



Implications of land use change for the sustainability of urban areas: A case study of Stellenbosch, South Africa



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ABSTRACT

Sustainable development, an objective of urban planning, is difficult to put into practice. Data to monitor sustainable land use management is often lacking, particularly in developing countries. This paper investigates the use of earth observation data for supporting sustainable land use planning. It proposes the use of decision consequence analysis (DCA) as a simple and structured way to put sustainable development into practice. The study demonstrates how land use change (LUC) which also includes land cover, the local land use mix index (LLUM) and land use frequency (LUF) can be used as indicators of objective land use sustainability. The results show that the use of DCA, consequence analysis, earth observation and land use indicators can aid local planning authorities to assess and monitor urban sustainability. Planners can also use the indicators to effect policy change and to support land use decisions.

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Introduction

Sustainable cities are prominent on the development agendas of many nations, but particularly important in developing countries experiencing alarmingly high rates of urbanisation (Shen, Ochoa, Shah, & Zhang, 2010; UN-HABITAT, 2009). Rapid urbanization often leads to land use practices that disregard future generations' needs and inevitably cause problems such as urban sprawl (Breheny & Batey, 1992), haphazard development (Hicken, 2009), collapse of public services (UN-HABITAT, 2002), brownfields (Burton, 2000), and overcrowding (WCED, 1987). This often leads to sedimentation of watersheds (Farrow & Winograd, 2001), urban pollution (Brandes, MacCleery, Peterson, & Johnston, 2010), increase of natural and man-made risks (World Bank, 1994), soil degradation (Sattler, Nagel, Werner, & Zander, 2010) and damage to pristine natural landscapes (Barredo & Demicheli, 2003; UN-HABITAT, 2002).

Many developing cities lack the necessary resources to effectively manage land use (UN-HABITAT, 2009) and, although some governments have tried to balance socio-economic development and environmental concerns, evidence indicates that such attempts have been ineffective (Klosterman, 1995). In addition, many of the institutional structures of local governments are inappropriate for dealing with high rates of urbanisation because they were established during colonial times and consequently designed

to deal with predominantly rural and agricultural societies (WCED, 1987). Over the last five decades the focus of developing nations' urban management policies shifted from a centralised to decentralised approach as governments went through phases of structural adjustments with their main concerns being good governance and privatisation issues (Repetti, Soutter, & Musy, 2005; World Bank, 1994). These changes have incapacitated many local planning authorities so that many still follow the master-planning approach which is ineffective in promoting the economic, social and environmental sustainability of urban areas (Barredo & Demicheli, 2003). Also, the availability of spatial information is often poor or non-existent, corruption is widespread, and an inadequate skills base pose formidable hurdles for planning, forecasting, modelling and monitoring land use change (Hicken, 2009). Earth observation data is a proposed solution to availability of spatial information.

Campbell (2011) defines earth observation as the practice of deriving information about features on the earth's surface using images acquired from an overhead perspective. Earth observation has the capability to provide quick synoptic views of urban areas and is invaluable for collecting information in developing countries where municipal records seldom keep pace with the rate of development (Hall, 2010a; Repetti et al., 2005). Earth observation can uncover aspects of the built environment often opaque to urban planners and social scientists (Barr & Ford, 2010) and it has been used in sustainability studies as a data source for indicator development (Liu, 2009; National Academy of Sciences, 2003). These indicators include land use and cover (Barredo & Demicheli, 2003), road network layout (Victoria Transport Policy Institute,

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2010) and building density (Angel, 2010). Collecting such data by other means (e.g. field surveys) is difficult, time-consuming and prohibitively expensive (National Academy of Sciences, 1998) in most developing countries.

Most developing cities and towns pursue sustainable development as their goal, yet little is being done to operationalise the concept. Clearly, new approaches and techniques are needed to support sustainable land use management in rapidly developing cities. This paper aims to demonstrate how maps of land use, derived through earth observation data and decision consequence analysis (DCA), can be used to develop land use indicators for monitoring sustainable urban land use in towns and cities.

Sustainable development and land use planning

Sustainable development is a fuzzy concept (Gunder, 2006; Winograd & Farrow, 2007) encapsulated in the seminal definition by the Brundtland Commission as “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987, p. 23). For urban land use to be sustainable it must meet the needs of the current as well as future urban citizens (Seghezze, 2009; Wolf & Meyer, 2010). Accordingly, city officials must heed the call by today’s citizens to alter land use without jeopardising future generations’ needs. Sustainable development and urban land use planning are noble concepts (Hall, 2010b), but the pressing challenge is to put them into practice (Freeman, 2004). Ideally, they should be incorporated into a comprehensive decision framework to guide daily, personal, business or policy decisions (Hall, 2010b; Holden, 2008; Ness, 2001). But these grand intentions are difficult to monitor and implement given their complexity, vagueness and, at times, immeasurable tenets (Zhang, Wu, & Shen, 2011). Sustainability often remains a condition that can be used and abused by various stakeholders without their clearly defining what sustainability implies in land use planning (Hall, 2010b). A model of sustainable development is required which accurately captures and allocates costs, such as environmental damage, pollution and land consumption. DCA is a worthwhile option for assisting the simplification of sustainable land use management.

Decision consequence analysis

DCA formalises decision-making by using decision theory, probability and statistics (Hall, 2010b). The process breaks down complicated problems, such as sustainable development and land use, into increasingly smaller units until the particular component can be accurately analysed and understood within the context of the overall problem. The basic elements of DCA are an unacceptable current condition and a desired future condition. To achieve a transition between the two conditions it is necessary to understand each condition, to identify possible pathways between the two and a way to measure the progression between them (Fig. 1).

High rates of urbanization in many developing countries often lead to unsustainable land use practices (Klosterman, 2001). Although much has been done to stifle or even reverse this trend, the main challenge is how progress from the current state (unsustainable land use) to the desired state or objective (sustainable land use practices) can be monitored. The use of objective indicators, developed using Geographical Information Systems (GISs) and earth observation, is proposed. Such indicators can be used as criteria for creating different land use scenarios and for supporting land use decisions. DCA is a structured and systematic approach to making complex and unstructured decisions concerning sustainable land use. DCA adheres to principles used in medical practice (Farrow & Winograd 2001) and can serve as a

robust tool for practical purposes (Fig. 2). Just as the lifestyle of a human being influences his or her health, land use change and high rates of urbanisation in cities and towns affects the sustainability of those urban areas. This condition requires a diagnosis which prompts a response.

Earth observation

Earth observation is a branch of remote sensing concerned with collecting information about the earth’s surface through the use of data obtained from airborne and satellite sensors (Esch et al., 2012). The remote sensing process begins with observation of physical objects by sensors to extract useful data and information as images, normally in digital format (Campbell, 2011). Obtaining useful information from these images depends on the spatial, temporal, spectral and radiometric resolution of the sensors. Spatial resolution refers to the smallest feature which can be discerned from an image, while temporal resolution is the frequency at which a satellite collects data or visits the same location. Radiometric differentiation defines the differences in brightness of objects and features, it also influences image contrast. Spectral resolution refers to a sensor’s ability to collect data at specific electromagnetic wavelength ranges. In general, sensors with higher spatial, temporal, radiometric and spectral resolutions provide better-quality information (Weng, 2012). However, the resolution is also a function of the research objectives. For example, due to the heterogeneity of urban surface materials hyperspectral data with the capability to distinguish between various urban materials is required. Similarly, creation of global urban footprint maps from VHR optical satellite imagery is impossible because of limitations regarding image acquisition, processing as well as image analysis techniques (Esch et al., 2012). Nevertheless, from medium resolution sensors, the image processing techniques allow for the development of global maps such as the Global Rural–Urban Monitoring (GRUMP).

Satellite images normally undergo pre-processing procedures such as image restoration, image enhancement, image classification and image transformation (Schaeppman, 2007). Restoration refers to correction and calibration of the image to fully represent the earth while enhancement involves modification to optimise visual appearance. Classification entails computer-assisted interpretation of images using software such as PCI Geomatica and eCognition, among others. Classification can be categorised as unsupervised or supervised, the latter involving the training of computer software to automatically map land cover classes according to the statistical characterisation of known data (i.e. training sites) (Addink, Van Coillie, & De Jong, 2012). Unsupervised classification involves using a clustering algorithm to classify an image into spectral classes which are interpreted and classified by an operator.

Image classification has traditionally been carried out on individual pixels (pixel-based approach), but recent advancements in image analysis software have made it possible to carry out object based classification. This geographic object based image analysis (GEOBIA) approach (Hay & Castilla, 2008) partitions remotely sensed imagery into meaningful image-objects (groups of contiguous pixels) and assesses their spatial, temporal, spectral and contextual characteristics to generate new geographic information in GIS-ready format (Blaschke, 2010; Qi, Yeh, Li, & Lin, 2012). GEOBIA is similar to visual interpretation as it uses tone, shape, size, pattern, texture and association in classification exercises. This not only improves the accuracy of classifications (Duro, Franklin, & Dubé, 2012), but enables the development of logical rules whereby information such as land cover can be extracted from images with greater cost-efficiency (Ardila, Bijker, Tolpekin, & Stein, 2012). These improvements in earth observation hold much potential for the development of sustainability indicators.

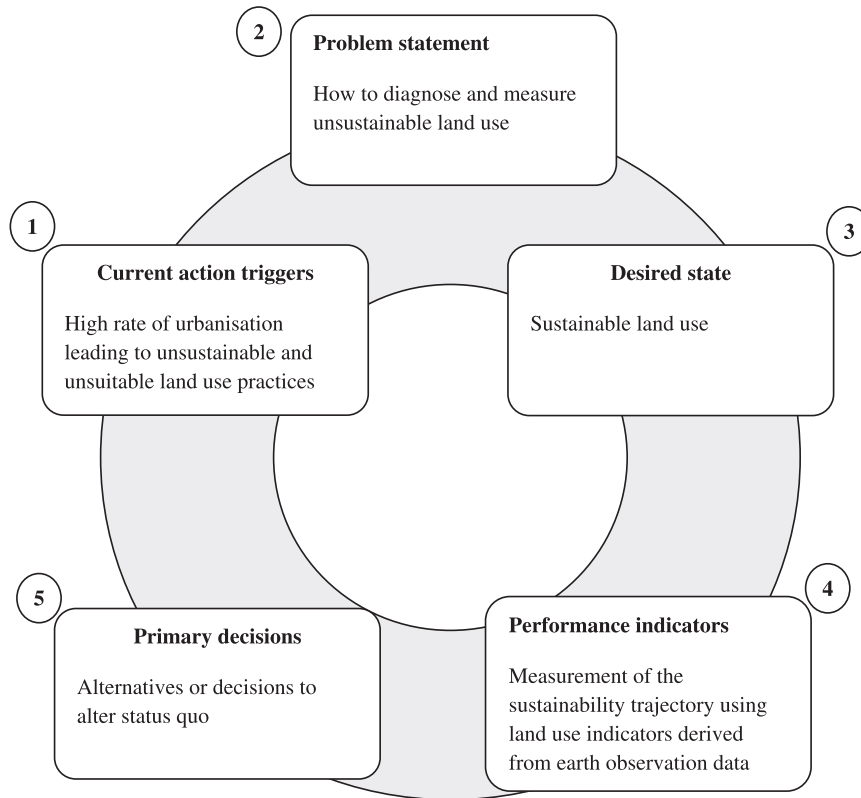


Fig. 1. Elements of decision consequence analysis. Source: Adapted from Hall (2010b).

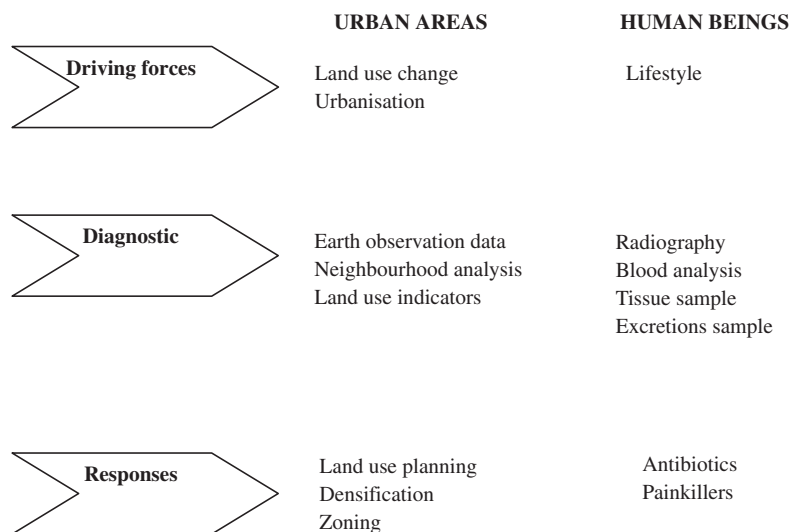


Fig. 2. Diagnostic process for ailments in human beings and urban areas. Source: Adapted from Farrow and Winograd (2001).

Sustainability indicators

Sustainability indicators are bellwether tests of sustainability and they reflect something basic and fundamental about the long-term economic, social, and environmental health of a community (Maclaren, 2004). Sustainability indicators are pointers toward progress or lack of the overall health of a community, neighbourhood, town, city, region or larger area. They must reflect the general well-being of urban land use, they should

have an integrating function, be forward-looking (Huang, Wong, & Chen, 1998; Maclaren, 2004), be distributional, and subject to feedback loops (Hall, 2010b). Examples of such indicators are land use change (Wang, Cheng, & Chen, 2011), land use mix (Song & Rodriguez, 2005) and land use frequency (Guindon & Zhang, 2005). Employing these indicators replaces the ubiquitous advocacy-based qualifications which both dominate the sustainability programmes in Africa and hinder sound decision making.

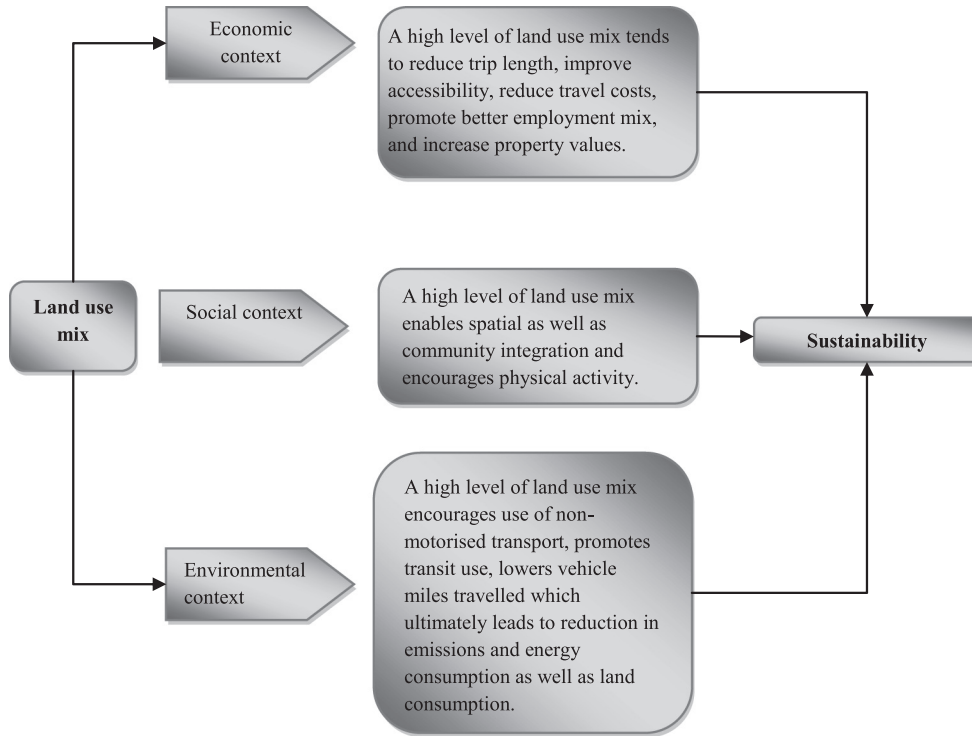


Fig. 3. Impact of land use mix on urban sustainability. Sources: Adapted from Litman (2010), Victoria Transport Policy Institute (2010).

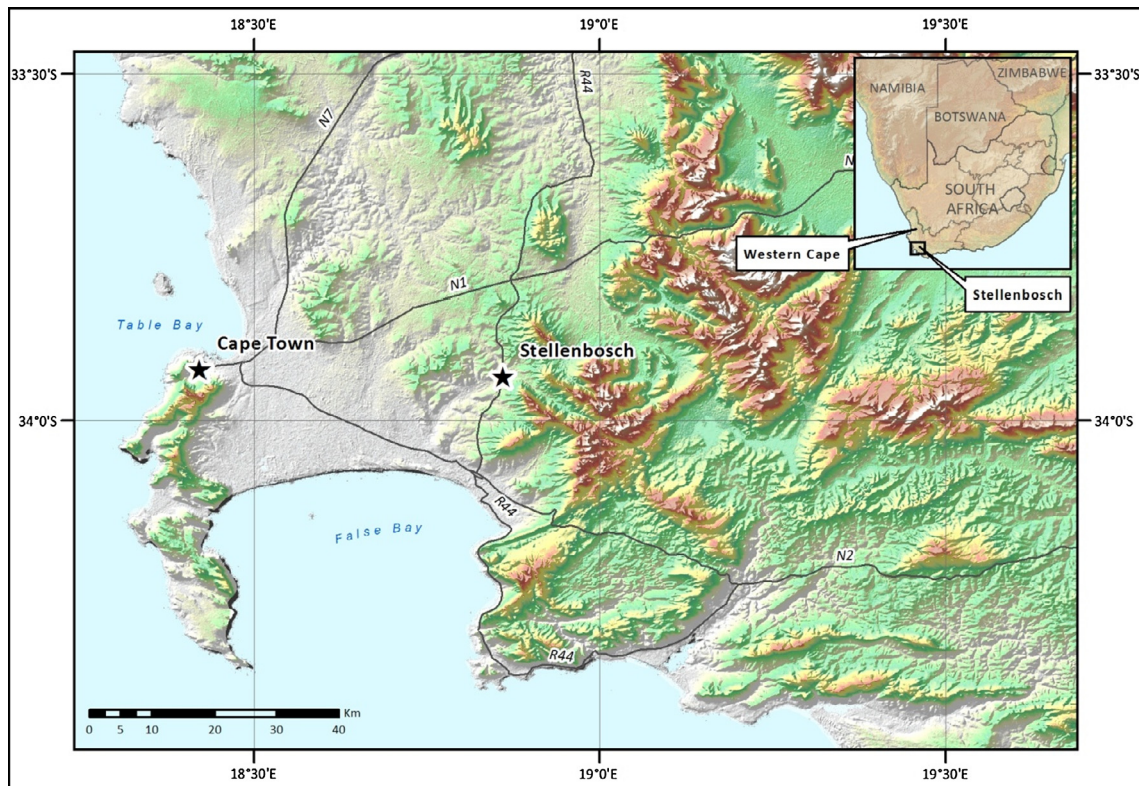


Fig. 4. Location of Stellenbosch in the south-western cape.

Land use change (LUC) is an important indicator in urban sustainability as it can be used to measure the rate of transformation of mostly agricultural and natural ecosystems into intensive urban

uses (Wang et al., 2011). It has been demonstrated that high rates of LUC (often due to urban growth) lead to increased motorised transport (Canadian Urban Institute, 2008; Victoria Transport

Policy Institute, 2010), energy consumption (Urban Land Institute, 2010), loss of agricultural land (Comber, Brunsdon, & Green, 2008), loss of biodiversity (Yang, Zhao, McBride, & Gong, 2009) and greater air pollution (Zhang et al., 2011). These effects pose serious threats to the attainment of urban sustainability and ultimately increase the rate of climate change (Renetzeder, Schindler, Prinz, Mucher, & Wrбка, 2010). Consequently, it is imperative to obtain

information on LUC to understand human-nature interactions in rapidly urbanising countries (Hall, 2010a).

The impact of land use mix (LUM) on urban sustainability has been demonstrated by Song and Rodriguez (2005). The land use mix index measures the degree to which land use activities are separated. Consequently, the LUM affects the way people move between different activities or different destinations such as home to

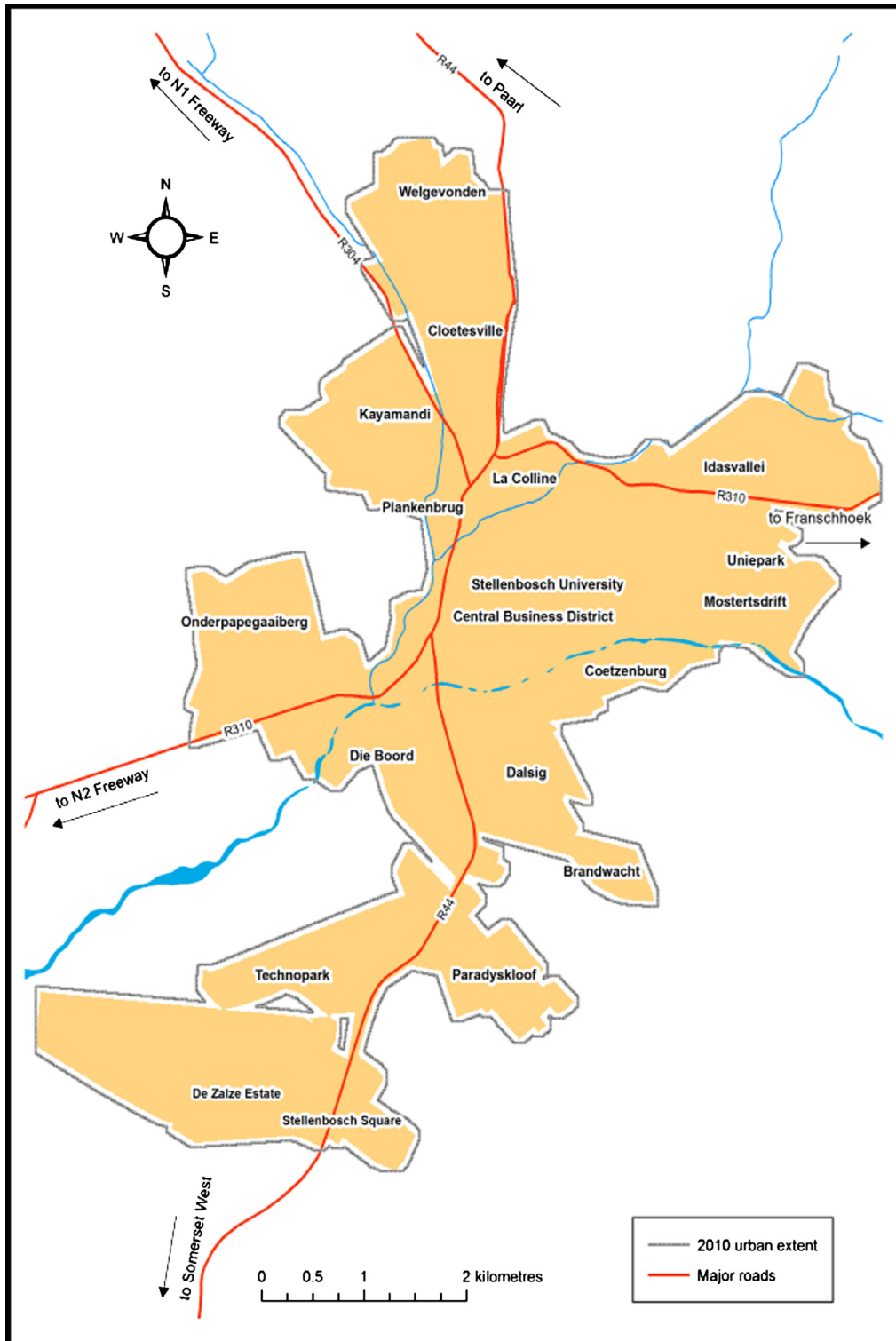


Fig. 5. Locality map of Stellenbosch.

workplace or shops, and home to civic institutions such as places of worship and parks (Litman, 2010; Polzin, 2006). The LUM index is thus a measure of variation (Song & Knaap, 2004), dispersion or diversity of land uses (NEAT GIS Protocols, 2010). The LUM index is defined as:

$$\text{LUM} = \{-\sum[(p_i)(\ln p_i)]\}/\ln k$$

Where p_i is the proportion of each land use class per neighbourhood; \ln is the natural logarithm; and k is the number of land use classes per neighbourhood. Essentially, the LUM index measures the extent to which land uses are heterogeneously distributed within a neighbourhood (NEAT GIS Protocols, 2010). The index values range from 0 to 1 where 0 indicates land use homogeneity and 1 represents heterogeneity (Song & Rodriguez, 2005). The LUM index can be calculated globally (GLUM) or locally (LLUM). GLUM is a measure of the overall land use mix of a city or town while the LLUM shows distribution of LUM within a city.

LUM affects sustainability through its impact on environmental, social and economic costs (Fig. 3). It has been demonstrated that, mixing of complementary land uses such as residential, retail, offices, commercial, non-obnoxious industrial use and civic uses is beneficial for urban sustainability. For example, recent empirical evidence suggests that a high level of land use mix reduces environmental costs because it increases use of non-motorised transport (NMT), promotes transit use, lowers vehicle miles travelled (VMT), reduces automobile use as well as emissions (Ewing & Nelson 2008; Litman, 2010) and promotes efficient usage of space and resources (Frank & Engelke, 2001). Mixing residential with civic, commercial, and retail land uses reduces social costs by enabling spatial integration as well as community interaction which in turn reinforce the idea of pavement cafes (Victoria Transport Policy Institute, 2010). A high degree of land use mix has an economic impact as it increases property values, lowers input costs (Jabereen,

2006; Jones & MacDonald, 2004), encourages a better employment mix and improves accessibility thereby reducing travelling costs (National Research Council, 2009; Polzin, 2006). Song and Knaap (2004) observed that a mixing of residential and commercial uses generally correlates with high land prices while other studies observed that land prices and the mixing of residential with open spaces are positively related (Song & Rodriguez 2005).

Calthorpe Associates (2010), Litman (2010), National Research Council (2009), Urban Land Institute (2010), and Victoria Transport Policy Institute (2010) have commented on the positive relationship between a high degree of land use mix and reductions in VMT, energy consumption and greenhouse gas (GHG) emissions. However, there is disagreement about the level of this impact, the National Research Council (2009) argue that a high degree of land use mix reduces VMT by 25%, whereas others maintain that a high degree of land use mix can reduce VMT by more than 50% (Calthorpe Associates, 2010; Ewing & Cervero, 2001; Litman, 2010). The studies show that changes to planning policy (particularly zoning) encourages mixing of land uses because activities can provide a platform for meeting the social, economic and environmental contexts of sustainable development. It is critical that the land use mix be monitored by planners, particularly in cities and towns experiencing rapid growth.

Land use frequency (LUF) refers to the number of land uses found in a neighbourhood or city. It is analogous to having a diversity of land uses such as commercial, residential, education and recreation within a neighbourhood (Song & Rodriguez, 2005). As with the LUM index, LUF is perceived to have social, environmental and economic impacts. A high LUF promotes active communities (Frank, Andersen, & Schmid, 2004), interaction (Frank & Engelke, 2001) and transit uses which in turn reduce transport costs (Ewing & Nelson, 2008). High LUF leads to lower automobile use (Guindon & Zhang, 2005), low rates of urban expansion and reductions in GHG emissions (Urban Land Institute, 2010).

Table 1
Land use classification scheme.

Land use	Density ^a	Spacing and pattern	Height ^b	Common features
Cluster housing	Ranges between low, medium and high	Building units at the centre of site or attached to another, while housing units can be similar or varied	Single storey, two storeys to three storeys	Housing units in an enclosed perimeter around a common space such as gardens, play areas, mall or water body
Residential (single family dwelling units)	Ranges between low, medium and high	Building units at centre of site, almost similar spacing between units and a discernible road pattern	Single storey, two storeys to three storeys	Gardens, driveways and swimming pools
Informal settlements	Very-high density, more than 60 units/ha	Irregular pattern as well as an indiscernible road hierarchy	Not applicable	Variety of substandard building material and lack of basic services and infrastructure
Industrial	Ranges between low, medium and high. Light manufacturing normally exhibits medium to high density	Buildings normally elongated and building pattern irregular for heavy industry	Minimum of two storeys for heavy industry, while for light industries height varies	Warehouses, masts, tanks, stockpiles of raw materials and waste, transportation facilities, chimneys, cooling towers, little or no vegetation in vicinity
Industrial parks	Building density normally medium (30–50 units/ha)	Building units at centre of site, almost similar spacing between units and a discernible pattern of building units	Varies with establishments	Well-manicured lawns, enclosed or defined perimeter, well-defined access points and discernible road hierarchy
Commercial (CBD)	High, more than 50 units/ha	Rectangular grid layout and buildings closely spaced	Average building height of two storeys	Sealed impervious surfaces, building material (concrete asphalt) and parking lots
Vertical mix	Depends on location	If in or next to CBD, buildings closely spaced	Average height of two storeys	Mix of uses within one building with uses stacked on top of each other
Horizontal mix	Low to high	Varies with location	Varies with location	Land use mix where different uses occur side by side

^a Density standards are defined as: fewer than 30 building units per hectare regarded as low density, 30–50 units/ha as medium density and more than 50 units/ha as high density (Urban land Institute, 2010, Western Cape Department of Environmental Affairs and Development Planning, 2009; Urban Land Institute, 2010).

^b Height is classified in storeys so as to generalise. Extensive field surveys were carried out to verify height obtained from the digital surface model (DSM). The height of buildings obtained from the DSM was divided by the average height of one storey to derive the number of storeys of a building. There were ten control points for each land use.

Table 2
Indicators sustainable land use. Sources: Adapted from Song and Knaap (2004) and Wang et al. (2011).

Indicator	Unit of measurement	Analysis scale	Significance and thresholds
Land use mix index	0–1	Neighbourhood	A land use index of 0 denotes low sustainability and 1 highly sustainable
Land use frequency	Frequency	Neighbourhood	A high number of complementary land uses per neighbourhood are desirable for sustainability, unlike low mixing intensity
Land use change	Percentage	City or town	Land use change impacts all the other indicators. The rate of land use change, type of land use change (urban to urban or non-urban to urban) and how it is managed determines land use sustainability

Methods

Study area and period

Stellenbosch, the second oldest town in South Africa, is the study area. The town is situated in the Western Cape province of South Africa approximately 55 km east of Cape Town's central business district (Fig. 4).

Stellenbosch is an appropriate study case as it has grown rapidly during last two decades. Its population increased from 60 000 in 2001 to 90 000 in 2010, at a mean annual growth rate of 8.5% (InterStudy, 2009; SA Statistics, 2001; Stellenbosch University, 2010). The town was earlier shown by Van der Merwe, Ferreira, and Zietsman (2005) to have the highest development potential of all 131 non-metropolitan settlements in the Western Cape. In 2010 it was rated as one of the six non-metropolitan settlements in the province with the highest development potential (Van Niekerk, Donaldson, Du Plessis, & Spocter, 2010).

Stellenbosch's economy has experienced a transition from servicing its rich agricultural hinterland to a diversified economy based on niche sectors such as tourism, finance, science and technology, the latter two ably supported by Stellenbosch University and Technopark an office park in the south eastern part of Stellenbosch (Fig. 5) (Stellenbosch Stellenbosch Municipality, 2011). Characteristically, Stellenbosch has suburbs of great wealth such as De Zalze, Paradyskloof, Uniepark, Mostersdrift, Dalsig, Onderpapegaaiberg, Die Boord, coexisting with an impoverished township (Kayamandi), informal settlements in Kayamandi, and poor households. Stellenbosch thus faces the challenges of balancing urban and economic growth against expansion into and consumption of scarce and valuable agricultural land as well as preserving natural and cultural heritage while simultaneously attempting to alleviate abject poverty. Stellenbosch was also selected because it is accessible to the authors and convenient for carrying out field visits. The availability of appropriate reference data to verify the findings was an important factor. The period of study is 2000–2010, mainly because of data availability. The study area was demarcated as the 2010 urban built up extent and consequently includes areas used in 2000 for non-urban purposes (e.g. agriculture).

Data collection and land use mapping

Very-high resolution (0.5 m) orthorectified colour aerial photographs of Stellenbosch were obtained from the Centre for Geographical Analysis (CGA) at Stellenbosch University, for 2000 and 2010. Multispectral and panchromatic SPOT5 imagery with resolutions 10 m and 2.5 m respectively, were acquired for 2010 from the South African National Space Agency (SANSA). A land use map of 2000 was supplied by Dennis Moss Partnership for verification purposes.

The SPOT5 imagery was pre-processed (orthorectified and subjected to atmospheric and radiometric corrections) in PCI Geomatica. The multispectral and panchromatic images were fused using the PANFUSE function. A land cover classification was performed on the fused imagery with a supervised geographical object-based

Table 3

Land use change within the 2010 urban extent of Stellenbosch since 2000.

Land use	Area (ha) 2000	Area (ha) 2010	Change (ha)	Percentage change
Agriculture	412.1	163.1	-249.0	-60.4
Cluster housing	13.4	75.9	62.5	467.7
Commercial	34.3	43.8	9.5	27.6
Community	25.8	26.4	0.6	2.4
Education	147.2	151.3	4.2	2.8
Government	82.8	67.6	-15.3	-18.4
Industrial	92.7	100.1	7.4	8.0
Informal	9.6	27.4	17.8	186.6
Mixed	21.5	26.9	5.4	25.2
Nature Reserve	5.6	5.6	0.0	0.0
Office park	56.5	66.3	9.8	17.4
Open space	124.1	104.3	-19.8	-16.0
Other ^a	34.3	68.2	33.9	98.7
Recreation	192.4	312.9	120.5	62.6
Residential	622.9	635.0	12.1	1.9
Transportation	6.3	6.7	0.4	6.1

^a Note: 'Other' consists of smallholdings and vacant land.

image analysis (GEObIA) approach and eCognition software. The accuracy of the resulting land cover map for 2010 was assessed during field visits and by comparing the map to the aerial photographs. The land cover map was visually interpreted along with ancillary data to develop a land use map. Land uses¹ were classified per land parcel in ArcGIS 10 by means of a land use classification scheme (Table 1), adapted from Anderson et al. (1976).

Urban areas are terrains of intensive use where much of the land is covered by building structures. Small areas surrounded by urban areas but having another land use (e.g. agriculture) were classified as urban. The land use classification exercise was complemented by extensive field visits to verify the accuracy of the classification. Land uses such as single-family dwelling units, informal settlements, cluster housing, commercial (CBD), educational and heavy industrial activities required relatively less groundtruthing due to their discernible shape, locational context and height (Table 1) which aided their identification on the remotely sensed imagery. For example, heavy industry was easily identifiable by its elongated buildings, waste-disposal sites and warehouses. Community facilities, such as churches, have discernible features and required little or no groundtruthing. However, mixed uses (vertical and horizontal), recreational areas and government use required extensive groundtruthing.

Due to the unavailability of SPOT5 imagery for 2000 (SPOT5 was launched in 2002), the authors had to rely on aerial photography to produce a comparable (i.e. one with a similar classification

¹ Land use is human activity directly related to the land (Anderson, Hardy, Roach, & Witmer, 1976) whereas land cover describes the vegetation and artificial constructions covering the land surface. Land use refers to the human use of land, for example residential or commercial purposes, whereas land cover refers to the physical and biological cover types that extend over an area, for example grass or pavement (Hall, 2010a).

scheme) land cover and land use map of 2000. By comparing the 2010 and 2000 imagery, it was possible in most cases to identify significant changes in land cover and land use. A land use map for 2000 was created by editing the 2010 map. The 2000 land use map developed by Dennis Moss Partnership was used to verify the created 2000 land use map.

Land use change, mix and frequency analyses

The land use maps of 2010 and 2000 were used to calculate LUC, GLUM, LLUM and LUF (Table 2). The latter two indexes were calculated for neighbourhoods 2×2 km in size. This neighbourhood size was selected as it corresponds to actual land use development patterns and is sufficiently large for use of non-motorised transport and automobile use (Ewing & Certero, 2001). Land use changes were determined at town level by overlaying GIS and cross-tabulation operations. A map was created that differentiates between changes from non-urban to urban use (i.e. urban expansion) and all other land use changes. All analyses were automated in the model builder tool of ArcGIS 10.

Results and discussion

Analysis of land use changes

The results of the LUC analysis are shown in Table 3. During the 10 year study period the area of land use within the built up urban extent of Stellenbosch increased from 1471 ha to 1881 ha (28%). Table 4 shows net land use transition from 2000 to 2010 and Fig. 6 displays the land use maps for the 2 years.

During the 10-year period there was a gain of 62.6 ha (468%) in cluster housing, 17.8 ha (187%) in informal housing, 33.3 ha (99%) smallholdings and vacant land (i.e. other), 5.4 ha (25%) in mixed use, 125 ha (63%) in recreation, 9 ha (28%) in commercial and 9.9 ha (17%) office park use (Table 3). Meanwhile, Table 4 shows that Stellenbosch's highly productive agricultural land in 2000 was significantly transformed to other uses by 2010, particularly recreation (113.4 ha), cluster housing (61 ha), as well as smallholdings and vacant land (i.e. other) (46.6 ha). Likewise, open space was reduced by 19.7 ha (-19%) as a result of a significant transition to informal (17.8 ha), industrial (8.3 ha), recreation (7.1 ha) and residential use (3.4 ha).

Fig. 7 portrays the land use changes between 2000 and 2010 according to urban and non-urban uses. Urban-to-urban changes are more sustainable than changes from non-urban to urban which imply loss of agricultural land and natural ecosystem services, hence adding adverse socio-economic and environmental costs. The most unsustainable (i.e. non-urban to urban) changes occurred in De Zalze, Kayamandi, Welgevonden, Paradyskloof, Die Boord and northern parts of Idas Vallei. Many of these changes led to loss of agricultural land and ecosystem services. Urban-to-urban land use changes occurred throughout Stellenbosch, the most significant ones in the western parts of Kayamandi. There were no cases of urban uses changing to non-urban uses.

Analysis of LUC is an effective way of gauging the sustainability trajectory of Stellenbosch, because each change contributes distinctively to sustainable urban development. Losses of agricultural land and open spaces, as well as the significant gains in informal settlements and minimal gain in transportation use do not augur well for sustainable urban development. The reduction in open space and agricultural land has a negative effect on sustainable urban development because these uses act as heat sinks and carbon sequestration spaces (Comber et al., 2008) and as habitat for animals and infiltration sinks. The results can be higher temperatures, reduction in biodiversity, increased runoff and loss of fertile

Table 4
Net land use transition measured in hectares in Stellenbosch between 2000 and 2010.

Landuse	Agriculture	Cluster housing	Commercial	Community	Education	Government	Industrial	Informal	Mixed	Nature reserve	Office park	Open space	Other ^a	Recreation	Residential	Transportation	Total change
Agriculture	61.0	-61.0	-7.2	0.0	-0.6	15.3	0.0	0.0	-1.5	0.0	-6.0	-15.5	-46.6	-113.4	-12.6	0.0	-249.0
Cluster housing	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	62.6
Commercial	7.2	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	9.5
Community	0.0	0.0	0.0	0.0	0	0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.6
Education	0.6	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	3.1	0.5	0.0	0.0	0.0	4.2
Government	-15.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-15.3
Industrial	0.0	0.0	-0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.3	0.0	0.0	0.0	0.0	7.5
Informal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.8	0.0	0.0	0.0	0.0	17.8
Mixed	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	0.0	5.4
Nature reserve	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Office park	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	0.0	0.0	0.0	9.9
Open space	15.5	-1.6	-1.5	-0.6	-3.4	0.0	-8.3	-17.8	0.0	0.0	0.0	-8.9	8.9	-7.1	-3.4	-0.4	-19.7
Other	46.6	0.0	0.0	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	-3.9	0.0	0.0	0.0	0.0	0.0	33.3
Recreation	113.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.1	0.0	0.0	0.0	0.0	120.5
Residential	12.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-3.9	0.0	0.0	3.4	0.0	0.0	0.0	0.0	12.1
Transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.4

^a Note: 'Other' consists of smallholdings and vacant land.

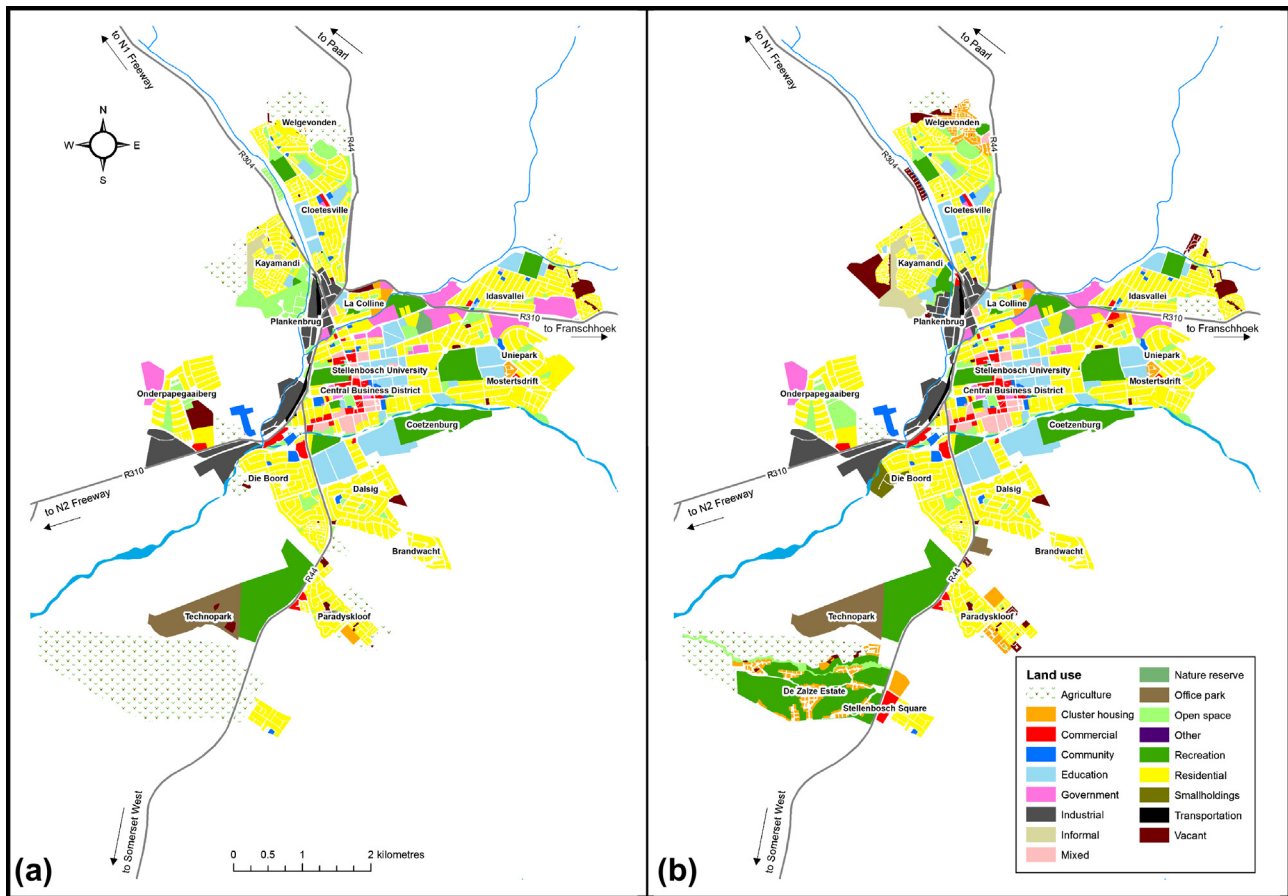


Fig. 6. Land use in Stellenbosch, (a) 2000 and (b) 2010.

agricultural land, all of which threaten the achievement of a sustainable urban environment (Yang et al., 2009).

The large increase in informal settlements and marginal increase in transportation are a concern. The notable growth in informal settlements indicates poor health of the urban system characterised by substandard shelter, overcrowding, lack of basic infrastructure and services, poverty and inadequate housing delivery (UN-HABITAT, 2002). The small change in land uses associated with transportation (from 6.3 ha in 2000 to 6.7 ha in 2010) also affects sustainable urban development negatively. During the study period only one new formal transit station (Bergzicht taxi rank) was established despite an 8.3% annual increase in population. No intra urban bus service is available and many local residents must rely on the erratic taxi service for public transport (Stellenbosch Municipality, 2011). This encourages use of private motor vehicles, which has resulted in increased congestion (Eikestad-Nuus, 2012), as well as more VMT and the emission of green-house gasses (GHGs).

By contrast, the significant gains in cluster housing (468%) and mixed use (25%) have a positive effect on sustainability because these land uses reduce environmental and economic costs through more efficient use of space (Guindon & Zhang, 2005). Cluster housing, as in Welgevonden Estate and De Zalze Estate, promotes spatial and civic integration, although the latter merit is a debated issue (National Research Council, 2009). Growth in mixed-use areas signals a sustainable urban development path because mixed use encourages interaction, spatial integration of activities (which enables ease of access and greater modal choice) (Urban Land Institute, 2010), use of NMT and a reduction in VMT (which reduces energy consumption and GHG emissions) (Zhang, Wu, and Shen, 2011).

The strong gains in commercial and industrial land (28% and 8% respectively) are indicative of increases in economic and employment opportunities which have positive effects on the socio-economic sustainability of Stellenbosch. The significant increase (17%) in office space between 2000 and 2010 is largely attributable to growth of Technopark, the office and industrial park in the south-western Stellenbosch. This has enhanced Stellenbosch's importance as a financial and innovation hub. The increase in office space in Stellenbosch can imply growth of economic opportunities, a better land use mix and more local work-related destinations as opposed to out-of-town destinations, thus reducing VMT and GHGs. Moreover, Technopark is located within a radius of 5 km from most major services (CBD, Stellenbosch Square and Stellenbosch University) and because it is a mixed-use development some trips will be intracomplex which can help in reducing VMT and GHG emissions (Frank & Engelke, 2001). However, Technopark is inaccessible to public transport, which often encourages automobile use as a mode of transport to and from work thereby increasing VMT and GHGs.

The analysis of LUC has revealed that some transitions in land use (e.g. cluster housing, mixed use, commercial use, and industrial) have a positive bearing on the town's sustainability. The sustainability trajectory of office space is indeterminate as it is difficult to gauge the cost and benefits of office use in Stellenbosch. Conversely, the changes in open space, agriculture, informal settlements and transportation are a presage of sustainable urban development. It is noteworthy that most of the growth occurred in the western (Kayamandi), southern (De Zalze Estate and Stellenbosch Square) and northern (Welgevonden Estate) parts of Stellenbosch (Figs. 6 and 7), while the consumption of agricultural land and open space by urban uses, as well as the increases in other uses

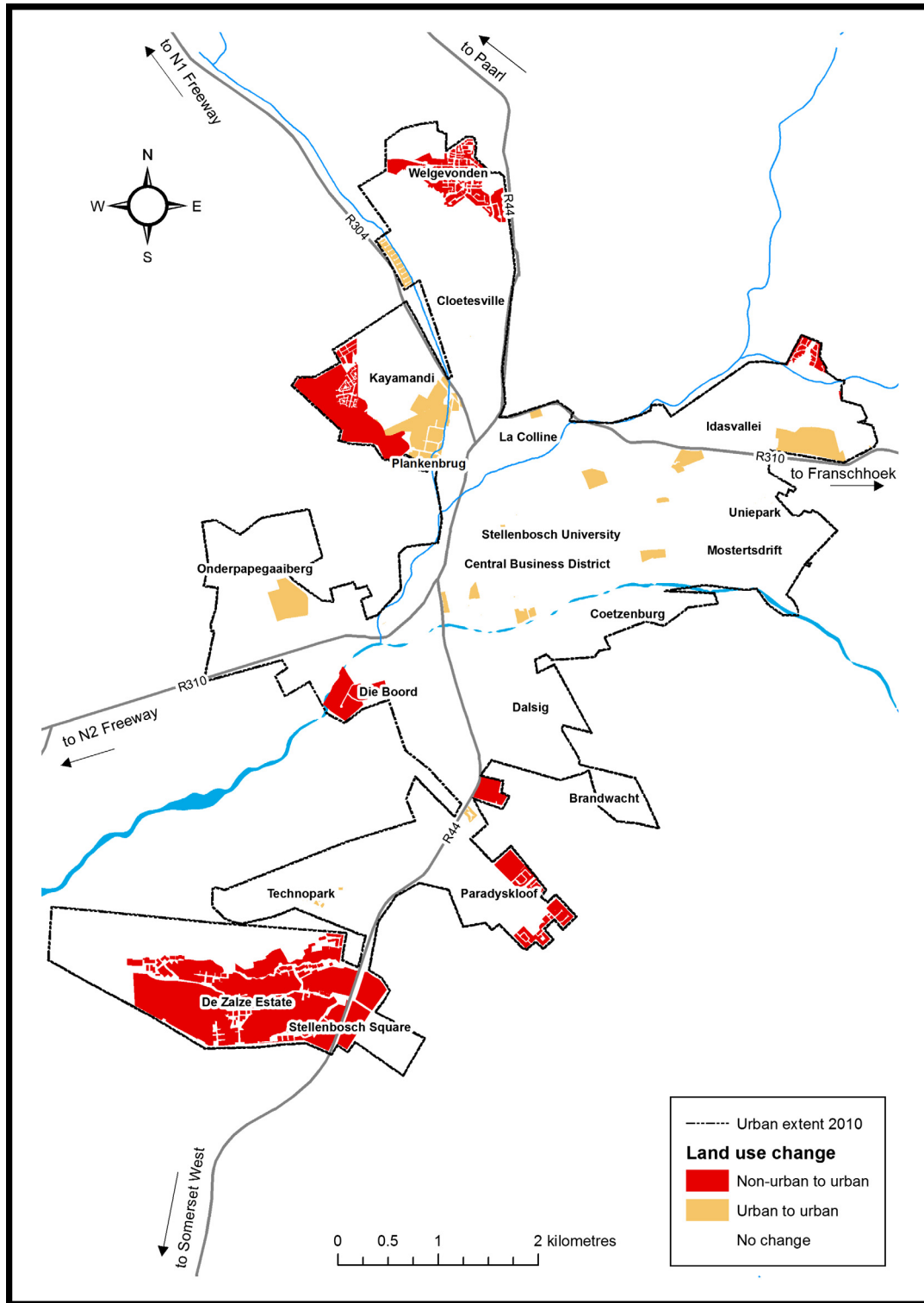


Fig. 7. Land use change map.

(i.e. smallholdings and vacant land) clearly indicate urban sprawl. The effects of LUC on sustainability are highlighted in the next section which considers the GLUM and LLUM of Stellenbosch.

Land use mix indexes

The GLUM index for Stellenbosch is relatively high at 0.74 and 0.72 in 2000 and 2010 respectively. This suggests relatively high

heterogeneity of land use patterns as well as good spatial integration. According to Song and Rodriguez (2005), high GLUM denotes a high level of social integration and is a proxy for the vibrancy of a town’s civic life. This does not reflect racial integration as Stellenbosch’s land use still reflects country’s history of spatial segregation (Donaldson, Morkel, & Paquet, 2012; James, 2000; Naudé, 2008; Todes and Watson; 1986). Given that South Africa’s post-apartheid spatial policy is geared toward integrated development,

the GLUM index is useful for measuring the spatial as well as social integration of towns.

Fig. 8 shows the distribution of LLUM for 2000 and 2010. The areas that had a low (0.4 or less) LLUM in 2000 included De Zalze, Technopark, Die Boord, Dalsig, Mostertsdrift and Uniepark. This points to a lack of diversity in land use, meaning high social, environmental and economic costs which presage unsustainable urban development. Note that in 2000 the De Zalze area was used for agricultural purposes (Fig. 6) hence its low LLUM. LLUM in this area increased significantly by 2010 with the transition of farmland to a residential golf estate (Fig. 6b). Thus the LLUM index is not a good indicator of sustainable urban development in this particular area because it suggests that urban sprawl has a positive effect on sustainable urban development. The LLUM in the Mostertsdrift and Uniepark areas remained low from 2000 to 2010. Interestingly, the area with low LLUM seems to have spread towards Coetzenburg due to changes from residential to mixed use and the locating of the new Stellenbosch Institute of Advanced Study (STIAS) on the University's Mostertsdrift terrain. LLUM increased slightly in Die Boord with a number of office developments there. Areas that had consistently high (>0.6) LLUM for both dates include Welgevonden, Kayamandi (western area), Plankenbrug, La Colline and Onderpapegaaiberg, suggesting that the diversity of land uses in these areas have low economic, social and environmental costs.

Kayamandi a 'township' created to house workers during apartheid, is relatively sustainable due to a high LLUM (<0.6). This is due to the complementary uses close to each other and social networks which reduces socio-economic costs. For example, Kayamandi is within a 3 km radius of Plankenbrug industrial area which is a major source of employment, close to the CBD, Kayamandi shopping mall and community facilities. Reduction in environmental costs

is only inferred given the close proximity of use which implies there will be less use of automobiles which reduces GHGs. This is in stark contrast to large sections of Uniepark and Mostertsdrift with very low LLUM (>0.6) because it is largely a residential area with little complimentary uses, which entails less vibrancy. Residents will have to use automobiles to access services such as industry, community facilities, the CBD and places of employment.

Land use frequency

The maps of LUF for Stellenbosch (Fig. 9) show slight increases between 2000 and 2010, particularly in the central and southern parts of the town. As with LLUM, the increase in LUF in the south can be attributed to the De Zalze Estate and Stellenbosch Square shopping centre developments. The LUF remained relatively constant in the rest of the town over the decade.

Visual comparison of Figs. 8 and 9 provides evidence that LUF does not necessarily correspond to LLUM. For example, neighbourhoods abutting the CBD such as Coetzenburg and La Colline have a high (>10) LUF, but a low (<0.6) LLUM. This is because LLUM is affected by the proportion of area of land uses in a neighbourhood while LUF denotes number (count) of land uses. A large number of relatively small spatial units with different land uses will consequently produce a high LUF, but may produce a low LLUM if one large spatial unit is present. This makes LUF less reliable than LLUM for capturing diversity, isolation, distribution and clustering of land uses (Song & Rodriguez, 2005). Therefore LLUM is a good indicator in capturing the socio-economic costs associated with sustainable land use. LLUM should not be used in isolation as it fails to incorporate urban sprawl, as demonstrated in the Stellenbosch Square (south) and Welgevonden (north) developments (Fig. 7).

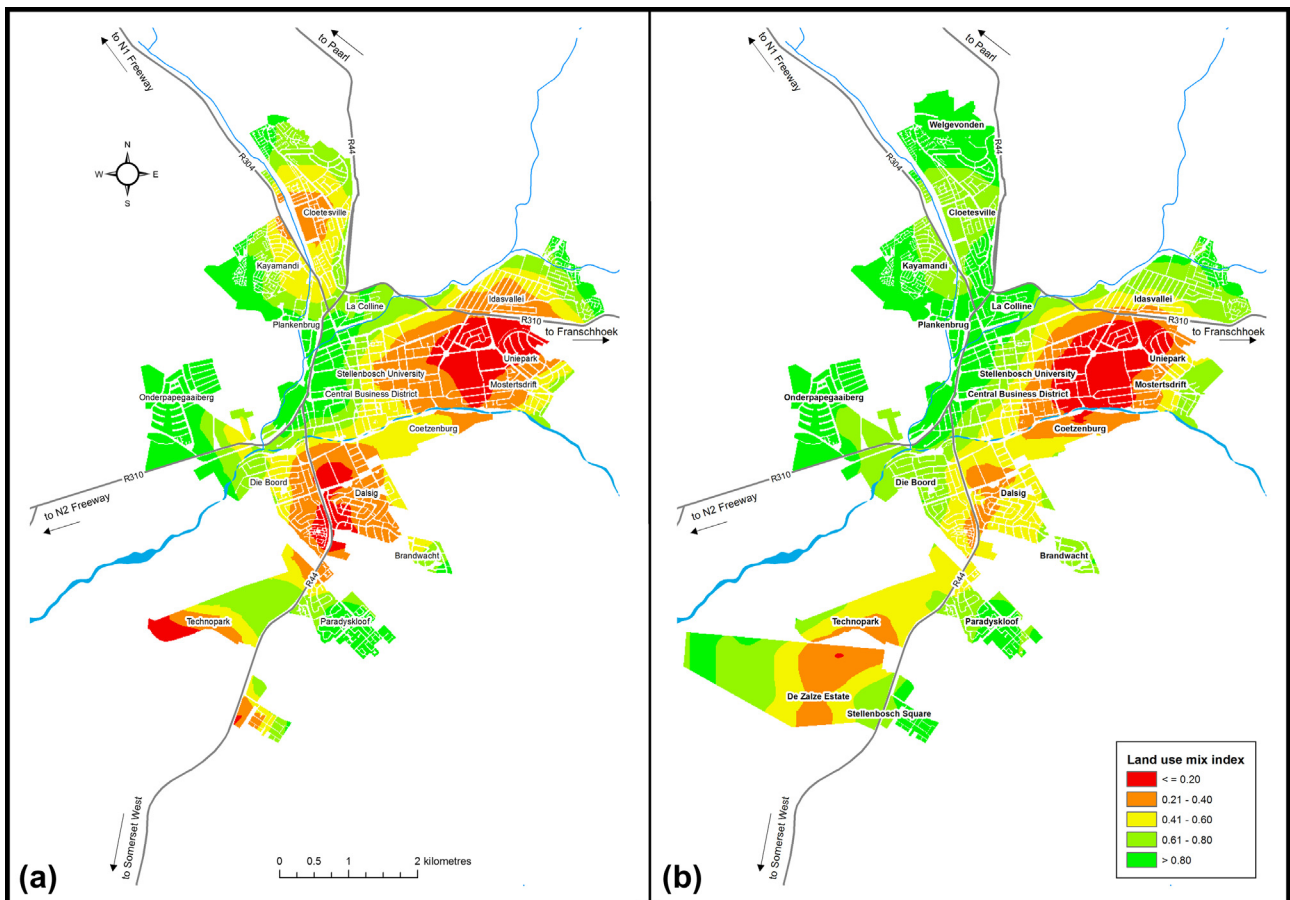


Fig. 8. Distribution of local land use mix index (LLUM) values in Stellenbosch, (a) 2000 and (b) 2010.

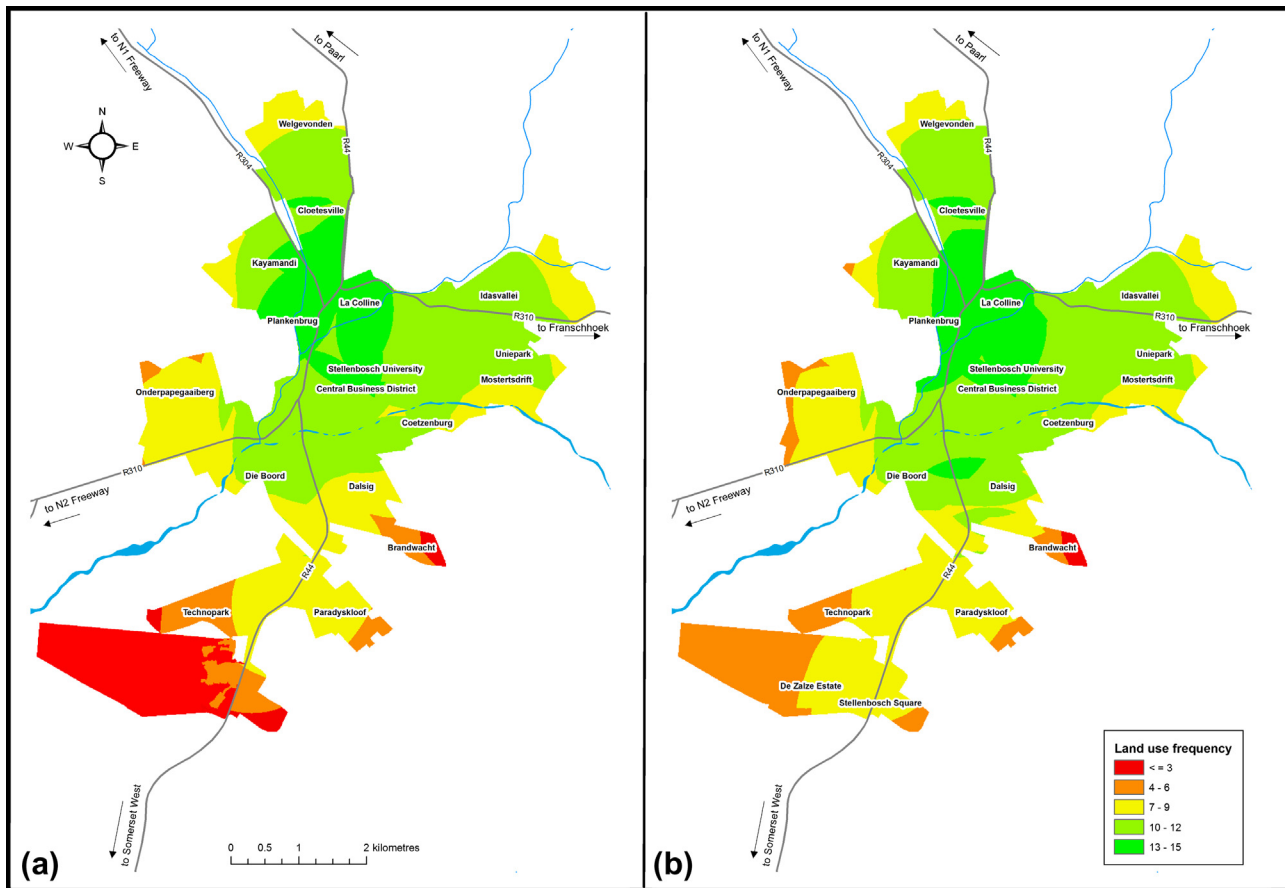


Fig. 9. Land use frequency (LUF) distribution in Stellenbosch, (a) 2000 and (b) 2010.

Practical implications and conclusion

Land use maps derived from earth observation data can be used to calculate GLUM, LLUM and LUF. These indicators can help local planning authorities to make better decisions regarding land use. The land use change analysis revealed that the informal settlements (in western Kayamandi) have grown significantly. Such developments are often associated with poor service delivery and living conditions and should be curtailed if Stellenbosch is to progress towards sustainable urban development. Moreover, the indicators suggested that cluster housing coupled with mixed use developments are relatively sustainable particularly in Welgevonden, De Zalze and Stellenbosch Square. The indicators can also be used as a basis to guide decisions on infill development to promote a better land use mix. For example Mostertsdrift with a low LLUM (<0.6) can be targeted for infill development with complementary land uses such as residential, offices, hi-tech industrial and commercial uses. Stellenbosch Municipality has an infill policy in place (Stellenbosch Municipality, 2011).

DCA was employed as a structured and simple model to develop a framework using earth observation data and GIS analysis to derive the GLUM, LLUM and LUF for assessing in which direction sustainable urban land use planning is evolving: i.e. toward or away from desired progress. This study has demonstrated that the observation of subtle changes in LLUM and LUF over time can assist in the identification of potential problem areas. Indicators such as LLUM and LUF can also help planners to produce sustainability reports that are less subjective and descriptive and they may serve as mechanisms to monitor interventions. The indexes are normalised, making them transferable to other areas and can even be used for

comparing areas with one another. More research is needed to determine how these indexes can be used in combination with other sustainability indicators (e.g. Moran index, building density, height and impervious surfaces) to improve decision making. These indicators are required to confirm the environmental costs of sustainable land use planning. The advent of very high-resolution earth observation data such as GeoEye, WorldView2 and Quickbird, as well as the continuous improvement of GIS analysis tools, will promote better monitoring of sustainable urban planning in developing countries.

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