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Earth Observation for Sustainable Urban Planning in Developing Countries: Needs, Trends, and Future Directions

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Abstract

Cities are constantly changing and authorities face immense challenges in obtaining accurate and timely data to effectively manage urban areas. This is particularly problematic in the developing world where municipal records are often unavailable or not updated. Spaceborne earth observation (EO) has great potential for providing up-to-date spatial information about urban areas. This article reviews the application of EO for supporting urban planning. In particular, the article overviews case studies where EO was used to derive products and indicators required by urban planners. The review concludes that EO has sufficiently matured in recent years but that a shift from the current focus on purely science-driven EO applications to the provision of useful information for day-to-day decision-making and urban sustainability monitoring is clearly needed.

Keywords

earth observation (EO), urban planning, sustainable urban development, rapid urbanization

Introduction

Cities are places of economic growth and wealth creation, yet poverty, inequality, and environmental degradation are still pervasive challenges, particularly in developing countries (UN-HABITAT 2009; United Nations Environmental Programme [UNEP] 2011). These challenges hinder the achievement of sustainable development and the mitigation of climate change (Heldens, Esch, and Taubenböck 2012). By 2030, countries in the southern hemisphere are expected to have more people living in their urban areas than in rural areas, which will put enormous pressure on the carrying capacity of existing cities (UN-HABITAT 2010; Taubenböck and Esch 2011). In many developing nations, urbanization is largely a result of rural–urban migration (World Commission on Environment, and Development [WCED] 1987) often leading to poor urban planning characterized by poor governance (Klosterman 1995, 2001) and poor access to essential services (UN-HABITAT 2009). Cities are constantly changing, thereby exerting immense pressure on city managers to make urban areas more liveable. Local authorities have a responsibility to provide accurate and timely spatial information for the monitoring and management of urban areas (Nichol et al. 2007). The synoptic and repetitive view that earth observation (EO) provides has been advocated as a solution for providing timely and accurate spatial data for monitoring cities (Hall 2010; Santos et al. 2011).

Patino and Duque (2012) reviewed the application of satellite remote sensing in urban and regional science. They focused on social problems with a spatial dimension, whereas Cowen and Jensen (1998) concentrated on the technical requirements of EO sensors for urban environments. Miller and Small (2003) highlighted the potential of EO in environmental research and policy. These studies demonstrate the vast potential of EO in supporting urban research and policy development. In this article, we overview EO applications in urban planning with an emphasis on urban sustainability and demonstrate how EO can support decisions relating to sustainable urban planning in cities of the developing world. The article starts off with a brief history of EO followed by a discussion of its suitability for supporting urban planning. A review of various applications of EO in urban environments is provided next. The article concludes with a discussion on recent EO developments and expected future trends and the likely impact that this will have for monitoring urban sustainability.

History of EO

EO refers to the collection, processing, modeling, and dissemination of data about the status as well as changes in the

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earth's natural and built environments (Kooistra 2012). EO gained importance due to the dramatic impact that modern human civilization is having on the earth, the need to minimize the negative impacts of development, and the opportunities EO provides to improve human well-being (Taubenböck and Esch 2011). Common EO instruments include remote sensing satellites, global positioning system (GPS) stations, cameras mounted on aeroplanes (Campbell 2011), and other in situ measurements and instruments such as weather stations (Kooistra 2012). EO has its modern beginnings with the discovery of infrared light and photography in the early eighteenth century (Bayhan 2011). In the early 1900s, the first aerial photographs were taken from aeroplanes, and this practice was refined in World War I for military reconnaissance (Campbell 2011). In the 1960s and 1970s, there was a shift from aerial photography to earth-orbiting satellites culminating in the launch of Landsat 1, the first earth-orbiting satellite specifically designed for the observation of the earth's surface land areas (Hall 2010). Subsequent EO satellites include Satellite Pour l'Observation de la Terre (SPOT) 1 (1986), IKONOS (1999), Quickbird (2001), SPOT 5 (2008), RapidEye (2008), GeoEye (2008), and more recently, Landsat 8 (2013) and SPOT 6 (2013). Google Inc's launch of Keyhole for Google Earth in 2005 sparked a geospatial revolution, significantly increasing the public's awareness of satellite imagery (Satellite Imaging Cooperation 2013).

The proliferation of EO data has also been aided by improvements in image-processing techniques to extract useful information (Schaepman 2007; Whiteside, Boggs, and Maier 2011). There are many methodologies for extracting information from images, including statistical, neural, and fuzzy classifiers (Weng 2012). Processing techniques have also shifted from pixel-based approaches to geographic object–based image analysis (GEOBIA; Hay and Castilla 2008; Addink, Van Coillie, and De Jong 2012), especially for very-high-resolution (VHR) imagery. Storage of EO data has changed from analogue to digital, culminating in the development of data warehouses that have increased public access to such data (Liu and Weng 2012). Nichol et al. (2007) point out that the practice of EO now has a multitude of superlatives (multispectral, hyperspectral, and GEOBIA), showing that it is maturing and gaining importance and significance in decision making, particularly for planning in hyperchanging environments. According to Lein (2009), errors in the analysis and display of EO data have limited the application of the technology in day-to-day decision and policy making. However, recent improvements in EO data (in particular the proliferation of commercial satellites providing VHR imagery) and advances in remote sensing techniques (e.g., GEOBIA, classification trees, support vector machines, random forests, and feature recognition) have enabled researchers to reduce errors in EO data and produce higher-quality maps with thematic accuracies exceeding 90 percent. As a result, the use of EO in professional planning is increasing (Addink, Van Coillie, and De Jong 2012; Erener 2012; Lein 2009; De Maeyer, Sotiaux, and Wolff 2010), and it is likely that this trend will continue as planners gain experience and confidence in the technology.

Why Apply EO?

EO data are increasingly being used in research owing to its advantages over in situ data collection methods such as field surveys (Barr and Ford 2010; Vintrou et al. 2012). EO provides a unique synoptic view from space or air, thereby enabling scientists and planners alike to customize the spatial boundaries of their studies (Miller and Small 2003; Hall 2010). The Center for International Earth Science Information Network (CIESIN 2010) maintains that EO uses a common algorithm, resulting in consistent and objective data. This enables intercountry comparisons that would be difficult, if not impossible, with national, regional, or local data sets (Skidmore et al. 1997). Hence, it is possible to draw conclusions by comparing the same phenomena in different countries, cities, regions, or even continents during the same period (Liu et al. 2012). Another feature of EO data is its capacity for routine, periodic, and unobtrusive updating (Esch et al. 2010). Moreover, EO has the capability to describe, classify, and measure critical physical properties that would be prohibitively expensive (Cowen and Jensen 1998), time-consuming (Sherbinin et al. 2002), or impossible to obtain in situ or from aggregating other sources (Barr and Ford 2010). EO consequently provides a quick way of developing spatial databases (Miller and Small 2003). These distinctive characteristics of EO have led to the establishment of international research institutes, such as CIESIN, the National Aeronautics and Space Administration (NASA), the German Aerospace Center, the Canada Center for Remote Sensing (CCRS), and the South African National Space Agency (SANSA) among others, to advance the use of EO by identifying new urban remote sensing applications for policy development and management (CIESIN 2010; Esch et al. 2010; Guindon and Zhang 2005; SANSA 2014).

Advanced cadastral and land ownership databases are often not available in cities of the developing world. By contrast, many cities in developed countries such as the United States have systems in place through which planners can easily access information such as property boundaries, ownership, tax, and type (land use) superimposed on orthophotos soil types, topography, and vegetation-related data (National Academy of Sciences 2003). In most developing countries, municipal records are often unable to keep pace with the high rate of urbanization and informal urban development (Repetti, Soutter, and Musy 2005). EO not only provides a quick synoptic view of urban areas but also allows planners to cross-check or complement other data sources such as censuses or field surveys, thereby improving the validity and reliability of research results (Baud et al. 2010). This has increased the use of EO and related geographic information systems (GIS), spatial decision support systems (SDSS), and planning support systems (PSS) for urban planning (Klosterman 2008). EO data also make these systems more effective through the provision of multitemporal data which enables manifold spatiotemporal analyses

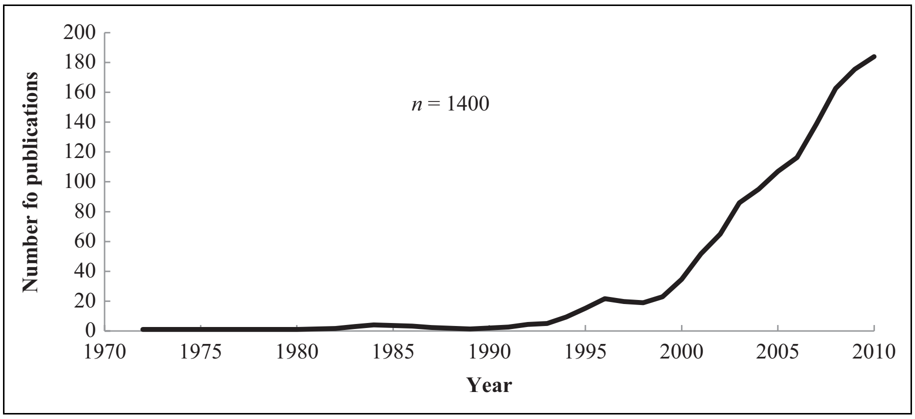

Figure 1. Annual publications on "earth observation" or "remote sensing" and "urban" indexed in Scopus from 1972 to 2010. Search conducted on May 5, 2013.

(Esch et al. 2010). Various independent layers of information can be derived from EO data, making it a one-stop source of data (Taubenböck and Esch 2011). The value of EO for rapid data collection may be of less value in developed countries where comprehensive GIS databases of urban areas exist (and are kept updated), but many developing countries do not have any GIS databases. Where they do exist, the rate of development is often too high for authorities to cost-effectively maintain databases using traditional methods (Musakwa and Van Niekerk 2013).

EO Applications in Urban Planning

A search on Scopus, the largest database of peer-reviewed journal articles (Weng 2012), revealed that the number of published items on EO and urban planning increased significantly over the past two decades. Figure 1 shows a 500 percent increase between 2000 and 2005. This is mainly attributable to recent technological advances that have made the high-resolution and VHR imagery needed for urban monitoring (Weng 2012) commercially viable (Liu et al. 2012). This surge in publications also coincided with rapid urbanization in developing countries (UN-HABITAT 2010) and the emergence of new methodologies and techniques (e.g., GEOBIA), which enable the extraction of better-quality data from VHR satellite imagery (Santos et al. 2011). It is clear that EO has emerged as a cost-effective way for supplying much-needed data for urban monitoring, climate change mitigation, and disaster management (Heldens, Esch, and Taubenböck 2012).

The Scopus search also revealed that the application of EO has been dominated by earth and planetary sciences (25 percent), engineering (22 percent), and computer sciences (22 percent), while limited publications were found within environmental (6 percent) and social (9 percent) sciences. Most urban planning applications were in the latter two domains. There is a well-documented gap between social science and EO application as a result of the imperfect coupling of EO and social data (Hall 2010). Esch et al. (2010) and Hall (2010) predict that, given the increased availability and quality of data, more use will be made of EO for urban planning in the future. Current applications of EO for urban planning are dominated by Asian (36 percent), North American (33 percent), and European (29 percent) counties with few applications in Africa (2 percent) where it is probably needed the most, given the rapid rates of urbanization (Figure 2).

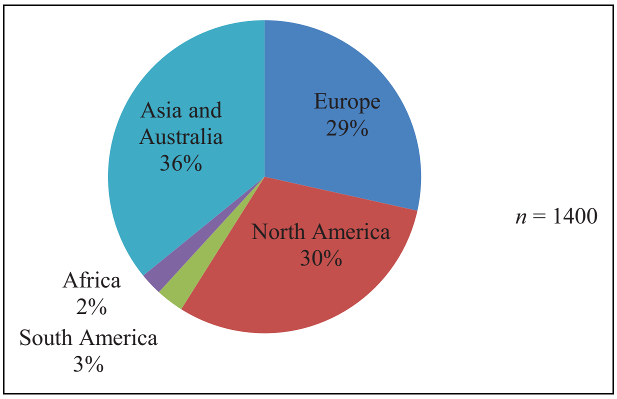

Figure 2. Percentage of publications related to earth observation indexed in Scopus from 1972 to 2010 by continent. Search conducted on May 5, 2013.

EO has been used in various aspects of urban monitoring. Examples include measuring physical properties, population, quality-of-life studies, analysis of land use cover change, building analysis, transportation studies and monitoring growth, and urban sprawl. These applications are discussed in more detail in the following sections.

Measurement of Physical Properties

EO has been applied in monitoring the urban environment by providing scientifically verifiable measurements of physical properties and their changes which are crucial to achieving sustainable urban development (CIESIN 2010). These include air quality (Zhang et al. 2008), vegetation cover studies (Mathieu, Freeman, and Aryal 2007), and the impacts of urban structure on microclimate (Christensen 2010). Schwarz (2010) and Keramitsoglou et al. (2011) employed moderate resolution imaging spectroradiometer (MODIS) data to demonstrate the urban heat island effect, whereas Santana (2007) derived leaf water content (LWC) and surface temperature from Landsat data to aid sustainable landscape design. A Landsat-derived normalized difference vegetation index (NDVI) was used by Weng, Lu, and Schubring (2004) to measure vegetation abundance in urban areas.

Environmental issues have become an increasingly important component in urban planning (Pickett et al. 2013). The GIS data that are traditionally used in urban planning are often not adequate for environmental monitoring as they tend to focus on the built environment and often exclude biophysical variables (e.g., changes in vegetation cover/density, impervious surfaces, and water quality). EO is an ideal tool for supplementing GIS databases with such environmental data and has a critical role to play in monitoring ecological services. Examples where EO has been employed for environmental monitoring in urban areas include Lakes and Kim (2012) who applied hyperspectral imagery to develop urban ecosystem services indicators, while Lein (2009) demonstrated how VHR satellite imagery can facilitate environmental monitoring in cities. The potential of EO in providing insights into how urban development is impacting climate change is also widely acknowledged (Miller and Small 2003).

Population and Quality-of-life Studies

EO has been shown to be useful in population studies and for estimating population size between censuses (Almedia et al. 2011; Levin and Duke 2012). The latter is particularly helpful in countries with high rates of population growth and urbanization or where censuses are infrequent (Baud et al. 2010). Such estimates are dependent on conditions such as knowledge of average household size and the availability of high-resolution spatial and multispectral imagery to differentiate informal building structures (Ural, Hussain, and Shan 2011). EO is also applicable in quality-of-life studies (Toure et al. 2012). In Athens-Clarke County in Georgia, for example, a high NDVI obtained from Landsat data correlated positively with high income, whereas in Detroit a high NDVI strongly correlated with severe social decay (Lo and Faber 1997). When Toure et al. (2012) compared Kompsat imagery with income data, they found that access to water supply is closely related to income. Satellite imagery has also been used in South Africa to support various socioeconomic studies including supporting informal settlement upgrading and settlement enumeration (SANSA 2014). Remote sensing can thus be used to identify and infer causal relationships which, in turn, aid decisions pertaining to sustainable urban development.

Land Use and Land Cover Classification

EO data have been extensively used for land use and land cover mapping in urban areas (Wang, Cheng, and Chen 2011). Land cover refers to the physical surface of the earth, for example, vegetation, soils, and anthropogenic features such as buildings (Council for Scientific and Industrial Research [CSIR] 2010; Heldens, Esch, and Taubenböck 2012). Conversely, land use is the human activity associated with land cover, such as residential or commercial use. Mapping of urban land use often requires VHR imagery (Department of Rural Development and Land Reform 2009; Weng 2012). Land uses such as recreation, mixed uses, office space, and community facilities are difficult to infer from land cover data, and they require image interpretation and field visits to confirm classification efforts (Department of Rural Development and Land Reform 2009; CSIR 2010; Zhang, Zhang, and Lin 2012).

Information on land use and land cover is required by planners for site selection, zoning regulation, resource allocation, monitoring the state of the environment, and urban growth management (Cowen and Jensen 1998). Land use and land cover maps are important for monitoring sustainability trajectories as land use change and cover transition can be employed as sustainability indicators (Musakwa and Van Niekerk 2013). For example, satellite images have been used to determine the rate of agricultural conversion in rural areas (Schneider, Friedl, and Potere 2010) as well as the transformation of natural environments to urban uses (Yang et al. 2009). In the United States, the National Resources Inventory (NRI) applies EO techniques to develop a national catalogue of land cover changes every five years. This catalogue is useful for assisting environmental conservation and sustainable urban planning (US Department of Agriculture 2013).

It has been demonstrated that high rates of land use and land cover change as a result of urban growth lead to increased motorized transport (Victoria Transport Policy Institute 2010), higher energy consumption (Urban Land Institute 2010), loss of agricultural land (Comber, Brunsdon, and Green 2006), loss of biodiversity (Stuckenberg, Munch, and Van Niekerk 2013; Yang et al. 2009), and an increase in water pollution (Zhang, Wu, and Shen 2011). These changes pose severe threats to the realization of urban sustainability and can ultimately contribute to climate change (Renetzeder et al. 2010; Heldens, Esch, and Taubenböck 2012). Although EO is often used for urban land use change analyses, more research is needed in using EO data for developing meaningful information such as mixed use, community, and government uses (Musakwa and Van Niekerk 2013). As a result, researchers and planners often have to interpret raw (unprocessed) imagery such as those provided by Google Maps and Google Earth Street View to extract the information necessary for urban planning.

EO of impervious surfaces, defined as anthropogenic features that water cannot infiltrate (e.g., rooftops and parking lots), have attracted increasing attention in recent planning literature (Weng 2012; Zhang, Zhang, and Lin 2012). Impervious surfaces are increasingly being recognized as key indicators of land use sustainability (Santos et al. 2011), global environmental change, and human–environment interaction (Schneider, Friedl, and Potere 2010). Municipal authorities, researchers, and nongovernmental authorities often map impervious surfaces as a measure of urban sustainability and for assessing flood-risk vulnerability (Nichol et al. 2007; Schwarz, Lautenbach, and Seppelt 2011). Various EO methods, including pixel-based (Whiteside, Boggs, and Maier 2011), artificial neural networks (Taubenböck and Esch 2011), image fusion (Beger et al. 2011), expert systems (Weng 2012), and object-based classification methods (Doxani, Karantzalos, and Strati 2012; Myburgh and Van Niekerk 2013) have been used to map impervious surfaces from satellite imagery (Heldens, Esch, and Taubenböck 2012). Qi et al. (2012) employed RADARSAT-2 polarimetric Synthetic Aperture Radar (SAR) data and observed that these data improved the accuracy of land cover and land use classification in urban areas. These types of data and extraction techniques have opened new possibilities for the use of EO in urban planning.

Although land use and land cover classification have been extensively researched, relatively little has been done on deriving measures of land use mix (Song and Knaap 2004; Song and Rodriguez 2005; NEAT GIS Protocols 2010) from land use data. Guindon and Zhang (2005), Zhang, Guindon, and Sun (2010), and Musakwa and Van Niekerk (2013) identified EO's key role in urban sustainability studies, particularly as a source of land use mix data (L. D. Frank, Anderson, and Schmid 2004; L. D. Frank et al. 2006) which is integral to the monitoring of urban sustainability (Song and Rodriguez 2005; L. Frank et al. 2010; L. D. Frank et al. 2010; Urban Land Institute 2010; Victoria Transport Policy Institute 2010).

Analysis of Urban Built-up Areas

Because buildings are an integral feature of urban areas, local authorities require area-wide and up-to-date inventories of buildings to monitor urbanization (Wei, Zhao, and Song 2004). EO data are a cost- and time-effective alternative to conventional methods for obtaining buildings data (Taubenböck et al. 2010), and it allows planners to monitor changes in the number (Mudau 2010), size and area (footprint; Erener 2012), density, layout (Geiss et al. 2011), height (Wurm, Taubenböck, and Roth 2009), and volume (Taubenböck and Esch 2011) of buildings. Despite satellite imagery being valuable in developing a buildings and structures database, there is not uniform approach to extracting building information from such imagery and none of the existing extraction methods have been effective in all scenarios (Santos et al. 2011). Extraction of buildings is a challenging task, even from VHR satellite imagery. This is mainly due to building obstructions and the heterogeneity of target features (Nichol et al. 2007). However, with the availability of light detection and ranging (LiDAR) data (Weng 2012), building information can be extracted with higher accuracy (Taubenböck and Esch 2011). Data fusion of LiDAR data and VHR satellite imagery has yielded better-quality information compared to using a single data source. Beger et al. (2011) used LiDAR and orthorectified aerial photographs to automate railroad extraction, while Wang, Zen, and Lerhbass (2012) employed LiDAR data and aerial images to detect building footprints. Data fusion is indispensable because it is highly unlikely that one EO sensor can provide all the necessary information for urban monitoring. Many metropolitan municipalities are consequently collecting LiDAR data for supporting various decisions including those related to zoning applications and for automatically collecting information on building shapes, volume, and density (City of Johannesburg 2014).

Transportation Studies

Motor vehicles are at the center of the sustainability debate as they are major contributors to greenhouse gas (GHG) emissions (Urban Land Institute 2010). Studies on vehicle movement include traffic counts, parking availability, road conditions, congestion, and road networks which are crucial to providing meaningful information (Cowen and Jensen 1998). EO can provide only limited information since most data on transportation, such as traffic counts, requires a very high temporal resolution (National Academy of Sciences [NAS] 2003). LiDAR data are a possible solution as it can provide information on traffic volumes, motor vehicle classifications, and queue sizes (Schwach, Morris, and Michalopoulos 2009), although such data are often only available for some cities and are usually not captured at high frequencies. More accessible data, such as Landsat imagery, have been used to derive sustainable transportation indicators such as road network connectivity, transportation sustainability assessments (Guindon and Zhang 2007), and for determining the impacts of land use patterns on sustainable transportation (Urban Land Institute 2010; Victoria Transport Policy Institute 2010; Litman 2010).

A number of studies have concentrated on the development of semiautomated and automated techniques for extracting roads from satellite imagery. For example, Nobrega, O'Hara, and Quintanilha (2008) devised a semiautomated GEOBIA technique to satisfactorily extract road features in informal settlements in Sao Paulo, Brazil, while Yuan et al. (2009) used a local excitatory global inhibitory oscillator network (LEGION) to automatically extract road networks from satellite imagery. Although various methods exist for extracting road networks, none are successful in a variety of contexts (Sobrino et al. 2012). Multisource data fusion ably improves the classification of roads from satellite imagery (Jin and Davis 2005). More research on automated road extraction is urgently needed as much resources are spent on capturing road data employing in situ methods or by using visual image interpretation (Nobrega, O'Hara, and Quintanilha 2008; Yuan et al. 2009).

Monitoring Urban Growth and Sprawl

Urban sprawl often has adverse environmental and socioeconomic effects like consumption of natural ecosystems by urban uses, increases in transport costs as well as infrastructure costs (Le Néchet 2012), and local authorities find it difficult to monitor rapid changes. EO has become a vital source of data on urban growth because of its high temporal resolution. For example, Landsat images were applied in demarcating the urban boundaries of Orlando, Florida (Sims and Mesev 2011), while on a broader scale Schneider, Friedl, and Potere (2010) used MODIS data to map the urban extents for 140 cities. Other studies applied high-resolution nighttime light satellite imagery (Townsend and Bruce 2010) and the US Defense Meteorological Satellite Program's operational line scan system (Sutton and Costanza 2002) to delineate urban extents. However, the use of nighttime lights was found to overestimate urban areas due to overglow while underestimating such areas when there are power outages, a common occurrence in sub-Saharan Africa (Sutton and Costanza 2002).

Several other indicators addressing various aspects of urban morphology have been derived using EO. These include Shannon's entropy (Jat, Garg, and Khare 2008), a shape and path index (Esch et al. 2010) and the degree of goodness of fit (Bhatta, Saraswati, and Bandyopadhyay 2010) which was used to determine the direction, extent, pattern, rate, and concentration of urban sprawl. It is clear from the literature (Anselin et al. 2000; Tsai 2005; Gerundo and Grimaldi 2011; Le Néchet 2012; Anselin 2012) that more spatial metrics and statistics (such as Moran statistics) that capture various aspects and relationships of urban growth are needed for urban planning.

Integrating EO into Monitoring Urban Sustainability

EO can supply much-needed data for urban planning, particularly in hyperchanging environments. To advance EO application in urban planning, there is a need to move from purely science-driven approaches of extracting data to the provision of practical information for precisely defined urban sustainability applications that entail coordinated user needs for day-to-day decision making (Taubenböck and Esch 2011). Hoalst-Pullen and Patterson (2011) emphasize that there is a disconnection between academic research on EO applications in urban planning and the actual adoption and use of remote sensing technologies as well as data by professional urban planners. Consequently, cities must become laboratories where EO is applied in decision making and where information is shared, published, and transferred to expand and improve the body of knowledge and ultimately to promote sound decision making.

Concerning the specific literature on "EO and urban sustainability," a Scopus search returned only five items while a combined search on Scopus and Science Direct revealed only five key authors on this subject. Most notable are Guindon and Zhang (2005, 2007) who applied satellite remote sensing to survey transport-related sustainability indicators. They concluded that EO significantly improves sustainability assessments done on census data, mainly by providing spatial data on land use and land use mix, urban form as well as a historical perspective on spatial growth. Other key researchers include Esch et al. (2010) who demonstrated how the increasing availability of EO data can add value for a wide variety of applications in urban sustainability studies.

Limitations and Outlook for EO in Urban Planning

The past decade has witnessed significant progress in the application of EO in urban environments (Nichol et al. 2007; Weng 2012). Still, urban remote sensing is riddled with technical and nontechnical challenges (Table 1). The nontechnical limitations include financial constraints (Hoalst-Pullen and Patterson 2011), many inhibiting institutional, political, organizational and human factors, along with license management issues (NAS 2003). Technical limitations include the spectral (Heiden et al. 2012), geometric (NAS 2003), textural (Klemas 2012), and contextual complexities (Miller and Small 2003) of urban areas, which make it difficult to extract target features. Weng (2012) points out a need to improve the temporal resolution required for urban mapping. Similarly, EO data for air pollution studies are still very coarse (low resolution) and in many cases it is unsuitable for detailed urban analyses (Nichol et al. 2007). Hopefully, new initiatives such as the scheduled launch of a dedicated spaceborne sensor for monitoring air pollution in 2017 (Chance et al. 2013) will address the lack of such data.

Many local governments have cited financial constraints as a hindrance to the adoption of remote sensing technology (Klosterman 2001). This is compounded by institutional, political, and organizational factors (Göçmen and Ventura 2010). It has been noted that it often takes time to convince political structures, particularly in local government, to support the use of EO. However, it is hoped that the demonstrated capabilities of EO will reduce political and institutional intransigence. Licensing also complicates the use of satellite imagery (NAS 2003). When government agencies or practitioners purchase satellite imagery it often comes with various licensing restrictions which is counterproductive and may create confusion. This acts as a deterrent to use the data. The lack of trained personnel has also been cited as a key reason why EO is not used by urban planners (Aneja et al. 2011). Lein (2009) proposes the use of "machine intelligence" to bridge the gap between advances in EO research and application in local governments. Machine intelligence would serve as a means to supply "expertise" in an automated form to assist an organization's need to address a problem where "in-house" expertise in unavailable. Similarly, the NAS (2003) acknowledges that the successful adoption of remote sensing technologies in urban planning depends on having a strong champion to convince policy and decision makers of the utility of remote sensing.

Despite these limitations, the future of urban remote sensing looks promising for a variety of reasons. The advent of LiDAR data, very high spatial resolution sensors (Ni 2012), EO data warehouses (Liu et al. 2012), and spaceborne hyperspectral images (Weng 2012) have extended the frontiers of urban remote sensing. This coincides with the emergence of advanced algorithms such as image fusion (Wang, Zen, and

Table 1. Strengths and Weaknesses of Earth Observation in Urban Planning.

Strengths	Weaknesses
Launch of more sensors resulting in increased data availability, a constant stream of data and reduction of costs. Moreover, increased public awareness of remotely sensed data from platforms such as Google Earth and Bing Maps has increased the use of remotely sensed data in decision making	Limited technological base as well as lack of trained personnel
Processing techniques of remotely sensed data and technological advances have vastly improved the geometric and thematic classification of urban areas. This has opened up new possibilities in urban planning applications	High costs of data especially VHR images
Synoptic view and nonobtrusive nature of EO data would be difficult and cumbersome to obtain from other research methods	A single satellite image or remotely sensed data source does not provide all the information
EO techniques allow for normalization and standardization of data, which enable comparisons, consistency, and reliability of results	Licensing issues
Normalized and standardized EO indicators also enable transferability of the methodology and development of place-independent (universal) planning support systems or models	Political, organizational, and institutional constraints
Simple integration of EO data with a GIS enables interoperability. Moreover, multiple remotely sensed data sources can be fused which produces data rich in quality and information.	Spectral, geometric, textural and contextual complexities make it difficult to extract urban features.
EO data and GIS analysis enables spatial, visual, quantitative, and temporal analysis. This enables identification of "hot spots" and "cold spots" of critical importance to decision making	EO data often require some ground truthing
EO-derived urban planning data can be used for other urban applications such as disaster management and population estimates for informal settlements	

Source: Klosterman (2001); Göçmen and Ventura (2010); Heiden et al. (2012).
Note: VHR = very high resolution; EO = earth observation; GIS = geographic information systems.

Lerhbass 2012) to extract data from satellite imagery, thus opening new possibilities for urban remote sensing applications (Kumar and Misra 2007; Almedia et al. 2011). Moreover, with the advent of publicly accessible EO data from Google Earth, Microsoft's Virtual Earth, and Streetmaps, it has become common and socialized, thus reducing nontechnical barriers to it. New tools are also being developed specifically for planning-related applications. A prime example is the Google Earth–based three-dimensional (3D) modeling tool that Isikdag and Zlatanova (2010) developed for supporting urban renewal projects.

Furthermore, advances in technology, greater computational power, and the integration of EO with GIS all bode well for expanded application of EO in urban planning (Drummond and French 2008). The launch of more sensors means the relative price of remote sensing data will continue to decline (Liu et al. 2012; Patino and Duque 2012). EO also allows for consistent unobtrusive updating of information (CIESIN 2010) which can be used for a wide variety of applications. Consequently, EO now provides unparalleled continuous, up-to-date, low-cost data collection for large areas of the globe. EO can also benefit from use of other in situ EOs and other forms of remote sensing.

Several urban sustainability studies have demonstrated that in situ observations using cell phone signals, street maps, crowdsourcing, and social media as well as remote sensing using unmanned aerial vehicles (UAVs) or drones provide useful information to augment satellite imagery (Calabrese et al. 2011). Calabrese et al. (2011) have, for example, developed a system for real-time monitoring of urban vehicular traffic and pedestrians using cell phone signals. Similarly, Bulatov et al. (2011) used UAVs for developing georeferenced 3D urban terrain models. Data from UAVs and cell phone signals can enhance urban planners' knowledge on urban sustainability when used in conjunction with the EO data. The coupling of EO data with other in situ observations plays an important role in the promotion of smart cities, since it supplies much need information on the dynamic changes in the city landscape. A smart city is characterized by information and communication technology (ICT) infrastructures, facilitating an urban system, which is increasingly smart, interconnected, and sustainable (Giffinger, Haindlmaier, and Kramar 2010). Detailed and up-to-date EO data enables urban mangers to make better decisions, predict future problems, and put preventative measures in place (Debnath et al. 2014).

Crowdsourcing, a mechanism for leveraging the collective intelligence of online users toward productive intelligence, has also been applied in urban planning (Brabham 2009). For example, Studiolab (2012) developed Mobile-cityscapes, a crowdsourcing mobile platform for knowledge on urban sustainability. Mobile-cityscapes merges features from process-based urban design, locative media art, and spatial practice theory. It uses GPS technology as a collaborative, participatory, and creative medium. Similarly, the use of cell phone applications (apps) technology has increasingly influenced urban planning decisions particularly those relating to urban traffic. The use of cell phone apps facilitates provision of real-time traffic information such as accident incidents, vehicle navigation, and traffic flow. Google, Samsung, Ericsson, and Apple have designed GPS-enabled mobile apps to capture traffic data, which has huge potential for use by planners (Tao et al. 2012). Similarly, the emergence of social media which encompass statistical and deliberative technologies such as blogs, forums, wikis, open-source software, social networking sites, media sharing sites, creative commons licensing, online polls, user-populated maps, and prediction markets (Planning Pool 2012) have an important role in the planning process. Social media (e.g., Facebook and Twitter) enable public sharing and participation which can lead to new ideas on urban sustainability. Urban planners have to embrace these new technologies as they have huge potential in facilitating the comprehension of urban changes and complexities.

Conclusion and the Way Forward

The application of EO for addressing urban sustainability issues has gained significant momentum during the last decade. This trend is likely to continue, given the availability of novel techniques such as GEOBIA, data fusion, and artificial neural networks and new technologies such as mobile apps, crowdsourcing, social media, and use of UAVs. However, there remains a disconnect between academic research on EO applications in urban planning and the actual adoption and use of remotely sensed technologies as well as data by professional urban planners. A shift from science-driven approaches to precisely defined user-orientated applications of EO for monitoring urban sustainability is urgently needed. Evidently, there is need for more research on obtaining urban sustainability indicators from EO and its application in urban planning. This is particularly important in the developing world, where high population growth and urbanization rates will increasingly put pressure on urban and regional planners and local authorities to provide essential services while ensuring environmental sustainability.

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References

Addink, E. A., F. M. B. Van Coillie, and S. M. De Jong. 2012. "Introduction to the GEOBIA 2010 Special Issue: From Pixels to Geographic Objects in Remote Sensing Image Analysis." *Special Issue on Geographic Object-based Image Analysis: GEOBIA* 15:1–6.

Almedia, C. M., C. G. Oliveira, C. D. Rennó, and Q. Feitosa. 2011. *Population Estimates in Informal Settlements Using Object-based Image Analysis and 3D Modelling*. Accessed May 5, 2013. http://www.earthzine.org/themes-page/urban-monitoring/.

Aneja, S., C. P. Gross, P. R. Soulos, and J. B. Yu. 2011. "Geographical Information Systems: Applications and Limitations in Oncology Research." *Oncology* 25:1221–25.

Anselin, L. 2012. "From SpaceStat to CyberGIS: Twenty Years of Spatial Data Analysis Software." *International Regional Science Review* 35:131–57.

Anselin, L., J. Cohen, D. Cook, W. Gorr, and G. Tita. 2000. "Spatial Analysis of Crime." Accessed December 7, 2011. https://www.ncjrs.gov/criminal_justice2000/vol_4/04e.pdf.

Barr, S., and A. Ford. 2010. *Integrating Urban Remote Sensing with GIS*. Berkeley: University of California.

Baud, I., M. Kuffer, K. Pfeffer, R. Sliuzas, and S. Karuppannan. 2010. "Understanding Heterogeneity in Metropolitan India: The Added Value of Remote Sensing Data for Analysing Sub-standard Residential Areas." *International Journal of Applied Earth Observation and Geoinformation* 12:359–74.

Bayhan, D. 2011. "History of Remote Sensing." Accessed January 26, 2012. web.itu.edu.tr/ . . . /remote_sensing/History_DUYGU_-BAYHAN.ppt.

Beger, R., C. Gedrange, R. Hecht, and M. Neubert. 2011. "Data Fusion of Extremely High Resolution Aerial Imagery and LiDAR Data for Automated Railroad Centre Line Reconstruction." *Advances in LiDAR Data Processing and Applications* 66:S40–51.

Bhatta, B., S. Saraswati, and D. Bandyopadhyay. 2010. "Quantifying the Degree of Freedom, Degree of Sprawl, and Degree-of-goodness of Urban Growth from Remote Sensing Data." *Applied Geography* 30:96–111.

Brabham, B. C. 2009. "Crowdsourcing the Public Participation Process for Planning Projects." *Planning Theory* 80:248–62.

Bulatov, D., P. Solbrig, H. Gross, P. Wernerus, E. Repasi, and C. Heipke. 2011. "Context-based Urban Terrain Reconstruction from UAV-videos for Geoinformation Applications." *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Proc. Conf. Unmanned Aerial Vehicle in Geomatics* 38:16–22.

Calabrese, F., M. Colonna, P. Lovisolo, D. Parata, and C. Ratti. 2011. "Real-time Urban Monitoring Using Cell Phones: A Case Study in Rome." *IEEE Transactions on Intelligent Transportation Systems* 12:141–51.

Campbell, J. B. 2011. *Introduction to Remote Sensing*. New York: Guilford Press.

Chance, K., Liu X., Suleiman R. M., Flittner D. E., Al-Saadi J., and Janz, S. J. 2013. Tropospheric Emissions: Monitoring of Pollution (TEMPO). In *SPIE Optical Engineering + Applications*, 88660D. Bellingham, WA: International Society for Optics and Photonics.

Christensen, P.2010. "New Opportunities for Urban Remote Sensing." Accessed January 5, 2011. http://cssa.asu.edu/sites/default/files/Phil%20Christensen%20Remote%20Sensing.pdf.

CIESIN (Center for International Earth Science Information Network). 2010. "Remote Sensing and the Social Sciences." Accessed January 5, 2011. http://sedac.ciesin.columbia.edu/tg/guide_glue.jsp?rd=rs&ds=5.

City of Johannesburg. 2014. "Online Maps." Accessed June 12, 2014. http://eservices.joburg.org.za/joburg/eservices/!ut/p/kcxml/04_Sj9SPykssy0xPLMnMz0vM0Y_QjzKLt4y39AXJgFmu-pHIIgbxxqb-oIo5wAV-P_NxU_SB9b_0A_YLc0NCIckdFAA_UfZY!/delta/base64xml/L3dJdyEvd0ZNQUFzQUMvNElVRS82XzlfOUs!#clkCntrl.

Comber, A., C. Brunsdon, and E. Green. 2008. "Using a GIS-based Network Analysis to Determine Urban Green Space Accessibility for Different Ethnic and Religious Groups.'' *Landscape and Urban Planning* 86:103–14.

Cowen, D. J., and J. R. Jensen. 1998. ''Extraction and Modelling of Urban Attributes Using Remote Sensing Technology.'' In *People and Pixels: Linking Remote Sensing and Social Science*, edited by D. Liverman, E. F. Moran, R. R. Rindfuss, and P. C. Stern, 164–88. Washington, DC: National Academy of Science.

CSIR (Council for Scientific and Industrial Research). 2010. *Land Cover Field Guide*. Pretoria, South Africa: Council for Scientific and Industrial Research.

Debnath, A. K., H. C. Chin, M. M. Haque, and B. Yuen. 2014. ''A Methodological Framework for Benchmarking Smart Transport Cities.'' *Cities* 37:47–56.

De Maeyer, M., A. Sotiaux, and E. Wolff. 2010. ''Comparison of Standardized Methods (Object-oriented vs Per. Pixel) to Extract the Urban Built up Area: Example of Lubumbashi DRC.'' Accessed February 3, 2011. http://www.isprs.org/proceedings/xxxviii/4-c7/pdf/De_Maeyer_%20geo54.pdf.

Department of Rural Development and Land Reform. 2009. *Development of a Methodology for National Land Use Mapping for Chief Directorate: Geo Spatial Information*. Cape Town, South Africa: Department of Rural Development and Land Reform.

Doxani, G., K. Karantzalos, and M. T. Strati. 2012. ''Monitoring Urban Changes Based on Scale-space Filtering and Object-oriented Classification.'' *Special Issue on Geographic Object-based Image Analysis: GEOBIA* 15:38–48.

Drummond, W. J., and S. P. French. 2008. ''The Future of GIS in Planning: Converging Technologies and Diverging Interests.'' *Journal of the American Planning Association* 74:161–74.

Erener, A. 2012. ''Classification Method, Spectral Diversity, Band Combination and Accuracy Assessment Evaluation for Urban Feature Detection.'' *International Journal of Applied Earth Observation and Geoinformation* 21:397–408.

Esch, T., H. Taubenböck, W. Heldens, M. Thiel, M. Wurm, C. Geiss, and S. Dech. 2010. ''Urban Remote Sensing—How Can Earth Observation Support the Sustainable Development of Urban Environments?'' Paper presented at the Cities for everyone. Liveable, healthy, prosperous, edited by Manfred Schrenk, Vasily V. Popovich, Peter Zeile, and Pietro Elisei, Real CORP, Vienna, Austria, May 18–20, 2010, 837–47.

Frank, L., J. Kerr, D. Rosenberg, and A. King. 2010. ''Healthy Aging and Where You Live: Community Design Relationships with Physical Activity and Body Weight in Older Americans.'' *Journal of Physical Activity and Health* 7:S82–90.

Frank, L. D., M. A. Andresen, and T. L. Schmid. 2004. ''Obesity Relationships with Community Design, Physical Activity, and Time Spent in Cars.'' *American Journal of Preventive Medicine* 27:87–96.

Frank, L. D., M. J. Greenwald, S. Winkelman, J. Chapman, and S. Kavage. 2010. ''Carbonless Footprints: Promoting Health and Climate Stabilization through Active Transportation.'' *Preventive Medicine* 50:S99–105.

Frank, L. D., J. F. Sallis, T. L. Conway, J. E. Chapman, B. E. Saelens, and W. Bachman. 2006. ''Many Pathways from Land Use to Health: Associations between Neighbourhood Walkability and Active Transportation, Body Mass Index, and Air Quality.'' *Journal of the American Planning Association* 72:75–87.

Geiss, C., H. Taubenböck, M. Wurm, T. Esch, M. Nast, C. Schillings, and T. Blaschke. 2011. ''Remote Sensing-based Characterisation of Settlement Structures for Assessing Local Potential of District Heat.'' *Remote Sensing* 3:1447–71.

Gerundo, R., and M. Grimaldi. 2011. ''The Measure of Land Consumption Caused by Urban Planning.'' *2011 International Conference on Green Buildings and Sustainable Cities (GBSC 2011)* 21:1152–60.

Giffinger, R., G. Haindlmaier, and H. Kramar. 2010. ''The Role of Rankings in Growing City Competition.'' *Urban Research & Practice* 3:299–312.

Göçmen, Z. A., and S. J. Ventura. 2010. ''Barriers to GIS Use in Planning.'' *Journal of the American Planning Association* 76:172–83.

Guindon, B., and Y. Zhang. 2005. ''Using Satellite Remote Sensing to Survey Transport-related Urban Sustainability: Part 1: Methodologies for Indicator Quantification.'' *International Journal of Applied Earth Observation* 8:149–64.

Guindon, B., and Y. Zhang. 2007. ''Using Satellite Remote Sensing to Survey Transport-related Urban Sustainability: Part II. Results of a Canadian Urban Assessment.'' *International Journal of Applied Earth Observation and Geoinformation* 9:276–93.

Hall, O. 2010. ''Remote Sensing in Social Science Research.'' *Open Remote Sensing Journal* 3:1–16.

Hay, G. J., and G. Castilla. 2008. ''Geographic Object-based Image Analysis (GEOBIA): A New Name for a New Discipline.'' In *Lecture Notes in Geoinformation and Cartography*, edited by T. J. Blaschke, S. Lang, and G. J. Hay, 75–89. Berlin, Germany: Springer.

Heiden, U., W. Heldens, S. Roessner, K. Segl, T. Esch, and A. Mueller. 2012. ''Urban Structure Type Characterization Using Hyperspectral Remote Sensing and Height Information.'' *Landscape and Urban Planning* 105:361–75.

Heldens, W., T. Esch, and H. Taubenböck. 2012. ''Climate Change in Cities—Can Remote Sensing Help to Optimise Mitigation Strategies?'' Paper presented at the REAL CORP 2012: *Re-mixing the City—Towards Sustainability and Resilience?*, edited by Manfred Schrenk, Vasily V. Popovich, Peter Zeile, and Pietro Elisei, 121–28. Schwechat, Austria.

Hoalst-Pullen, N., and M. W. Patterson. 2011. ''Applications and Trends of Remote Sensing in Professional Urban Planning.'' *Geography Compass* 5:249–61.

Isikdag, U., and S. Zlatanova. 2010. ''Interactive Modelling of Buildings in Google Earth: A 3D Tool for Urban Planning.'' In *Developments in 3D Geo-information Sciences*, edited by T. Neutens and P. De Maeyer, 52–70. Berlin, Germany: Springer.

Jat, M. K., P. K. Garg, and D. Khare. 2008. ''Monitoring and Modelling of Urban Sprawl Using Remote Sensing and GIS Techniques.'' *International Journal of Applied Earth Observation and Geoinformation* 10:26–43.

Jin, X., and C. H. Davis. 2005. ''An Integrated System for Automatic Road Mapping from High-resolution Multi-spectral Satellite Imagery by Information Fusion.'' *Information Fusion* 6:257–73.

Keramitsoglou, I., C. T. Kiranoudis, G. Ceriola, Q. Weng, and U. Rajasekar. 2011. ''Identification and Analysis of Urban Surface Temperature Patterns in Greater Athens, Greece, Using MODIS Imagery.'' *Remote Sensing of Environment* 115:3080–90.

Klemas, V. 2012. "Remote Sensing of Algal Blooms: An Overview with Case Studies." *Journal of Coastal Research* 28:34–43.

Klosterman, R. E. 1995. "The Appropriateness of Geographic Information Systems for Regional Planning in the Developing World." *Computers, Environment and Urban Systems* 19:1–13.

Klosterman, R. E. 2001. "The What if? Planning Support System." In *Planning Support Systems: Integrating Geographic Information Systems, Models, and Visualization tools*, edited by R. Brail and R. E. Klosterman, 268–84. Redlands, CA: ESRI Press.

Klosterman, R. E. 2008. "A New Tool for a New Planning: The What If? (Planning Support System)." In *Planning Support Systems for Cities and Regions*, edited by R. K. Brail, 85–99. Cambridge, MA: Lincoln Institute of Land Policy.

Kooistra, L. 2012. "Accessibility of Earth Observation Data." Accessed March 26, 2013. http://www.geo-informatie.nl/courses/grs20306/course/Schedule/Accessibility-of-EO-data.pdf.

Kumar, A. S. K., and T. Misra. 2007. "Sensors Technology for Earth Observation: An ISRO Perspective." *International Astronautical Federation—58th International Astronautical Congress* 2007 4: 2133–42.

Lakes, T., and H.-O. Kim. 2012. "The Urban Environmental Indicator "Biotope Area Ratio"—An Enhanced Approach to Assess and Manage the Urban Ecosystem Services Using High Resolution Remote-sensing." *Ecological Indicators* 13 (1): 93–103.

Lein, J. K. 2009. "Implementing Remote Sensing Strategies to Support Environmental Compliance: A Neural Network Application." *Environmental Science and Policy* 12:948–58.

Le Néchet, F. 2012. "Urban Spatial Structure, Daily Mobility and Energy Consumption: A Study of 34 European Cities." *CyberGeo: European Journal of Geography*. Accessed October 16, 2014. http://spi.cybergeo.revues.org/24966

Levin, N., and Y. Duke. 2012. "High Spatial Resolution Night-time Light Images for Demographic and Socio-economic Studies." *Remote Sensing of Environment* 119:1–10.

Litman, T. 2010. *Land Use Impacts on Transport: How Land Use Factors Affect Travel Behaviour*. Vancouver, Canada: Victoria Transport Policy institute.

Liu, S., C. Han, S. Wang, and Q. Luo. 2012. "Data Warehouse Design for Earth Observation Satellites." *Procedia Engineering* 29:3876–82.

Liu, H., and Q. Weng. 2012. "Enhancing Temporal Resolution of Satellite Imagery for Public Health Studies: A Case Study of West Nile Virus Outbreak in Los Angeles in 2007." *Remote Sensing of Environment* 117:57–71. doi:http://dx.doi.org/10.1016/j.rse.2011.06.023.

Lo, C. P., and B. J. Faber. 1997. "Integration of Landsat Thematic Mapper and Census Data for Quality of Life Assessment." *Remote Sensing of the Environment* 60:143–57.

Mathieu, R., C. Freeman, and J. Aryal. 2007. "Mapping Private Gardens in Urban Areas Using Object-oriented Techniques and Very High-resolution Satellite Imagery." *Landscape and Urban Planning* 81:179–92.

Miller, R. B., and C. Small. 2003. "Cities from Space: Potential Applications of Remote Sensing in Urban Environmental Research and Policy." *European Planning Studies* 6:129–37.

Mudau, N. 2010. "Spot Building Count Supporting Informed Decisions." *Position IT* 10:51–52.

Musakwa, W., and A. Van Niekerk. 2013. "Implications of Land Use Change for the Sustainability of Urban Areas: A Case Study of Stellenbosch." *Cities* 33:143–56.

Myburgh, G., and A. Van Niekerk. 2013. "Effect of Feature Dimensionality on Object-based Land Cover Classification: A Comparison of Three Classifiers." South African Journal of Geomatics 2:13–27.

NAS (National Academy of Sciences). 2003. *Using Remote Sensing in State and Local Government: Information for Management and Decision Making*. Washington, DC: National Academy of Science.

NEAT GIS Protocols (Neighbourhood Environment for Active Transport–Geographic Information Systems). 2010. *Neighbourhood Environment for Active Transport-geographic Information Systems Version 5.1*. New York: Design for Health.net, Cornell University.

Ni, L. 2012. "Object and Rule Based Approach for Classification of High Spatial Resolution Data over Urban Areas." Proceedings of SPIE—The International Society for Optical Engineering 8203, p. 82030V.

Nichol, J., B. King, D. Quattrochi, I. Dowman, M. Ehlers, and X. Ding. 2007. "Earth Observation for Urban Planning and Management: State of the Art and Recommendations for Application of Earth Observation in Urban Planning." *Photogrammetric Engineering and Remote Sensing* 73:973–79.

Nobrega, R., C. O'Hara, and J. Quintanilha. 2008. "An Object-based Approach to Detect Road Features for Informal Settlements Near Sao Paulo, Brazil." In *Object-based Image Analysis*, edited by Thomas Blaschke, Stefan Lang, and Geoffrey Hay, 589–607. Berlin, Germany: Springer.

Patino, J. E., and J. C. Duque. 2012. "A Review of Regional Science Applications of Satellite Remote Sensing in Urban Settings." *Computers, Environment and Urban Systems* 37:1–17.

Pickett, S. T. A., C. G. Boone, B. P. McGrath, M. L. Cadenasso, D. L. Childers, L. A. Ogden, and J. M. Grove. 2013. "Ecological Science and Transformation to the Sustainable City." *Cities* 32:S10–20. Accessed May 5, 2013. doi:http://dx.doi.org/10.1016/j.cities.2013.02.008.

Planning Pool. 2012. "Why Mix Urban Planning and Social Media." Accessed February 3, 2013. http://planningpool.com/about/mix-urban-planning-social-media/.

Qi, Z., A. G.-O. Yeh, X. Li, and Z. Lin. 2012. "A Novel Algorithm for Land Use and Land Cover Classification Using RADARSAT-2 Polarimetric SAR Data." *Remote Sensing of Environment* 118: 21–39. doi:http://dx.doi.org/10.1016/j.rse.2011.11.001.

Renetzeder, C., S. Schindler, M. A. Prinz, C. A. Mucher, and T. Wrbka. 2010. "Can We Measure Ecological Sustainability? Landscape Pattern as an Indicator for Naturalness and Land Use Intensity at Regional, National and European Level." *Ecological Indicators* 10:39–48.

Repetti, A., M. Soutter, and A. Musy. 2005. "Introducing SMURF: A Software System for Monitoring Urban Functionalities." *Computers, Environment and Urban Systems* 30:687–707.

SANSA (South African National Space Agency). 2014. "Supporting Government Outcomes Using SPOT 6." Accessed May 9, 2014. http://www.sansa.org.za/spot6/doc/Spot6%20S0-4%20Paida%20Mangara.pdf.

Santana, L. M. 2007. "Landsat ETM + Image Applications to Extract Information for Environmental Planning in a Colombian City." *International Journal of Remote Sensing* 28:4225–42.

Santos, T., S. Freire, J. A. Tenedório, A. Fonseca, N. Afonso, A. Navarro, and F. Soares. 2011. "The GeoSat Project: Using Remote Sensing to Keep Pace with Urban Dynamics." Accessed February 24, 2012. http://www.earthzine.org/themes-page/urban-monitoring/.

Satellite imaging Cooperation. 2013. Other sensors. Accessed July 8, 2013. http://www.satimagingcorp.com/satellite-sensors/other-satellite-sensors/.

Schaepman, M. E. 2007. "Spectrodirectional Remote Sensing: From Pixels to Processes." *Advances in Airborne Electromagnetics and Remote Sensing of Agro-Ecosystems* 9:204–23.

Schneider, A., M. A. Friedl, and D. Potere. 2010. "Mapping Global Urban Areas Using MODIS 500-m Data: New Methods and Datasets Based on 'Urban Ecoregions'." *Remote Sensing of Environment* 114:1733–46.

Schwach, J. A., T. L. Morris, and P. G. Michalopoulos. 2009. *Rapidly Deployable Low-cost Traffic Data and Video Collection Device*. Minneapolis: Centre for Transportation Studies, University of Minnesota.

Schwarz, N. 2010. "Urban form Revisited—Selecting Indicators for Characterising European Cities." *Landscape and Urban Planning* 96:29–47.

Schwarz, N., S. Lautenbach, and R. Seppelt. 2011. "Exploring Indicators for Quantifying Surface Urban Heat Islands of European Cities with MODIS Land Surface Temperatures." *Remote Sensing of Environment* 115:3175–86.

Sherbinin, A., D. Balk, K. Yager, M. Jaiteh, F. Pozzi, F. Giri, and A. Wannebo. 2002. "Social Science Applications of Remote Sensing." Accessed July 6, 2010. http://sedac.ciesin.columbia.edu/tg/guide_glue.jsp?rd=rs&ds=1.

Sims, S., and V. Mesev. 2011. "Measuring Urban Sprawl and Compactness: Case Study Orlando, USA." Proceedings of the 25th International Cartographic Conference, International Cartographic Association, Paris, France.

Skidmore, A. K., W. Bijker, K. Schmidt, and L. Kumar. 1997. "Use of Remote Sensing and GIS for Sustainable Land Management." *ITC Journal* 3:302–15.

Sobrino, J. A., R. Oltra-Carrió, J. C. Jiménez-Muñoz, Y. Julien, G. Sòria, B. Franch, and C. Mattar. 2012. "Emissivity Mapping over Urban Areas Using a Classification-based Approach: Application to the Dual-use European Security IR Experiment (DESIREX)." *International Journal of Applied Earth Observation and Geoinformation* 18:141–47.

Song, Y., and G. J. Knaap. 2004. "Measuring Urban Form." *Journal of the American Planning Association* 70:210–25.

Song, Y., and D. A. Rodriguez. 2005. *The Measurement of the Level of Mixed Land Uses: A Synthetic Approach*. Chapel Hill, NC: Carolina Transportation Program.

Stuckenberg, T., Z. Munch, and A. Van Niekerk. 2013. "Multitemporal Remote Sensing Land-cover Change Detection for Biodiversity Assessment in the Berg River Catchment." *South African Journal of Geomatics* 2 (3): 190–205.

Studiolab. 2012. "Mobile Cityscapes: Crowdsourcing Knowledge for a Sustainable City." Accessed January 7, 2013. http://community.studiolabproject.eu/group/mobile-cityscapes-crowdsourcing-knowledge-sustainable-city.

Sutton, P. C., and R. Costanza. 2002. "Global Estimates of Market and Non-market Values Derived from Night-time Satellite Imagery, Land Cover, and Ecosystem Service Valuation." *Ecological Economics* 41:509–27.

Tao, S., V. Manolopoulos, S. Rodriguez Duenas, and A. Rusu. 2012. "Real-time Urban Traffic State Estimation with A-GPS Mobile Phones as Probes." *Journal of Transportation Technologies* 2: 22–31.

Taubenböck, H., and T. Esch. 2011. "Remote Sensing—An Effective Data Source for Urban Monitoring." Accessed February 18, 2013. http://www.earthzine.org/themes-page/urban-monitoring/.

Taubenböck, H., T. Esch, M. Wurm, A. Roth, and S. Dech. 2010. "Object-based Feature Extraction Using High Spatial Resolution Satellite Data of Urban Areas." *Journal of Spatial Science* 55: 117–32.

Toure, N. M., A. Kane, J. F. Noel, V. Turmine, V. Nedeff, and G. Lazar. 2012. "Water–poverty Relationships in the Coastal Town of Mbour (Senegal): Relevance of GIS for Decision Support." *International Journal of Applied Earth Observation and Geoinformation* 14:33–39.

Townsend, A. C., and D. A. Bruce. 2010. "The Use of Night-time Lights Satellite Imagery as a Measure of Australia's Regional Electricity Consumption and Population Distribution." *International Journal of Remote Sensing* 31:4459–80.

Tsai, Y.-H. 2005. "Quantifying Urban Form: Compactness versus Sprawl." *Urban Studies* 42:141–61.

UNEP (United Nations Environmental Programme). 2011. "Making the Economic Case for Greening Cities." Accessed March 27, 2012. http://www.unep.org/newscentre/default.aspx?DocumentID=2656&ArticleID=8895.

UN-HABITAT. 2009. "Habitat Partner University Network." Accessed November 10, 2010. http://www.unhabitat.org/content.asp?typeid=19&catid=570&cid=6002.

UN-HABITAT. 2010. *State of the World's Cities 2010/2011 Bridging the Urban Divide*. London, UK: Earth Scan.

Ural, S., E. Hussain, and J. Shan. 2011. "Building Population Mapping with Aerial Imagery and GIS Data." *International Journal of Applied Earth Observation and Geoinformation* 13:841–52.

Urban land Institute. 2010. *Land Use and Driving: The Role Compact Development Can Play in Reducing Greenhouse Gas Emissions*. Washington, DC: Urban Land Institute.

US Department of Agriculture. 2013. *Summary Report: 2010 National Resources Inventory, Natural Resources Conservation Service*. Washington, DC: Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa.

Victoria Transport Policy Institute. 2010. "Land Use Impacts on Transport: How Land Use Patterns Affect Travel Behaviour." *Accessed October* 22, 2011. www.vtpi.org/landtravel.pdf.

Vintrou, E., A. Desbrosse, A. Bégué, S. Traoré, C. Baron, and D. Lo Seen. 2012. "Crop Area Mapping in West Africa Using Landscape Stratification of MODIS Time Series and Comparison with Existing Global Land Products." *International Journal of Applied Earth Observation and Geoinformation* 14: 83–93.

Wang, J., Q. Cheng, and J. Chen. 2011. "A GIS and Remote Sensing Based Analysis in Land Use Change Using Asymmetric Relation Analysis Method: A Case Study from the City of Hangzhou, China." *Mathematical Geosciences* 43:435–53.

Wang, J., C. Zeng, and B. Lehrbass. 2012. "Building Extraction from LiDAR and Aerial Images and its Accuracy Evaluation." Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International, pp. 64–67.

Wei, Y., Z. Zhao, and J. Song. 2004. "Urban Building Extraction from High-resolution Satellite Panchromatic Image Using Clustering and Edge Detection." *Geoscience and Remote Sensing Symposium, 2004. IGARSS'04. Proceedings. 2004 IEEE International* 3:2008–2010.

Weng, Q. 2012. "Remote Sensing of Impervious Surfaces in the Urban Areas: Requirements, Methods, and Trends." *Remote Sensing of Environment* 117:34–49.

Weng, Q., D. Lu, and J. Schubring. 2004. "Estimation of Land Surface Temperature–vegetation Abundance Relationship for Urban Heat Island Studies." *Remote Sensing of Environment* 89:467–83.

Whiteside, T. G., G. S. Boggs, and S. W. Maier. 2011. "Comparing Object-based and Pixel-based Classifications for Mapping Savannahs." *International Journal of Applied Earth Observation and Geoinformation* 13:884–93.

WCED (World Commission on Environment, and Development). 1987. *Our Common Future*. Oxford, UK: Oxford University Press.

Wurm, M., H. Taubenböck, and A. D. S. Roth. 2009. "Urban Structuring Using Multisensoral Remote Sensing Data by Example of German Cities Cologne and Dresden." Accessed November 9, 2012. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5137555&tag=1.

Yang, J., L. Zhao, J. McBride, and P. Gong. 2009. "Can You See Green? Assessing the Visibility of Urban Forests in Cities." *Landscape and Urban Planning* 91:97–104.

Yuan, J., D. Wang, B. Wu, L. Yan, and R. Li. 2009. "Automatic Road Extraction from Satellite Imagery Using LEGION Networks." In *Neural Networks, 2009. IJCNN 2009*. International Joint Conference on IEEE, Atlanta, GA, June 14–19, 2009, 3471–76.

Zhang, Y., B. Guindon, and K. Sun. 2010. "Concepts and Application of the Canadian Urban Land Use Survey." *Canadian Journal of Remote Sensing* 36:224–35.

Zhang, C., L. Luo, W. Xu, and V. Ledwith. 2008. "Use of Morans I and GIS to Identify Pollution Hotspots of Pb in Urban Soils of Galway, Ireland." *Science of The Total Environment* 398:212–21.

Zhang, X., Y. Wu, and L. Shen. 2011. "An Evaluation Framework for the Sustainability of Urban Land Use: A Study of Capital Cities and Municipalities in China." *Habitat International* 35: 141–49.

Zhang, H., Y. Zhang, and H. Lin. 2012. "A Comparison Study of Impervious Surfaces Estimation Using Optical and SAR Remote Sensing Images." *International Journal of Applied Earth Observation and Geoinformation* 18:148–56.

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