machine classifications of Landsat mosaics with grey-level co-occurrence matrix features. Landscape metrics are used to investigate changes in landscape composition and configuration and to draw preliminary conclusions about environmental impacts. Speed and magnitude of urbanization is calculated by urbanization indices and the resulting impacts on the environment are quantified by ecosystem services. Growth of urban areas and urban green spaces occurred at the expense of cropland in both regions. Alongside a decrease in natural land cover, urban areas increased by approximately 120% in Shanghai, nearly ten times as much as in Stockholm, where the most significant land cover change was a 12% urban expansion that mostly replaced agricultural areas. From the landscape metrics results, it appears that fragmentation in both study regions occurred mainly due to the growth of high density built-up areas in previously more natural/agricultural environments, while the expansion of low density built-up areas was for the most part in conjunction with pre-existing patches. Urban growth resulted in ecosystem service value losses of approximately 445 million US dollars in Shanghai, mostly due to the decrease in natural coastal wetlands while in Stockholm the value of ecosystem services changed very little. Total urban growth in Shanghai was 1768 km^2 and 100 km^2 in Stockholm. The developed methodology is considered a straight-forward low-cost globally applicable approach to quantitatively and qualitatively evaluate urban growth patterns that could help to address spatial, economic and ecological questions in urban and regional planning.

Introduction

Cities as functional centres of human agglomeration are, and have always been of tremendous importance. Due to a global increase in population and urbanization rates, accurate land use and land cover information is crucially important to support functional and sustainable development as well as the preservation of ecological and environmental conditions and processes in urban areas. Therefore, tools and methods are needed for the evaluation of urbanization and its environmental impacts. Remote sensing can provide timely and reliable information on urban land cover at local, regional and even global scales (Ban and Jacob, 2013; Niu and Ban, 2013; Ban et al., 2014a,b), urban change detection (Ridd and Liu, 1998; Ban and Yousif, 2012) or urbanization studies that target impact analyses of urban expansion on the natural environment (Zhang et al., 2011; Haas and Ban, 2014). More recently, the idea of remotely sensing ecosystem services (ES) or supporting information that helps in determining ecosystem functions has enjoyed increasing popularity (Lakes and Kim, 2012) although it must be said that the formation of well-established links between ES and remote sensing (Feng et al., 2010) and between ES and landscape metrics (LM) should be further explored (Syrbe and Walz, 2012).

LM derived from processed remote sensing data are well-established tools to measure land cover fragmentation which in turn may indicate environmental impacts on habitat and connectivity (Forman and Godron, 1986; Turner, 1990). LM have proved, in the field of landscape ecology, to be good predictors of an ecosystem's ability to support important ecosystem functions (Turner and Gardner, 1991). ES as indicators of functional ecosystems and ecological conditions have been used in practice since the beginning of the 1990s (De Groot, 1992; Costanza et al., 1997; Daily, 1997). Continuing research expanded the concept to urban areas (Bolund and Hunhammar, 1999), different valuation schemes (De Groot et al., 2002; Xie et al., 2008) and to remote sensing of ES (Feng et al.,

* Corresponding author. Tel.: +46 8 790 7345; fax: +46 8 790 8580.
E-mail address: jhaas@kth.se (J. Haas).

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2010). Efforts that integrate ES as possible indicators of environmental impacts resulting from urbanization are found in Li et al. (2010). To be able to compare the effects of urbanization on the environment at a common scale and to enable comparisons with other studies, the well-known valuation scheme of Costanza et al. (1997) is used. It should be however noted that ES values calculated here do not represent actual ES values for several reasons (qualitative differences between urban, rural and global importance of ecosystems functions and services; a lacking standardized urban valuation scheme; varying marketing and pricing principles and that they should rather be regarded relative to each other and to LULC changes).

For the planning goal of developing Stockholm into the most attractive metropolitan area in Europe (Office of Regional Planning, 2010), sustainable ecological development is crucial. Urbanization in the Stockholm region from 1986 to 2006 and the impact of urban growth on the environment by indicators derived from remotely sensed and environmental data has recently been investigated by Furberg and Ban (2013). In one of the first studies to highlight ES in an urban context, Bolund and Hunhammar (1999) identified the six ES that are regarded as most important for Stockholm as air filtering (gas regulation), micro-climate regulation, noise reduction (disturbance regulation), rainwater drainage (water regulation), sewage treatment (waste treatment), and recreational/cultural values. Some studies have focused on evaluating environmental impacts of urban growth in Stockholm city on the municipal level (Mörtberg et al., 2007; Andersson et al., 2009), but very little research is found at the county level. One such study was recently performed by Mörtberg et al. (2012) who model two scenarios of future development of Stockholm's metropolitan area and evaluate LULC changes and urban sprawl in terms of their impact on a prioritised ecological profile.

Numerous studies exist that investigate the effect of urbanization on the environment in Shanghai, e.g. in terms of changes in erosion and sedimentation and heavy metal concentrations in soils, ecological footprint analyses, effects on the eco-environment in terms of water resources, water quality (Ren et al., 2003), air pollution and increased urban heat island effects (Li et al., 2012), changes in plant diversities, changes in extent and pattern of urban areas (Zhang and Ban, 2008; Hu et al., 2009; Zhang et al., 2009; Li et al., 2010; Zhang and Ban, 2010; Ban and Yousif, 2012) or urban growth simulations (Zhang et al., 2011). Most of these studies only shed light on one particular aspect of urbanization or its effects. An exception is the study of Haas and Ban (2014) that use a similar approach as proposed here with the exception that regional instead of intra-urban development trends are observed.

As there is to date no comprehensive valuation scheme for ecologically important areas within urban areas, the value definition for urban green spaces (UGS) in addition to the scheme from Costanza et al. (1997) is a novel feature that in combination with the newly devised urban green index (UGI) might be an asset in further urbanization studies in respect to sustainability and ecological urban development. The combined approach of using LM and ES as tools for evaluating the effects of urbanization captures not only the spatial component of urban development in terms of landscape composition/configuration and possible impacts on the natural and rural environment, but also integrates an economic factor that extends the implications of LULC changes to a societal dimension. Ideally, the results from this study can provide insight into ways of how the two different regions are urbanizing and indicate which areas need management attention in order to promote more sustainable and environmentally friendly growth.

The study aims to assist in finding a standardized environmental impact evaluation and assessment approach that works in diverse environments and ideally could be applied to urban areas around the world. Well-established and reliable remote sensing techniques and environmental indicators are combined and their application tested to quantify and compare urban development and to draw preliminary conclusions about resulting environmental impacts through the use of LM and ES valuation in the two diversely growing metropolitan regions of Stockholm, Sweden and Shanghai, China between 1989 and 2010. The geographic setting, population, environmental conditions and rates of population growth and urban expansion differ sharply between the two locations and present a good case study setting for testing the methodology's applicability in different regions.

Study area and data

Study area

The study areas for the comparison are diverse, both in location, climate, population and development over the past decades. Stockholm is the largest city in Scandinavia and the cultural, economic and political centre of Sweden. In 2010, the population of Stockholm's metropolitan area reached 2.05 million inhabitants with the municipality being the largest contributor with around 850,000 people living centrally. A constant increase in population is expected and by 2030 it is estimated that 2.5 million people will reside in Stockholm's metropolitan area (Office of Regional Planning, 2010). The Stockholm County boundary limits the study area, covering approximately 7150 km^2. Major LULC classes in the area are low-density residential areas (LDB), high density built-up areas (HDB) including industrial/commercial areas, forest, agricultural/open land, parks/urban green areas and water. The region's characteristic "green wedges" or large forested areas are located relatively close to the city centre but extend further beyond, providing several of the region's essential ES.

Shanghai, located at the Chinese east coast, is currently the largest Chinese city with a total population of 23.03 million in 2010 and is both a major Chinese financial and economic centre. An increase in population up to 28.4 million is expected by 2025 (United Nations, 2012). The total area of Shanghai covers about 6340 km^2. The landscape is composed of high density built-up areas, high-rise, commercial and industrial areas, UGS, airports, ports and residential areas. Urban areas are surrounded by agriculture with villages and strips of rural residential areas and farms. Water bodies occur in the form lakes and rivers, aquaculture and wetlands (inland and coastal). Naturally grown forests are scarce and connected tree stands can mostly be found in the city centre in form of managed UGS. The LULC classes in the study are defined as HDB, LDB, UGS, agriculture, forest, water, wetlands and aquaculture.

Data

A set of Landsat TM images was chosen as data source for the study as Landsat provides global reliable coverage, enabling repeatable analyses and comparative studies. The dataset consists of twelve Landsat TM images from around 1989, 2000 and 2010. All images are part of the global land survey (GLS) series and were acquired through the USGS Earth Explorer. In some cases, the difference in image dates is not exactly 10 years but can deviate up to a year due to the fact that there simply are no images available at the same anniversary or that images that lie closer to the decennial anniversary suffer from high cloud cover or haze in the case of Shanghai. The images were however taken during the peak vegetation season (from May to September) and are considered the most suitable Landsat images for the purpose of the study. The six false colour composites (FCC) in Fig. 1 depict excerpts from the original Landsat mosaics and cover the central parts of the study areas prior to classification.