

The Morphology of African Cities

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WORLD BANK GROUP

Social, Urban, Rural and Resilience Global Practice Group

December 2016

Abstract

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be linked to transportation. Second, it takes a closer look at the land cover in each city using a semi-automated texture based land cover classification that identifies neighborhoods that appear more regular or irregularly planned. Lastly, for the higher resolution images, this work studies the changes in the land cover classes as one moves from the city core to the periphery. This work also explored the classification of slightly coarser resolution imagery which allowed analysis of a broader number of cities, sixteen, provided the lower cost.

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JEL classification: R14, R30, O21

Keywords: Urban Development; Geographic Information Systems; Urban Land Supply and Markets; Urban Participatory Planning; Urban Governance and City Systems

Background¹

According to a 2014 United Nations World Urbanization Prospects report, roughly 40 percent of Africans live in urban areas, and by 2050 that number is expected to rise above 55 percent.² Once considered a predominately rural continent, Africa is now experiencing rapid urbanization. While this transformation offers African cities a tremendous opportunity for economic growth, it is also necessary to ensure that these cities become livable places that can attract both firms and people. As African cities rapidly grow and densify, governments face the challenge of supporting a swelling population with adequate infrastructure and services.

As a nation urbanizes, more people have the chance to benefit from the economic and social opportunities cities have to offer. These benefits include access to a larger job markets and higher quality public services. For those looking to start a business, cities offer a larger pool of customers and closer proximity to suppliers. But such rapid growth also brings about great challenges for governments. A swelling population can overwhelm a city's infrastructure in various ways: clogging the streets with traffic, generating a housing shortage, and overloading its public services. If poorly managed, growth can exacerbate inequalities and lessen access to services, employment and housing- creating an environment where the benefits of a city are not equitably shared. Evidence of this inequality is reflected in the high rates of urban poverty in African cities. According to the United Nations, urban poverty in Sub-Saharan Africa is growing at a rate of 3.6%, double the global rate.³

Population increase places high demands on infrastructure and housing. A recent UN Habitat report stresses that the "lack of modern infrastructure is an impediment to Africa's economic development and a major constraint on poverty reduction."⁴ African cities lag behind other low income areas when it comes to high quality roads and affordable housing. A recent study found that the average density of paved roads per capita in Sub-Saharan Africa is roughly 65% less than that of other low-income countries outside the region.⁵ The supply of formally constructed and affordable housing in Africa also remains low. The Centre for Affordable Housing Finance in Africa estimates that only 10-15% of Africans can afford the cheapest housing option available through mortgage financing. As a result, slums and unregulated housing are also expanding at unprecedented rates, with roughly 70% of all African city dwellers living in 'slum' like conditions.⁶

Smart land use planning will be instrumental in limiting the growth of urban slums and encouraging the construction of quality housing. Efforts in integrating transport investments with land use management decisions can improve a city's mobility, thus connecting more residents to more jobs and giving them more freedom and options when picking a place to live. In addition, creating flexible yet enforceable building regulations can encourage more livable and durable construction. Lastly, planners should

¹ This work was done as part of the Spatial Development of African cities project (P148736) and funded by UK DFID through the MDTF for Sustainable Urban Development TF071544.

² United Nations. Departments of Economic and Social Affairs, World Urbanization Prospects 2014.

³ United Nations Population Division, World Urbanization Prospects: The 2011 Revision (New York: United Nations, 2012).

⁴ UN Habitat Infrastructure for Economic Development and Poverty Reduction in Africa 2011.

⁵ Vivien Foster and Cecilia Briceno-Garmendia. Africa's Infrastructure: A Time for Transformation. 2009.

⁶ Tibaijuka, A.J., 'Africa on the move: An urban crisis in the making', United Nations Human Settlements Programme, December 2004, <http://www.preventionweb.net>.

prioritize expansion of public services to reach marginalized neighborhoods, so that basic services, such as waste collection, water supply, and electricity grids, reach even the most poor.

Accurate spatial data and city maps are a crucial ingredient to smart land use and city planning. Historically, shanty areas have often been omitted from city planning maps, making it difficult to address the improvements these neighborhoods need. When the master plans for many African cities were drafted, the current rates of growth and poverty were unforeseen.⁷ By accurately identifying and including slums in city land maps, policy makers will be better equipped to properly guide the planning of inclusive urban development. Furthermore, precise and up-to-date maps of a city can help facilitate better coordination between transportation projects and current land use, and prioritize areas in need of housing upgrades.

Urban developers can leverage spatial data to not only improve planning, but also to better understand the interactions between firm locations, residential growth, and unplanned expansion. Advances in geographic information systems (GIS) and satellite imagery provide policy makers with new tools to analyze the changing morphology of cities. A better understanding of the composition of cities, and how land (residential, commercial, green space) changes throughout a city, can provide helpful insights for city planning. For example, In London city planners have relied upon GIS to plan and create more “livable streets” that encourage walking, cycling, and transit trips. Planners depend upon land use data and transport layers to target arterial roads and intersections that could be redesigned without significantly impacting the movement of motorized vehicles, but at the same time benefiting the greatest number of pedestrians.⁸ In Madrid developers consult a GIS application before breaking ground on new construction. Following the national guidelines and regulations, the system identifies buildable land, ensures compliance with historical preservation rules, and informs users of land use restrictions.⁹ These are just a few of many examples where accurate and timely spatial data is a crucial component to planning and decision making.

⁷ Watson, Vanessa and Batatunde Agbola. 2013. Who will Plan Africa’s Cities? Africa Research Institute: Understanding Africa Today. <http://www.africaresearchinstitute.org/publications/counterpoints/who-will-plan-africas-cities/>.

⁸ UN Habitat. 2013. Streets as Public Spaces and Drivers of Urban Prosperity. Page 83.

⁹ SGGAGE. GIS Application: ESRI Solutions City Planning <https://sggage.wordpress.com/2011/01/12/gis-application-esri-solutions-city-planning/>.

In what follows, this paper illustrates how the capabilities of GIS and satellite imagery can be harnessed to explore and better understand the urban form of several large African cities (Addis Ababa, Nairobi, Kigali, Dar es Salaam, and Dakar). To allow for comparability across very diverse cities, this work looks at the above mentioned cities through the lens of several spatial indicators and relies heavily on data derived from satellite imagery. First, it focuses on understanding the distribution of population across the city, and more specifically how the variations in population density could be linked to transportation. Second, it takes a closer look at the land cover in each city using a semi-automated texture based land cover classification that identifies neighborhoods that appear more regular or irregularly planned. Lastly, for the higher resolution images, this work studies the changes in the land cover classes as one moves from the city core to the periphery. This work also explored the classification of slightly coarser resolution imagery which allowed analysis of a broader number of cities, 16, provided the lower cost.

URBAN DENSITY

Urban economists have long argued that a compact and well-connected city is necessary for the development of an economically strong and livable city. The benefits of dense cities are well documented and empirically proven. Advantages include, among many others, higher firm and worker productivity¹⁰ and improved consumer access to goods and services.¹¹ In dense cities, firms face stiff competition, thus making only the most efficient and productive likely to survive. When nestled among many other businesses, firms are also encouraged to interact more frequently with their neighbors, promoting a drop in cost and an increase in speed of business transactions.¹² Consumers can also benefit from this density, with the opportunity for shorter commutes, lower travel costs, and more variety of available products.¹³ Additional benefits include reduced per capita energy consumption and greater access to running water, sewerage, waste disposal, and public institutions like schools, hospitals and law enforcement.¹⁴

There are several well documented methods to calculating urban density. The first and most common approach is to divide total population living within the city limit by the total area of the city. Figure 1 shows the overall density of the four African cities in this study, and compares them to other major cities in the world.

Figure 1 – Overall density of African cities compared to several international cities

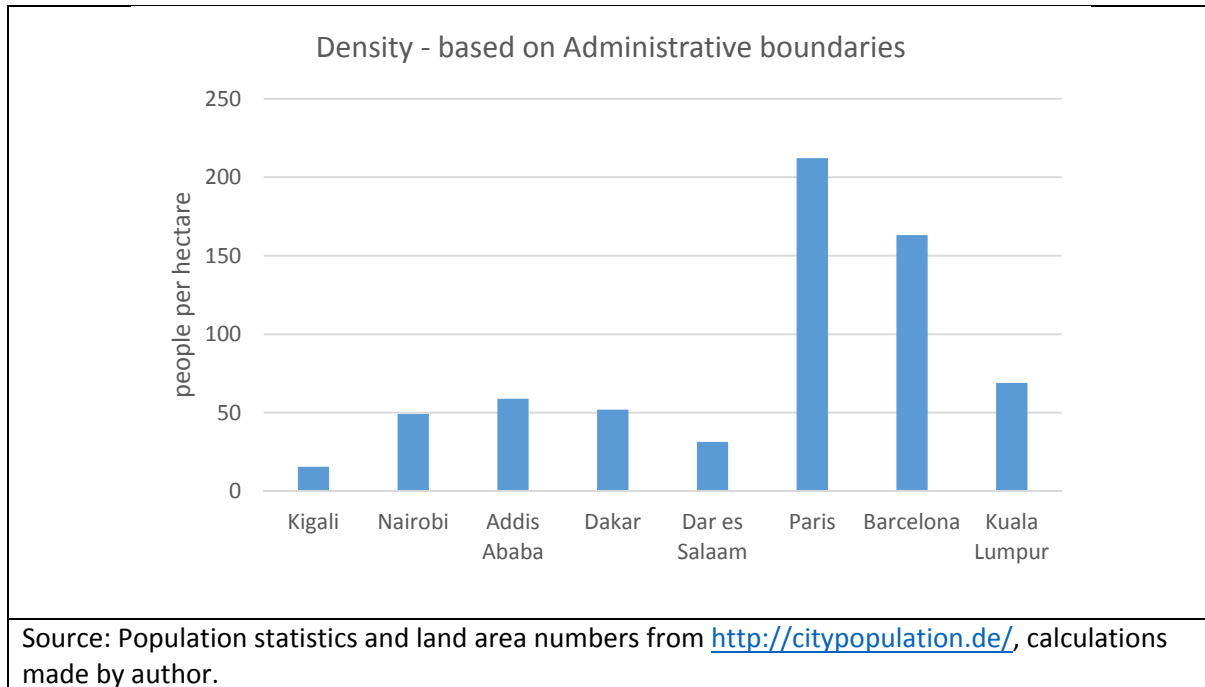
¹⁰ Melo, Patricia C., Daniel J. Graham, and Robert B. Noland. 2009. A meta-analysis of estimates of urban agglomeration economies. *Regional Science and Urban Economics* 39(3):332–342.

¹¹ Glaeser, Edward L., Jed Kolko, and Albert Saiz. 2001. Consumer city. *Journal of Economic Geography* 1(1):27–50.

¹² Pierre-Philippe Combes, Gilles Duranton, Laurent Gobillon, Diego Puga, and Sébastien Roux in their article 'The productivity advantages of large cities: Distinguishing agglomeration from firm selection', published in *Econometrica* 80(6), November 2012: 2543-2594.

¹³ Couture, Victor. Valuing the Consumption Benefits of Urban Density, Preliminary Draft: 26 November 2012. University of Toronto.

¹⁴ Larivière, Isabelle and Lafrance, Gaetan. Modelling electricity consumption of cities: effect of urban density. *Energy Economics*. Volume 21, Issue 1, 1 February 1999, Pages 53–66.



While this measurement provides a helpful indication of overall density, it relies on administrative boundaries rather than the ‘true’ physical boundary of the city, and does not provide insight into variation within the city’s landscape. To overcome this limitation, alternative more in depth approaches have been developed which ignore political lines and examine the varying levels of density throughout a city. Using data sets derived from satellite imagery and disaggregated population estimates, modeled population grids such as Landscan, can be used to measure how a city’s population density changes across space. Referred to as an urban density profile, this graph can shed light on how a city’s population changes as one moves away from the center to the periphery. Previous studies by Bertaud (2001, 2003),^{15 16} Muth (1967)¹⁷ and many others have demonstrated the value of density profiles when studying urban form.

A variation in a city’s population density is arguably more influential and indicative of its performance than its average density. Following a monocentric model that assumes most jobs are located in the city center and that residents will tend to cluster around those jobs, a population gradient will show a higher concentration of people living near the city center than the periphery. In this simplified model, residents will choose to live near the center because they are likely to benefit from shorter commutes to work, school and other destinations.¹⁸

If the gradient reveals something different than a gradual decline, such as a spike or dip in population density, it might be indicative of unusual land use. For example, if a city has a population density

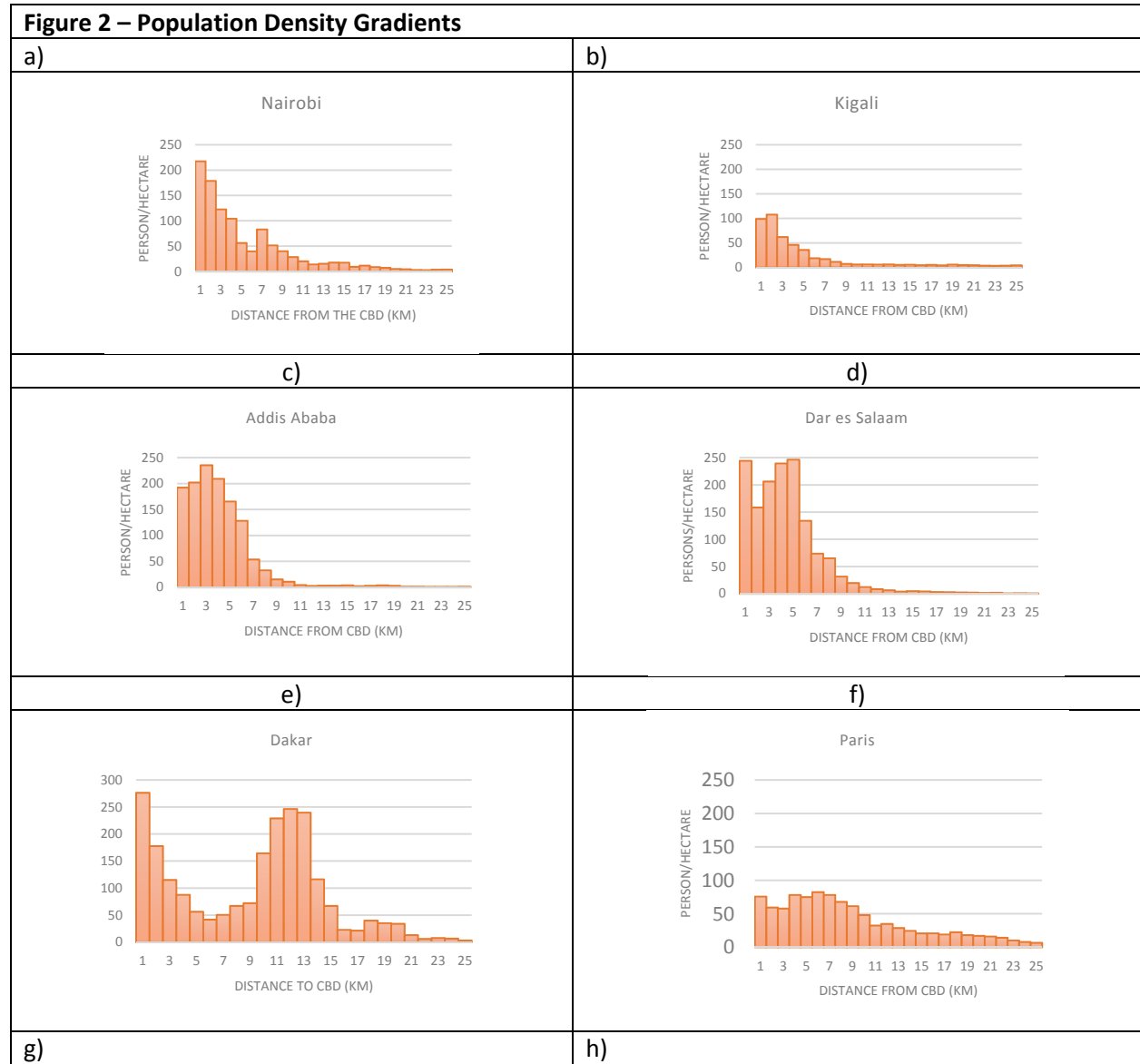
¹⁵ Bertaud, Alain. (2001) Metropolis: A Measure of the Spatial Organization of 7 Large Cities. 29 April 2001.

¹⁶ Bertaud, Alain and Stephen Malpezzi. (2003) The Spatial Distribution of Population in 48 World Cities: Implications for Economies in Transition.

¹⁷ Muth, Richard. (1967). Determinants of Investment Behavior. Chapter title: ‘The Distribution of Population Within Urban Areas’ NBER (p. 271 - 299).

¹⁸ Bertaud, Alain. Metropolis: A Measure of the Spatial Organization of 7 Large Cities. 29 April 2001.

gradient that generally increases rather than decreases, this trend may be telling of the government’s land use policies (as seen in Moscow where the government built large peripheral estates, or Johannesburg where residential land was highly regulated). A sharp increase in population density toward the periphery of the center might be indicative of an efficient and effective transportation system that allows residents to comfortably live in the outskirts of the city and still reach jobs in the center (as seen in Paris and to some degree London). Whatever the trend, urban population density gradients provide a comprehensive way to capture the distribution of a city’s population and offer insight into the dynamics of the city’s land use.



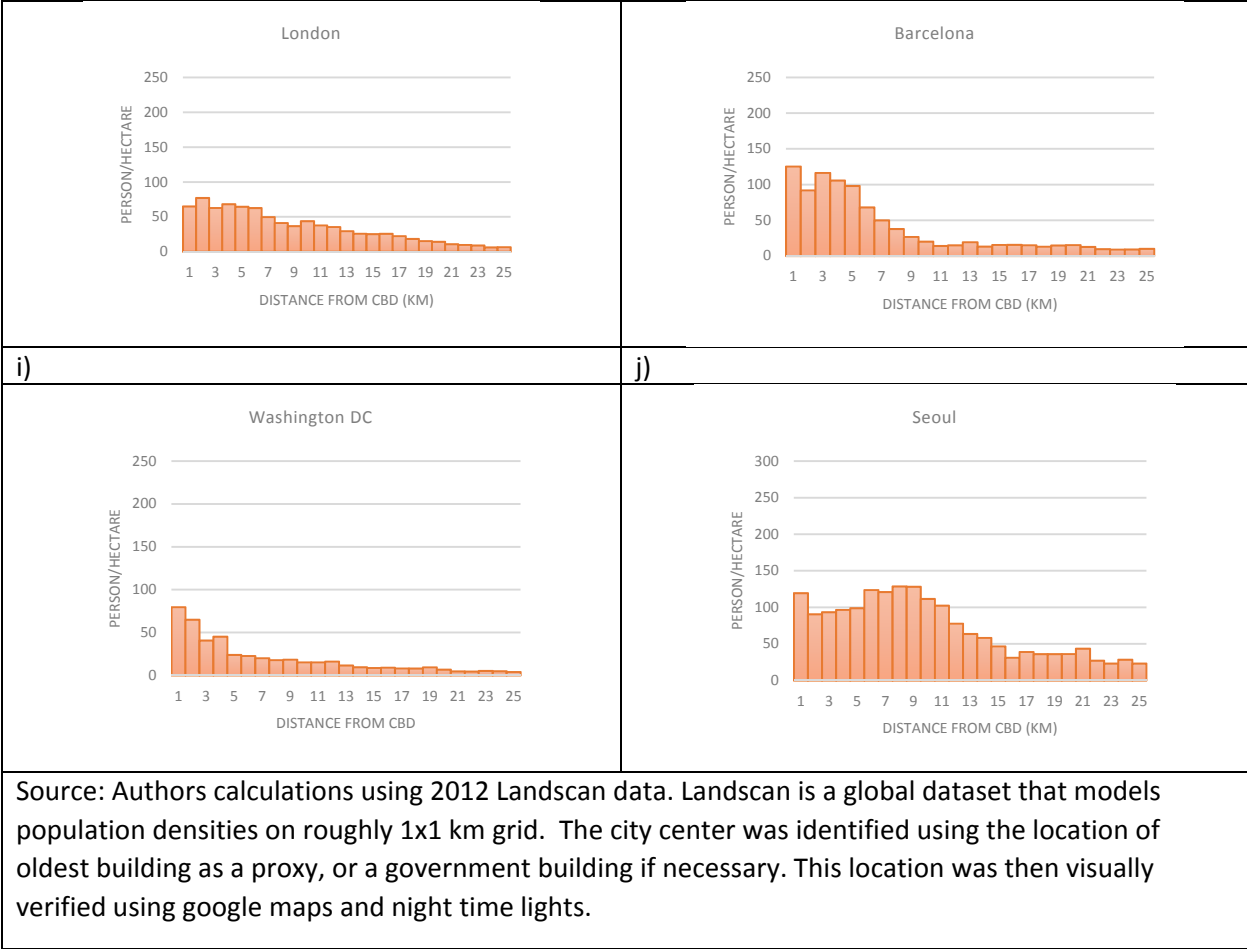


Figure 2 above show the density profiles for Nairobi, Kigali, Addis Ababa, Dar es Salaam, Dakar and other major international cities. In the African cities of Nairobi, Kigali, Addis Ababa, Dar es Salaam, there appears to be a high concentration of population near the CBD and a rapid decline as one moves towards the periphery, suggesting a strong monocentric pattern in all cases. Dakar’s is a bit of an anomaly, with its unique physical geography strongly influencing its gradient. Located on a narrow peninsula, data averages are greatly influenced by land restrictions.

In Dar es Salaam, there is a slight dip in density between 1 and 3 km of the city center, due to a large industrial park that is only a few kilometers from the CBD. In Nairobi, a similar drop is seen slightly further out, and can be attributed to a portion of land taken up by an airfield base and railroad infrastructure. In Addis Ababa’s gradient, a slight immediate rise and then fall is consistent with the existence of a large number of parks and government buildings right in the heart of the CBD. Lastly, while Kigali is a considerably smaller and less dense city, it shares a similar monocentric pattern as the other three cities analyzed.

These gradients also reveal that, despite the variation in the size of the city footprints, a quick decline in population density is observed for all African cities roughly 6-8 kilometers from the CBD. This could be an indicator that many people are forced to live within walking distance from their jobs. According to a 2013 UN report, “the share of walking trips in Sub-Saharan Africa is higher than in any other region of

the world.”¹⁹ For example, In Dar es Salaam, an estimated 70 percent of all travel is done on foot and roughly 20 percent is by minibus.

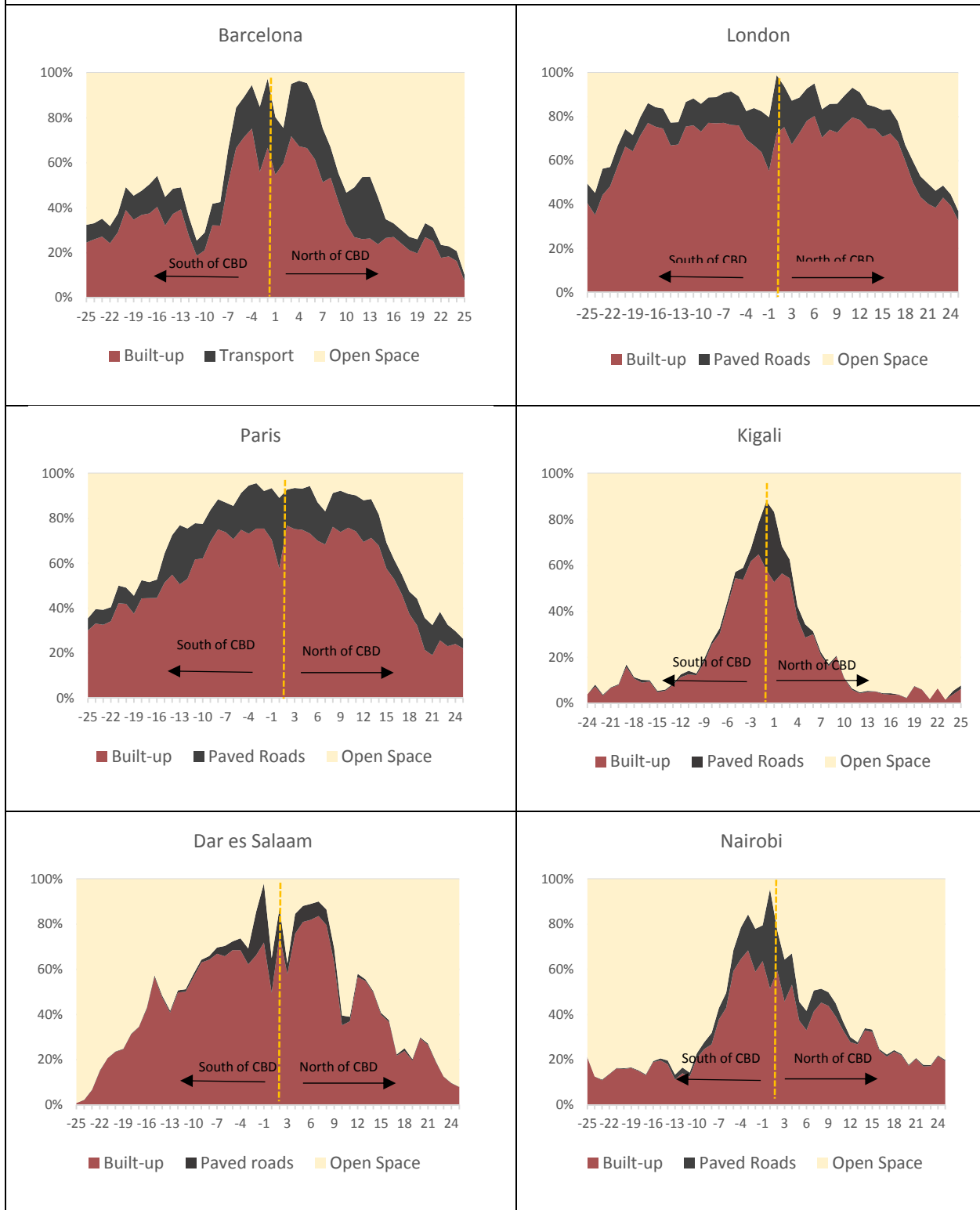
In African cities, residents lack access to efficient and affordable transit systems and are thus forced to live close to the city center. In contrast, cities like Barcelona, London, Washington DC and Paris all have extensive and proficient transport systems. Barcelona has a population of 1.6 million, similar in size to Dar es Salaam’s 1.4 million, but in Barcelona 33 percent of commuters rely on public transportation, while in Dar es Salaam only 5 percent of its residents use public transit. As a result, the gradients in Figure 2 show African cities have a steeper decline in population density than the European cities in Figure 2 with well-developed transport infrastructure. While all the cities seem to follow a monocentric model, in Africa density drops off more dramatically than in European and Asian cities.

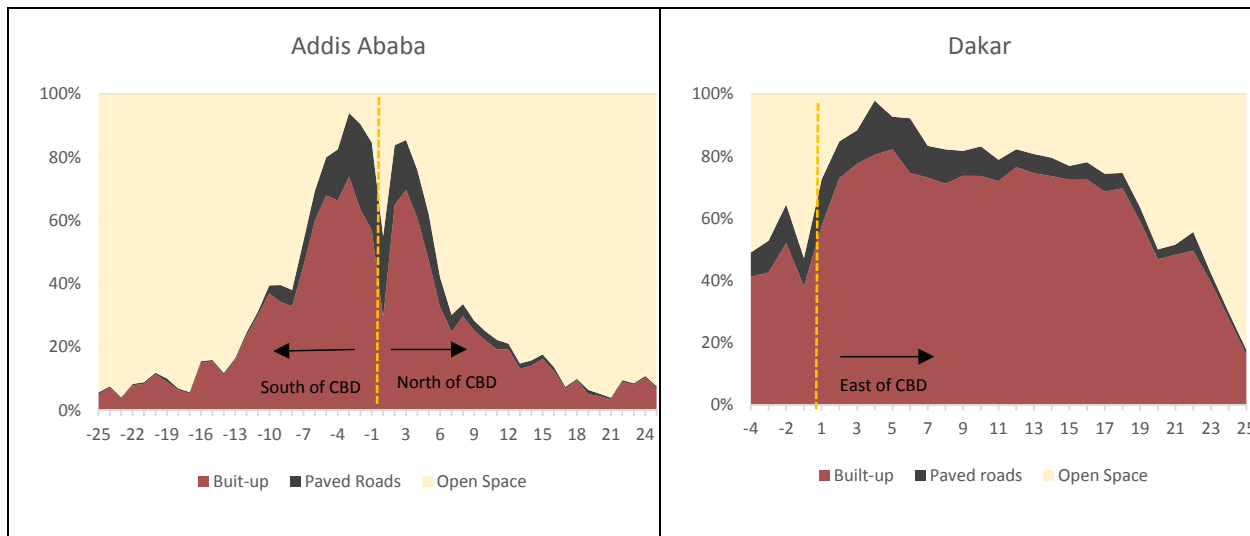
In a smartly planned well-functioning monocentric city, one would expect to see a high peak in population density near the city center, followed by a gradual decline moving away from the city center. A strong and far reaching urban transit system allows residents to efficiently and affordably reach jobs and amenities that might be many miles from their homes. This gives residents the freedom to live in the periphery of the city and still benefit from the job opportunities in the urban core. In European cities a high proportion of central and peripheral land is dedicated to transport, in contrast African cities tend to have a much lower share of land used for transport with a rapid decline near the edges of the city. The land cover charts shown in Figure 3 provide a visualization of how the share in land cover changes as one moves to either the north or south of the city center. In Paris, roughly 16% of the land within 10kms of the CBD is dedicated to paved roads. In urban planning literature Paris is often held up as an example of a city with a sustainable and effective urban form.²⁰ With a prominent core and high land use density, Paris also benefits from high accessibility through a well-developed road network. In contrast, a city like Dar es Salaam devotes only 7% of its land within 10kms to paved roads, and beyond 12kms the amount of paved roads drops off rapidly. This dramatic drop is consistently observed in almost all the Africa cities examined in this study, and is suggestive of low peripheral connectivity and limited accessibility of the city’s core.

¹⁹ UNEP (2013) Share the Road: Design Guidelines for Non Motorised Transport in Africa.

²⁰ Rodger L. Kemp and Carl J. Stephani. Global Models of Urban Planning: Best Practices Outside the United States. Originally published as “Paris: A New Blue Print” Urban Land Vol. 69 No. ¾ (March/April 2010), by the Urban Land Institute, Washington DC.

Figure 3 Change in land share by distance to the city center (CBD)





Source: Author's calculations using land classification from high resolution satellite imagery (see annex A for more details) and Felkner, Lall, & Lee (Forthcoming). European cities were analyzed using Urban Atlas data layers published by the European Environment Agency (EEA) (<http://www.eea.europa.eu/data-and-maps/data/urban-atlas>)

LAND COVER CLASSIFICATION

Poorly managed, dense urban areas can become congested, polluted, and poorly equipped to provide basic services for their inhabitants. In Africa, evidence of this challenge is apparent in the growth of informal settlements; tightly packed small houses that have been constructed from nondurable materials. Households in these dense neighborhoods often lack sufficient living space, sanitation, electricity, and safe water. Historically, many governments have been reluctant to grapple with such settlements, weary of the social and political risks associated with displacing vulnerable populations.²¹ Furthermore, a lack of up-to-date and accurate spatial data on these areas adds to the challenge. In order for policy makers and planners to make well informed decisions, high quality maps are essential.

This study uses high resolution satellite imagery to detect and identify land that appears to have slum-like characteristics, or more accurately put, 'irregular' neighborhoods with tightly packed roofs, surrounded by minimal vegetation, and often irregular rooftop angles. This identification was achieved using a semi-automated classification approach that examines the texture and structural composition of various neighborhoods, and then groups land with similar patterns to the same class. This method was originally developed to accurately detect shanties in cities throughout the world, and has been proven effective in a diverse set of cities.²² It has since been adopted by the US Census Bureau and US Department of Energy's Oakridge Laboratory.²³ In this work, we also explored its ability to detect commercial/industrial land, barren land, and vegetation. Commercial and industrial areas were

²¹ UN Habitatat. Urban Patterns for a Green Economy: Leveraging Density.

²² Jordan Graesser et al. 2012 Image based Characterization of formal and informal neighborhoods in an urban landscape. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 5 (4) August:1164-1176.

²³ High-Resolution Urban Image Classification Using Extended Features: Data Mining Workshops (ICDMW), 2011 IEEE 11th International Conference Dec. 2011. Author: Vatsavai, R.R. Published by IEEE.

combined into a single class, due to the challenge of distinguishing between large factory buildings and large retail buildings.²⁴

Data and Classification Methodology

The imagery used in this paper was multispectral high-resolution imagery (>1m). To gain full coverage of each city, several scenes from multiple sensors were mosaicked to create a single seamless image.

For each city, high spatial resolution imagery containing 4 bands (Red, Green, Blue, and Near Infrared) was obtained. A combination of sensors (GeoEye, IKONOs, and Worldview) was necessary to obtain full coverage of each city. All scenes were then mosaicked and resampled to a resolution of 1m. Each image was captured between 2010 and 2013 and contained minimal cloud cover. All imagery and analysis layers are projected as WGS 1984 UTM Zones

Areas of interest (AOI) are defined using official administrative borders and local knowledge. An effort was made to include all the official city land and also areas of peripheral growth whenever possible. Due to the large size of the cities, and high spatial resolution of the imagery, the data were aggregated and summarized to a 0.5x0.5km grid. This larger unit of measure minimizes the effects of any single pixel misclassification and simplifies the data for better visualization.

Following the method outlined in Graesser et al. 2012, the images for each city were classified into six classes: Residential (Regular), Residential (Irregular), Commercial/Industrial, Vegetation, Barren, and Water. The built-up classes (Regular residential, Irregular residential, and Commercial/Industrial) were defined according to the image characteristics summarized in Figure 4. The natural environment classes (vegetation, water and barren) were classified using simple optical analysis.

Figure 4.		
Regular Residential Neighborhoods	Irregular Residential Neighborhoods	Commercial/Industrial Neighborhoods
<p>The majority of these neighborhoods have the following characteristics:</p> <ul style="list-style-type: none"> • Rooftop Area: 100m² to 300m² • Building Materials: Low variance • Rooftop Type: Flat or Slanted • Building Orientation: Homogeneous (structures face the similar ways to each other) • Building Shadow: May or may not be shadows • Road Type: Paved or Unpaved; intersect at 90 degree angles • Building Shape: more complex (more corners, more edges) • Housing Isolation: Houses may be isolated from other houses (beyond a 15m buffer) • Housing Density: Moderately packed housing units or sparsely packed housing units (room for yards/cars) 	<p>The majority of these neighborhoods have the following characteristics:</p> <ul style="list-style-type: none"> • Rooftop Area: 30m² to 100m² • Building Materials: High variance • Rooftop Type: Flat • Building Orientation: Heterogeneous (structures face different ways from each other) • Building Shadow: little to no shadow • Road Type: Unpaved; do not intersect at 90 degree angles; narrow or unidentifiable • Building Shape: least complex (4 corners and 4 edges = rectangle) • Housing Isolation: Houses must be within 15m of another house • Housing Density: Tightly packed housing units (no room for yards/cars) 	<p>The majority of these neighborhoods have the following characteristics:</p> <ul style="list-style-type: none"> • Rooftop Area: greater than 300m² • Building Materials: Low variance • Rooftop Type: Flat or Slanted • Building Orientation: Homogeneous (structures face the similar ways to each other) • Building Shadow: longer, dark shadows • Road Type: Paved or Unpaved; intersect at 90 degree angles • Building Shape: more complex (more corners, more edges); includes elongated buildings and buildings with courtyards

²⁴ Ibid.

This classification approach utilizes spatial and textural characteristics of the imagery at the neighborhood level. A combination of spatial features and spectral information was extracted from the original imagery using the open source MapPy python script library available on GitHub. A set of six spatial features and two spectral features was extracted using the python scripts, and are listed below:

- Differential Morphological Profiles (DMP) segment imagery according to an area's degree of homogeneity.²⁵
- Fourier Transform (FT) examines edges by decomposing the image into different spatial frequencies.²⁶
- Gabor Filters are edge extraction filters at different scales and orientations.²⁷
- The Histogram of Oriented Gradients (HOG) captures the distribution of structure edge orientations in a histogram.²⁸
- Local Binary Pattern Moments (LBPM) is a texture algorithm that examines relationships between a center pixel and its neighboring pixels. The layout of the pixel group represents the local pattern as flat areas, edges, corners, and line ends.²⁹
- PanTex is a contrast texture designed specifically to identify buildings. It is derived from the Gray Level Co-Occurrence Matrix (GLCM), an algorithm that determines how often adjacent pixels have the same gray level value.³⁰
- The Normalized Difference Vegetation Index (NDVI) is a simple spectral indicator that assesses whether a pixel has green vegetation.³¹
- The local mean of each of the original four bands and composite image was also computed.

Each of the features was computed with a block size (output resolution) and scale size (window size). Block size represents the output layer resolution. Because this analysis focuses on neighborhoods, rather than individual buildings, block sizes that produced output resolutions closest to 15m were used.³² A block size of 32 produced an output classification resolution of 16m (0.5m input imagery X block size 32 = 15m output resolution). Scale size represents the window size, or the amount of pixels from which the spatial feature algorithm will extract contextual information. Three scale sizes, starting at the block size and increasing in octaves, were chosen (32, 64, and 128). Once all feature layers were computed, they were layered into a virtual stack.

Training Sites

Training sites are small polygons that analysts draw over 'stereotypical' land area. Figure 5 below shows sample training sites for Commercial/industrial, Residential Irregular and Vegetation in Dar es Salaam. For each city, similar polygons were created throughout the image, resulting in roughly 40 training sites (each measuring approximately 15,000 sq meter) per class. Once these training sites were created, 500

²⁵ Klaric et al. 2005.

²⁶ Smith 1997.

²⁷ Daugman 1985.

²⁸ Dalal & Triggs 2005.

²⁹ Wang & He 1990.

³⁰ Pesaresi et al. 2008.

³¹ Jensen 2007.

³² Graesser et al. 2012.

random points were generated throughout each class. These points are then used to ‘teach’ the classifier how to best determine which areas in the image should be assigned to each class.

Figure 5: Example Training sites



Source: QuickBird imagery 2013

The image was classified using a Random Forest (RF) classifier. RF is a machine learning algorithm that constructs multiple decision trees and outputs the most frequently chosen class. This RF classifier used 100 trees that mapped the area at the block size described earlier. The image was then smoothed using a 5x5 majority filter, which eliminates anomalous pixels and creates contiguous and fluid land cover class regions. Finally, the paved roads were derived from the high resolution imagery, and added into the layer post classification (Felkner, Lall, & Lee, forthcoming). Clouds and cloud shadows were masked from the final classification to avoid misclassification errors. Accuracy assessments were performed on the final classified layers using 50 randomly generated points per class, resulting in a 400 point sample (see Table 1). In all cases, accuracy levels were above 87 percent, reaching levels as high as 92 percent for the most recent images for Nairobi and Addis Ababa.

Table 1. Accuracy Assessment Results	
City	Overall Accuracy
Addis Ababa c. 2000	87.8%
Addis Ababa c. 2010	92.0%
Dar es Salaam c. 2000	88.0%
Dar es Salaam c. 2010	87.3%
Kigali c. 2000	87.3%

Kigali c. 2010	87.0%
Nairobi c. 2000	90.3%
Nairobi c. 2010	92.3%

LAND COVER ANALYSIS RESULTS

Dar es Salaam, Tanzania

Dar es Salaam’s rapid population growth of 5.6% annually from 2002-2012 makes it Africa’s 3rd fastest growing city. In 1963 the Ministry of Lands, Housing and Urban development used aerial photography to estimate that there were roughly 7,000 units in unplanned areas. By 1972 that number had more than tripled to 28,000.³³ In 2002, Tanzania’s Community Infrastructure Upgrading Project estimated that about 68% of the city’s population lived in unplanned settlements.³⁴ The UN echoes this estimate, approximating that in 1995, 70% of Dar es Salaam’s population resided in informal settlements. While the methodology used in the study cannot quantify ‘slums’ or informal settlements as they are defined by the UN (it is impossible to determine land tenure or sanitation from satellite imagery) this methodology is able to detect residential neighborhoods that appear irregularly planned. This analysis therefore uses ‘irregular’ as a proxy for slum or shanty.

Figure 6 below shows the land cover classification for Dar es Salaam. Land with irregular residential characteristics is shown in red, and appears predominately towards the core of the city in the western and northern side. The center of the city is marked with a black dot. Just beyond the commercial/industrial city center, irregular housing begins to appear with many of them found clustered near the large industrial park that transects the city (shown in purple in Figure 6). Upon closer inspection, small pockets of irregular settlements are detected directly adjacent to large warehouses and transit infrastructure.

In order to quantify these observed trends, the classified data layer was summarized by distance to the city center. Figure 6 shows how the coverage of residential (regular and irregular) and commercial/industrial land changes as one moves from the center to the periphery of the city. As expected, the first few kilometers of built-up land around the CBD is dominated by commercial/industrial and residential regular, with a noticeable low percentage of irregular residential. It is not until 3 to 4 kilometers beyond the city center that residential irregular begins to appear, it then peaks between 6 to 9 kilometers with residential irregular occupying roughly 18% of the built-up land.

In contrast, residential regular neighborhoods are spread throughout the city. The residential regular class captures neighborhoods with moderately dense housing units, some lawns/trees and gridded or well organized road network. Given this rather broad/encompassing definition, the class includes both attached homes (townhouses) within the city center that have a gridded road, as well as large development single family houses near the periphery. While there is a slight increase in residential

³³ UN Habitat (2010) Dar es Salaam: A Rapidly Urbanising Informal City.

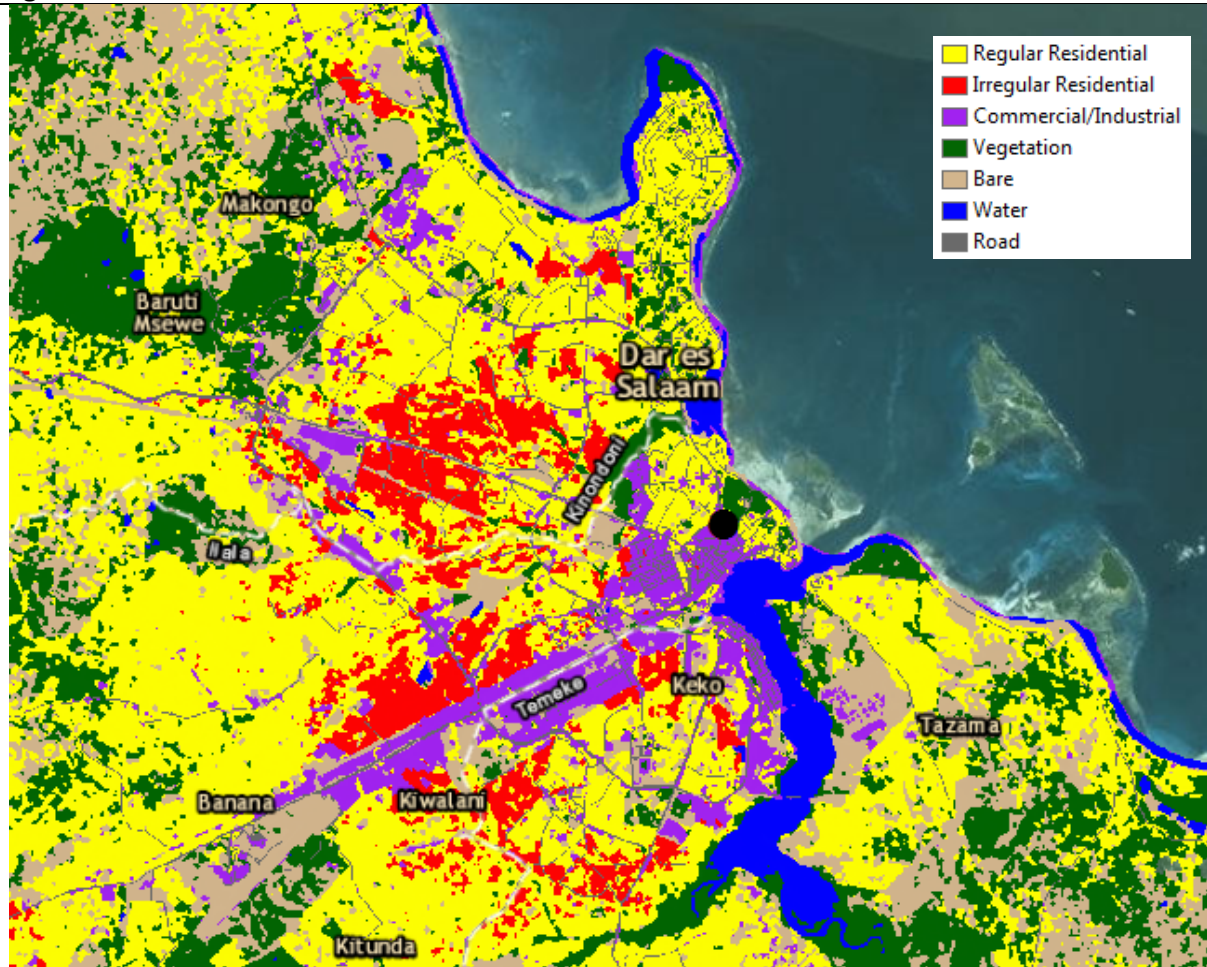
³⁴ CIUP, 2004. Dar es Salaam Infrastructure Development Programme. [Community Infrastructure Upgrading Project](#).

regular land cover as one leaves the city center (shown in Figure 7), the coverage remains fairly consistent, and within the first 15 kilometers covers 72% of the built-up land.

Commercial and Industrial land is much more concentrated in the city center (marked with a black dot in figure 6) but even as one moves away from the city center it remains to occupy a relatively large percentage of land. Within 10 kilometers of the city center roughly 20% of the land is commercial/industrial. This is in stark contrast to Addis and Kigali that have averages closer to 10%. The high prevalence industrial land likely stems from the large industrial corridor that surrounds the railroad infrastructure entering the city (figure 6).

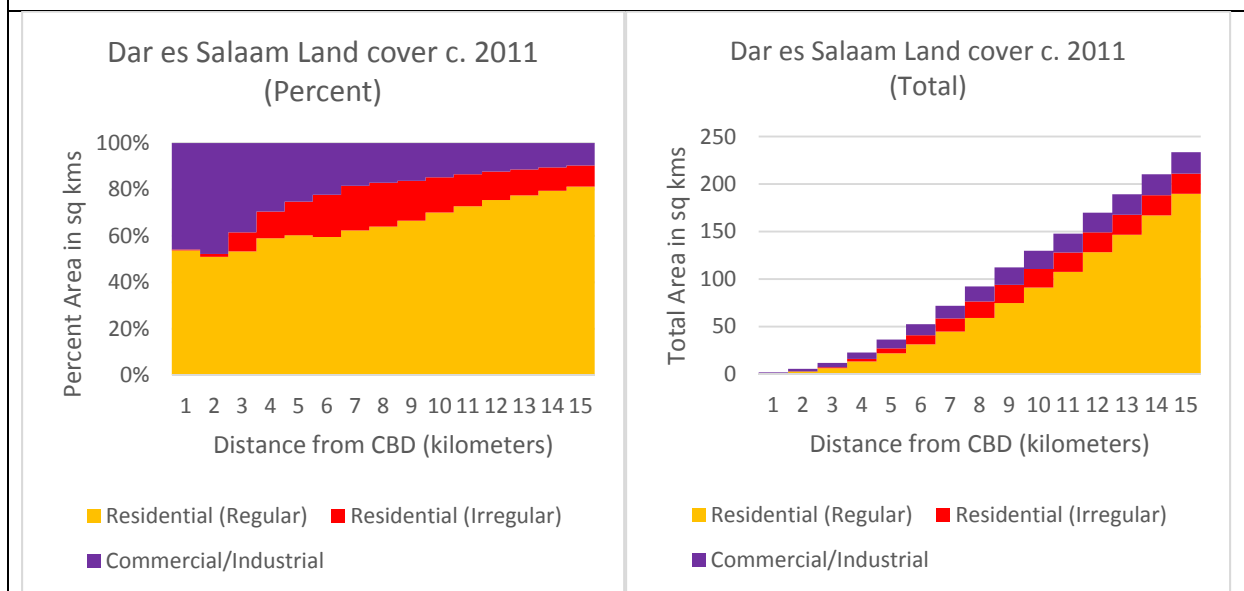
It should be noted that this study's irregular residential land estimates are significantly lower than the UN's estimations, but this discrepancy is not surprising. The UN's definition of shanty or informal settlement is more encompassing and as previously discussed, the classification algorithm used in this study can only analyze the physical condition of a building. Therefore, this land cover map provides an underestimation of the extent of slums as it excludes areas with good physical conditions, clearly delineated roads and lots of vegetation but that lack access to basic services or a property title. It also cannot predict the tenure status of any unique parcel, and is limited to what can be observed from space.

Figure 6: Land cover classification of Dar es Salaam



Source: Author's classification, see annex X for explanation of methodology

Figure 7 – Land Cover Classes and Distance to City Center - Dar es Salaam



Source: These charts have been calculated using land cover classification layers derived from high resolution satellite imagery (<1m) circa 2011/2012.

Nairobi

The landlocked city of Nairobi is home to more than 3.14 million people, making it the second largest city by population in the African Great Lakes Region, after Dar es Salaam.³⁵ This centrally located capital is a major hub for commerce, transport and regional development, generating roughly 45% of the nation’s GDP and employing 25% of the nation’s work force. Despite its economic strength, inequality among its inhabitants has grown at a much higher rate than the rest of the country. The UN-Habitat estimates that roughly 60% of its population lives in slum households, and 78% of those slum household have no running water.³⁶ Nairobi is also home to the largest urban slum in Africa, Kibera, which houses a rough estimate of 700,000 people living in extreme poverty in a 225ha area. This slum is strategically situated close to the CBD in order to provide cheap and local labor. The high proportion of unplanned and crowded housing units creates massive drainage and sanitation issues in the area.³⁷

The imagery derived land cover classification of Nairobi, shown in Figure 8, reveals the distribution of residential (irregular), residential (regular) and commercial/industrial land throughout the city. The city center (marked as a black circle in figure 8) is dominated by land covered with commercial, industrial and transportation structures. Irregular neighborhoods are predominately found around 3-8 kilometers from the city center, with the closest identified near Kariokor in the north east (Pumwani, Mjengo estate

³⁵ Kenya Central Bureau of Statistics. 2009. “The 2009 Kenya Population and Housing Census. Volume IC, Population Distribution by Age, Sex and Administrative Units.

³⁶ UN Habitat. 2006. Nairobi Urban Sector Profile: Rapid Urban Sector Profiling for Sustainability (RUSPS).

³⁷ <http://mirror.unhabitat.org/content.asp?typeid=19&catid=548&cid=4962>.

and Kitui Village). Larger irregular residential neighborhoods appear slightly further out and consist of Mukuru, Kibera, Mathare, and Kiambiu (shown in red in figure 10). In 2005, the Government of Kenya released a land use map based on 2003 aerial photography that identifies certain residential land as 'slum'. Figure 10 shows a map of the slum areas identified by the government in black outline, overlaid with a classified layer this study created using imagery from 2003. While there is not a perfect alignment of the two areas, the classified image clearly identifies residential shanty in the same areas the government considered 'slum' in 2003. A comparison of the classification derived using land coverage with the information provided by government sources on land use, suggests that the classification is that the result of the semi-automated classification congruent with reality. Box 1 presents some additional discussion on these issues. (See Box 1 for further discussion.) Figure 11 further supports this assessment, with the red hashed bars showing the 'slums' identified by the government as a percentage of land cover, as one moves away from the city center. The red line shows the same trend, but calculated using the land cover layer derived from 2003 satellite imagery.

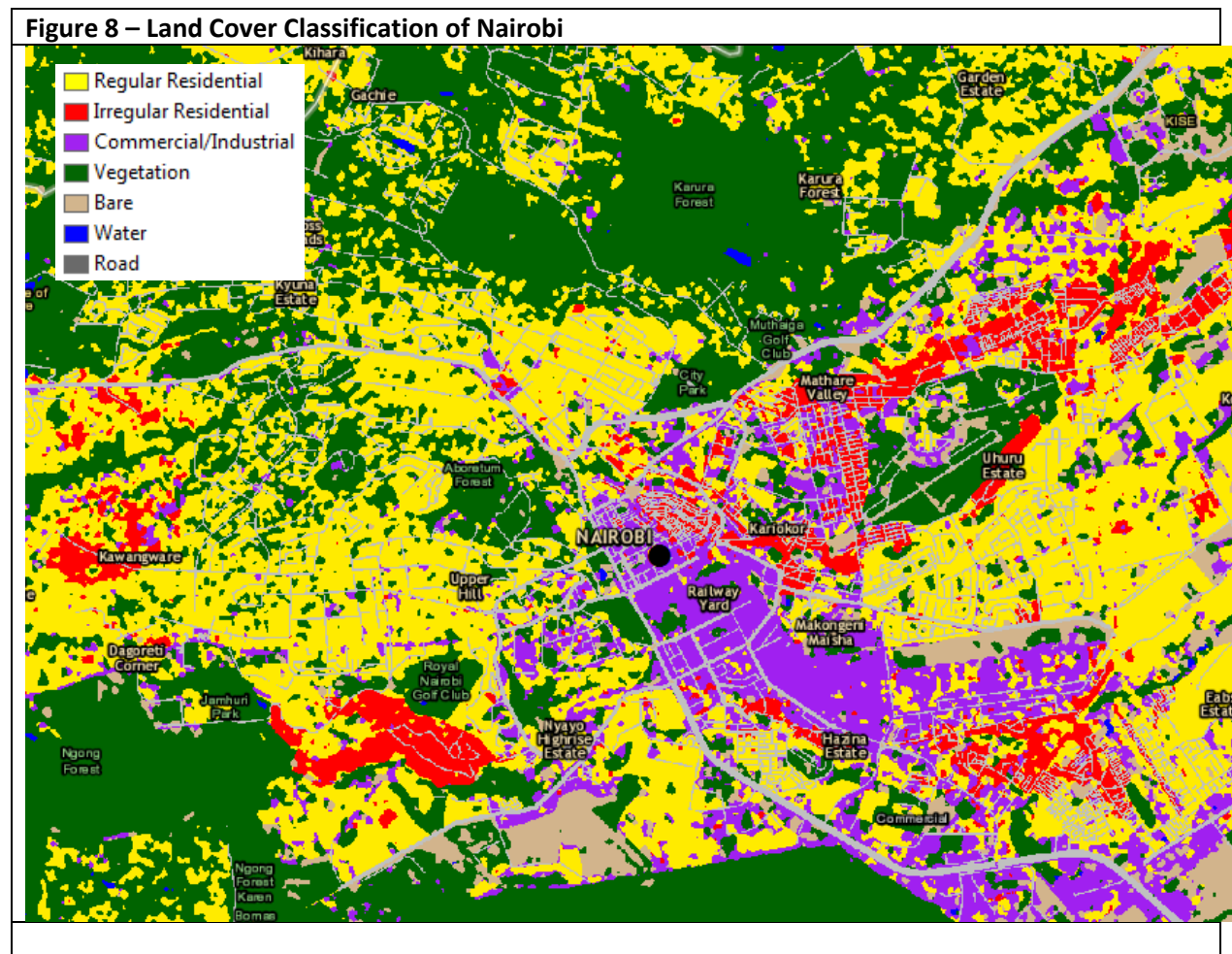
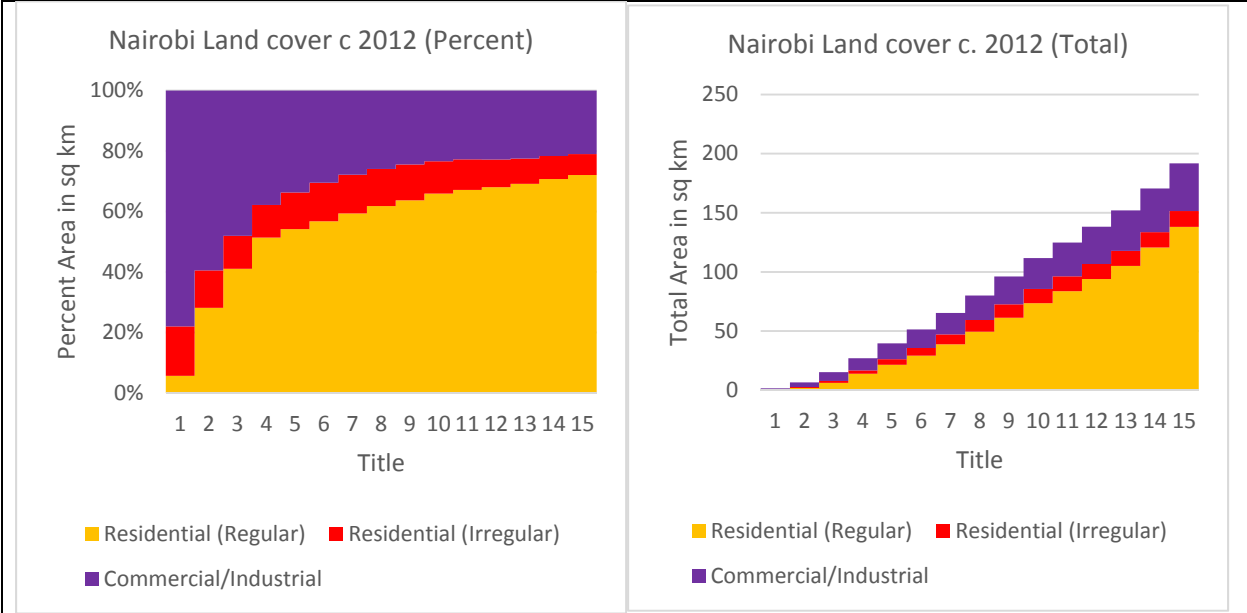
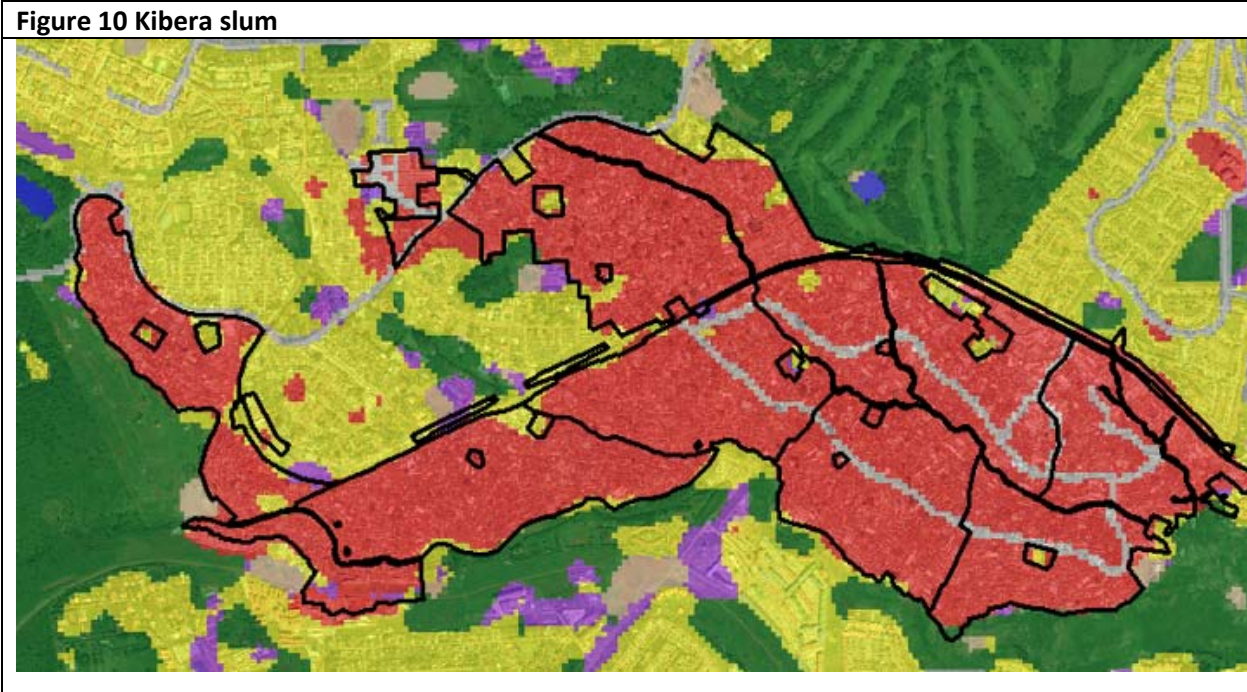


Figure 9 – Land Cover Classes and Distance to City Center - Nairobi



Source: Author's calculations based on land classification, see annex X for explanation of methodology



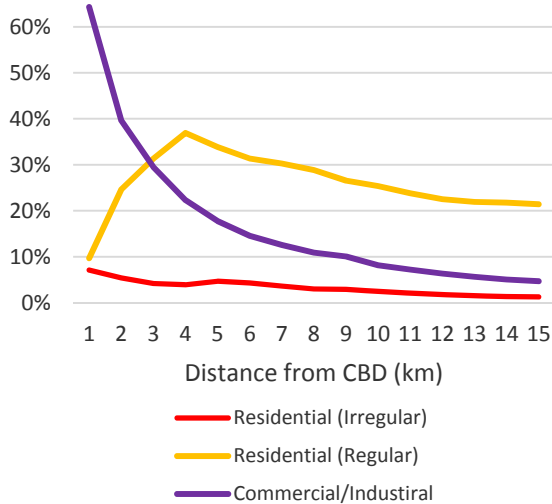
Source: Land classification 2012 and land use map 2003 (Columbia University and Center for Sustainable Urban Development's (CSUD) Nairobi. Layer can be downloaded [here](#)

Box 1. Nairobi: Land Cover vs Land Use –Is There a Difference?

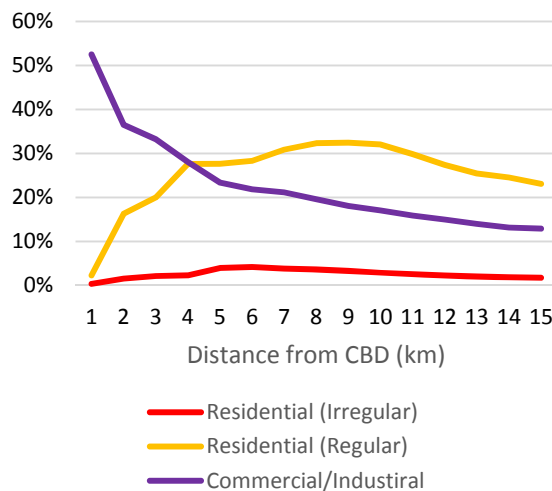
Land use vs Land cover

In 2005 the Government of Nairobi released a city land use map based on the manual digitizing of 2003 aerial photos. Land was divided into many more categories than used in this study, making it difficult to compare results. For example, the land use map has land owned by universities and churches labeled as ‘institutional’. But if these institutions have large fields or parking lots a land cover map would label part of this land as vegetation or barren. Despite these inconsistencies, the classification of informal settlements is loosely comparable. The land use map identified slums as areas with “small mostly temporary buildings that re randomly distributing in high density clusters” and warned that the distinction between residential formal and residential slum “was highly subjective.”³⁸ Similarly the algorithm in this study attempted to identify neighborhoods with small tightly packed roof tops and label them as “Residential shanty”. The graphs below compare the results, showing how the coverage of slum/irregular land changes as one moves away from the city center. In the first 4 kilometers the land use map claims almost no slums, while the land cover map identifies a small portion. After the 5 kilometer mark, the maps agree almost perfectly, with a steady rise in slum/irregular land followed by a tapering off at around 10 kilometers. Similar comparisons between a semi-automated approach and manual digitization have been explored in Accra Ghana.³⁹ This study found the land cover layer derived from VHR imagery was able to accurately detect 94% of the land designated as ‘slum’ by the UN Habitat/Accra Metropolitan Assembly (UNAMA).

Nairobi Land Cover c. 2003
(semi-automated classification)



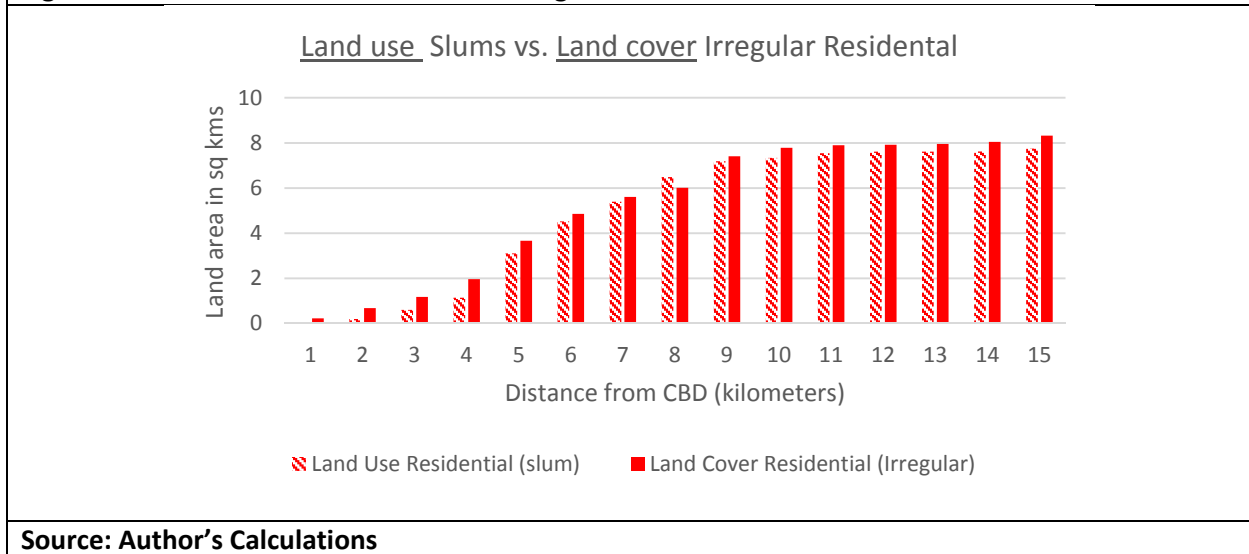
Nairobi Land Use 2003
(manual classification)



³⁸ 2005. Nairobi Land Use Memo. Download from [Nairobi GIS Maps](#).

³⁹ Engstrom et al (2015). Mapping Slums Using Spatial Features in Accra, Ghana. IEEE.

Figure 11: Land use Slums vs Land cover Irregular Residential circa 2003



Kigali, Rwanda

Home to roughly 1 million, Kigali, the capitol of Rwanda, is considerably smaller in population size than Dar es Salaam and Nairobi. Prior to 1994, Kigali's landscape was relatively free of informal construction due to government regulations that restricted rural to urban migration.⁴⁰ But over the past two decades the city of Kigali has experienced rapid urbanization with population growth rates of 4% per annum (2002-2012) a rate only slight below Dar es Salaam and Nairobi.⁴¹ ⁴² By 2020 the population of Kigali is expected to double.⁴³ This increase in urban population has placed considerable pressure on Kigali's housing stock, and resulted in the construction of informal settlements. To meet projected housing demands, Kigali would need to construct roughly 344,000 formal housing units by 2022, but currently less than 1,000 are constructed annually.⁴⁴

This high demand for housing has left much of the population living in substandard conditions. In 2012 roughly half of Kigali's housing stock was considered by the government as "Low quality, overcrowded units which need to be replaced". Rwanda's Environment Management Authority echoed this concern, recently reporting that 83% of Kigali's population was living in slum housing quality, with many neighborhoods built on steep or sandy slopes, and lack basic access to utilities and transport networks

⁴⁰ Uwimbabazi, Penine and Ralph Lawrence. Compelling Factors of Urbanization and Rural-Urban Migration in Rwanda. Rwanda Journal Volume 22, Series B, 2011: [Social Sciences](#).

⁴¹ National Institute of Statistics of Rwanda. 2012. "2012 Population and Housing Census: Report on the provisional Results." Published November 2012.

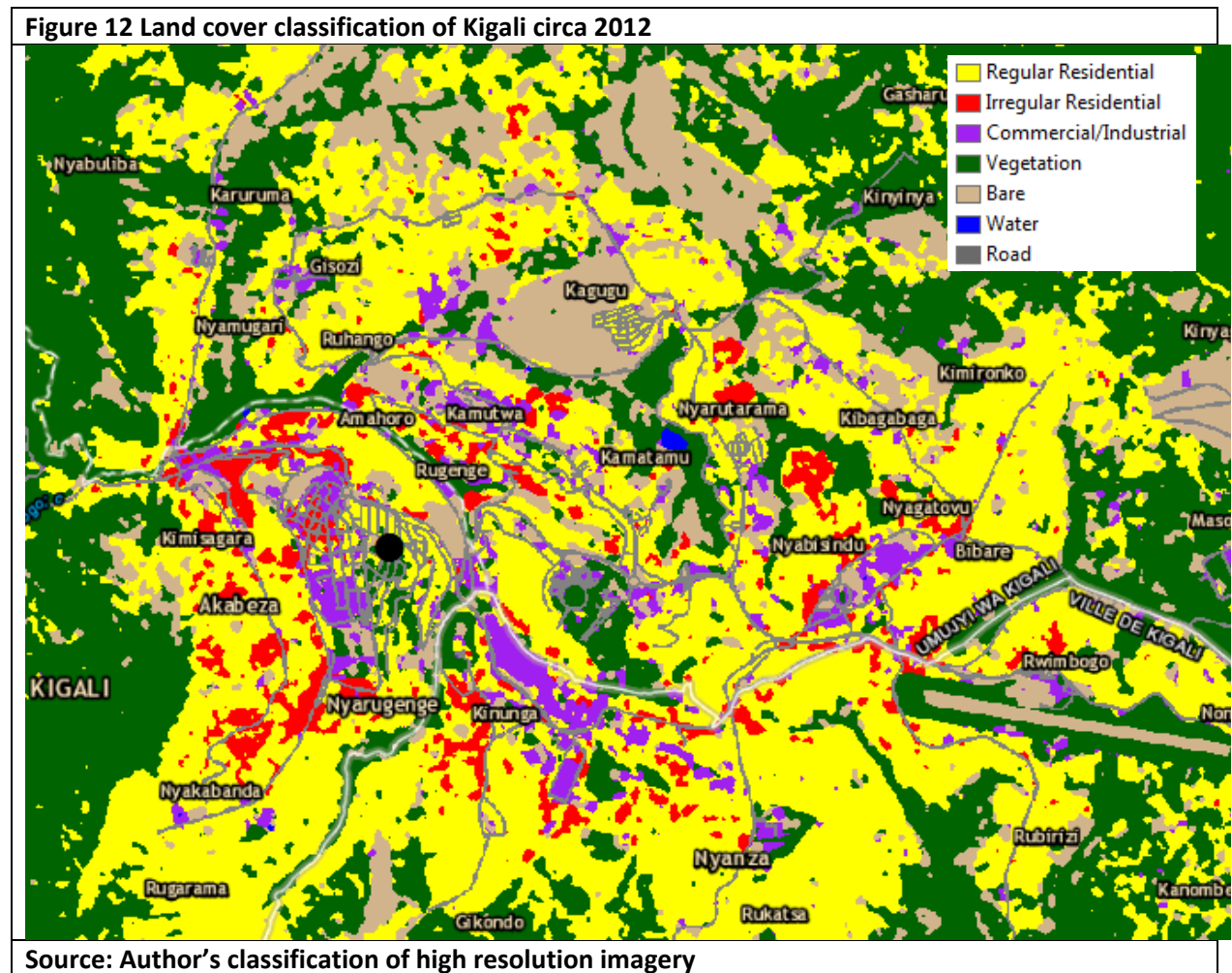
⁴² 2015 "City Mayors: World's fastest growing urban areas". Retrieved August 2015.

⁴³ Institute of Statistics, Rwanda 2012 (<http://www.kigalicity.gov.rw/>).

⁴⁴ 2012, City of Kigali. The Kigali Housing Market Brochure.

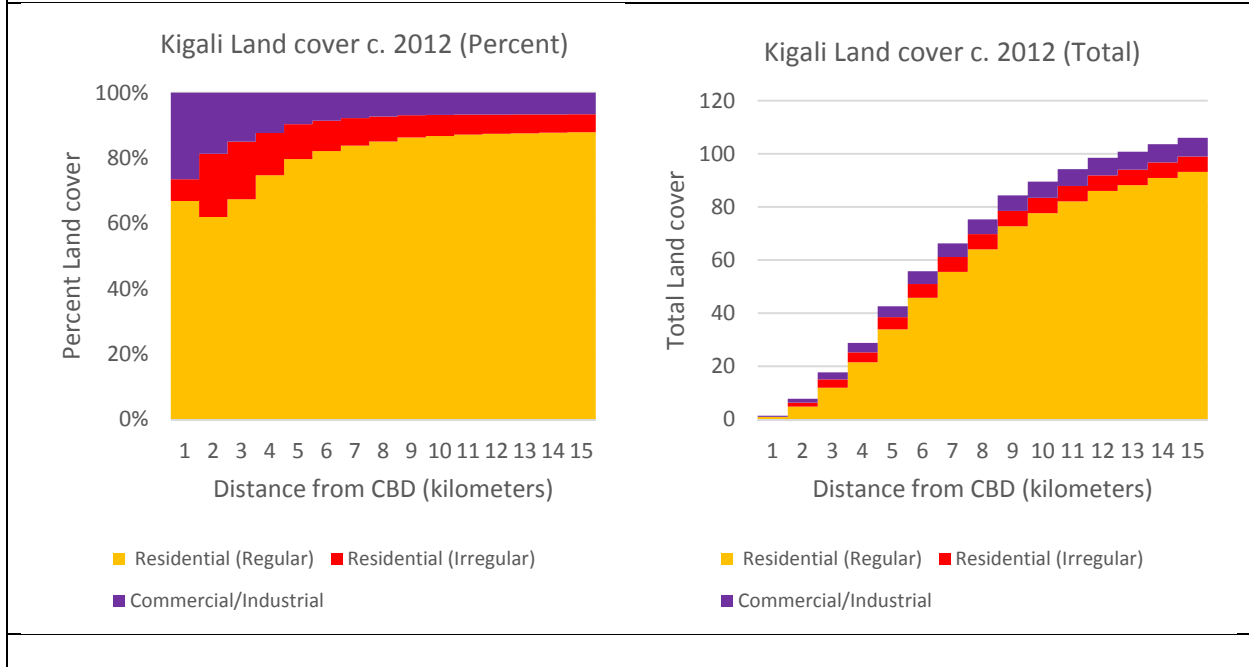
as a result.⁴⁵ As discussed previously, the classification in this study cannot identify households that lack tenure, sanitation, or exist on marginalized land. However, the land classification can identify neighborhoods that lack planning (constructed haphazardly, have no paved roads, and minimal green space).

The imagery derived land cover classification of Kigali, shown in Figure 12, reveals the distribution of residential (irregular), residential (regular) and commercial/industrial land throughout the city. Overall Kigali is a considerably smaller and less built-up city than Dar es Salaam, Nairobi, and Addis Ababa, with much more green space in the city center (marked with a black dot in figure 12). But despite its differences, several patterns remain similar. Regular residential land is consistently spread throughout the city. Likewise, as one leaves the city center and moves towards the periphery commercial/industrial land tapers off but does not disappear. This is probably due to the fact that Kigali has no large industrial zone like Dar or Nairobi, but rather small pocket. Residential Irregular also appears in small pockets, and peaks between 2-3 kilometers from the city center. Within 4 kilometers of the city center, approximately 17% of Kigali’s built-up land is occupied by residential irregular neighborhoods.



⁴⁵ Rwanda Environment Management Authority. 2013. Kigali: State of Environment and Outlook Report. http://www.minirena.gov.rw/fileadmin/Media_Center/Documents/.

Figure 13 – Land Cover Classification and Distance to City Center - Kigali



Addis Ababa, Ethiopia

Addis Ababa is one of the oldest and largest cities in Africa, making it a central urban hub for many Ethiopians in search of better living and employment conditions. The city accounts for approximately 20% of the country’s GDP, although it is home to less than 5% of the country’s residents.⁴⁶ According to the 2007 Ethiopian census, roughly 2.7 million people live in Addis, a number that has doubled every decade since 1984. This rapid growth is expected to continue, with the UN Habitat estimating a population of 12 million by 2024.^{47 48}

Triggered by this population growth, Addis is undergoing a construction boom. With new condominiums, office buildings and infrastructure projects breaking ground almost simultaneously throughout the city. Unfortunately this development has not always followed government regulations, resulting in roads cut off due to building construction, or major road intersections being built with no means for pedestrian crossings.⁴⁹ While this new development has created jobs and raised tax revenues, it often lacks coordination and the support of a strong transport system. As a result, neighborhoods are mostly medium density and possess an ‘urban village’ type environment, where residents are in walking distance to all of their amenities. While satellite imagery cannot detect these pockets of mixed use land, the classification in Figure 12 clearly depicts small pockets of various land cover throughout the city,

⁴⁶ Cour, Jean-Marie. 2004. “Assessing the ‘benefits’ and ‘costs’ of urbanization in Vietnam”. Annex to “Urbanization and Sustainable Development: A DemoEconomic Conceptual Framework and its Application to Vietnam”. Report to Fifth Franco-Vietnamese Economic and Financial Forum, Ha Long, November 2004.

⁴⁷ http://www.csa.gov.et/newcsaweb/images/documents/surveys/Population%20and%20Housing%20census/ETH-pop-2007/survey0/data/Doc/Reports/Addis_Ababa_Statistical.pdf.

⁴⁸ Un Habitat. 2008. Ethiopia: Addis Ababa Urban Profile.

⁴⁹ Young, Adrian. 2014. “No pain, no gain? Rapid urban growth and urbanism in Addis Ababa. UrbanAfrica.net.

while in contrast, cities like Dar es Salaam and Nairobi have large areas of industrial land or irregular residential (see figure 6 and 8).

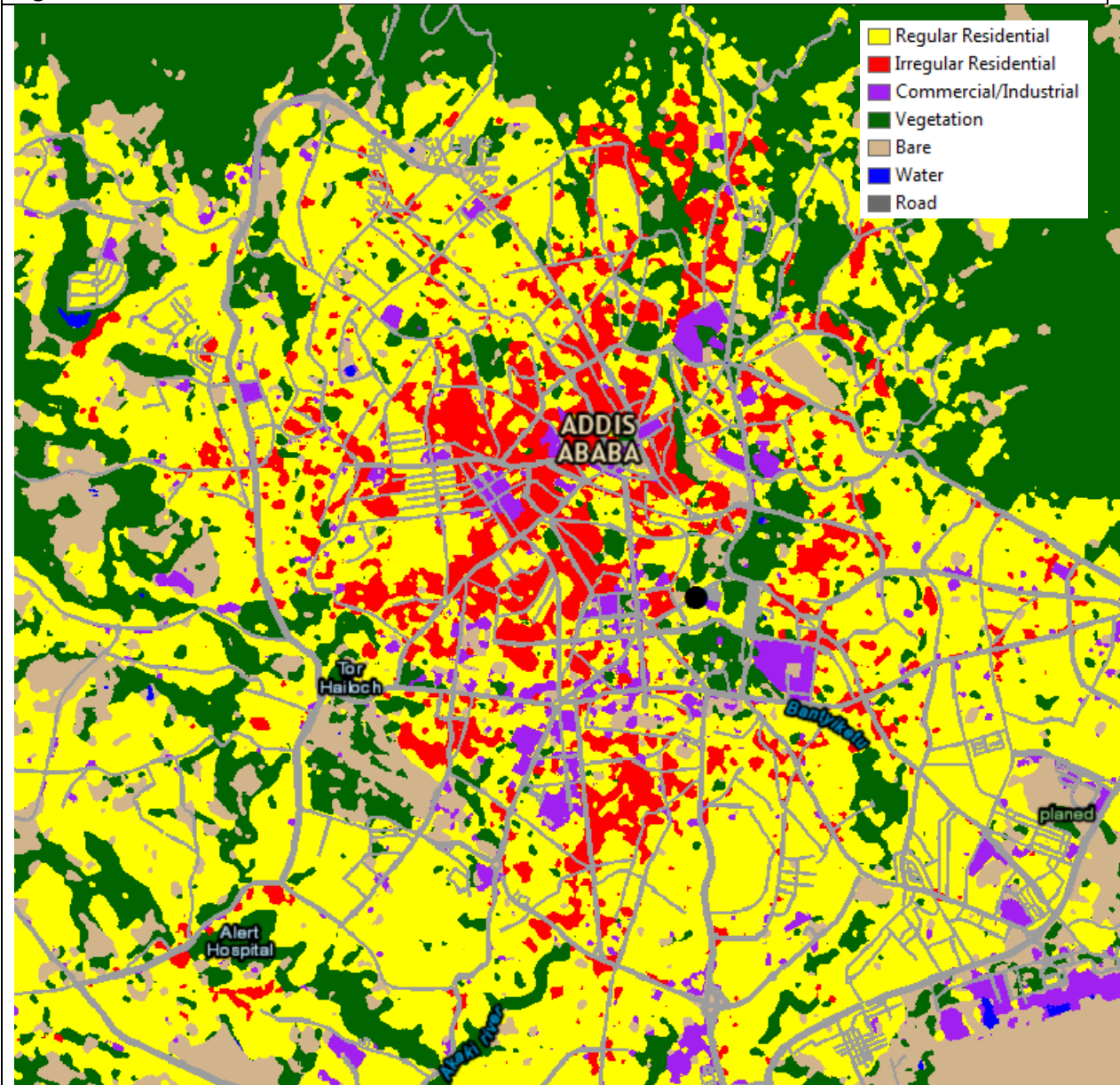
This rapid expansion has also impacted the quality of the housing stock. Fast construction has led many buildings to be made with low quality and nondurable material. The UN Habitat estimated in 2007 that some 75% of all buildings had been constructed with mud and wood, and lacked a proper foundation. Furthermore, a startling 97% of all buildings were single story, and only 17% could be considered in good condition. Currently it is estimated that between 70% and 80% of housing units are considered slums, with a bulk of these dwellings located in prime central locations, thus preventing its use for more productive activity.^{50 51}

The land cover classification map of Addis created in this study reflects many of the trends mentioned above. In Figure 14 irregular residential settlements are colored red, and appear to be highly concentrated in and around the city center. In contrast to Nairobi, Dar es Salaam and Kigali, a significant proportion of land in the city center is being occupied by irregular residential (Figure 14X). Within the first 4 kilometers from the city center about 26% of the built-up land is residential Irregular, with this number dropping off dramatically around to around 8% around 6 kilometers outside of the city center. Pockets of Irregular residential continue to appear towards the city's periphery, but there are no single large sized slums like Kibera in Nairobi. Industrial and Commercial land (shown in purple in Figure 14) is also found in small pockets throughout the city rather than concentrated in large zones like in Dar es Salaam and Nairobi. This pattern of small pockets of land cover might be indicative of the 'urban village' environment described in the literature.

⁵⁰ Un Habitat. 2008. Ethiopia: Addis Ababa Urban Profile.

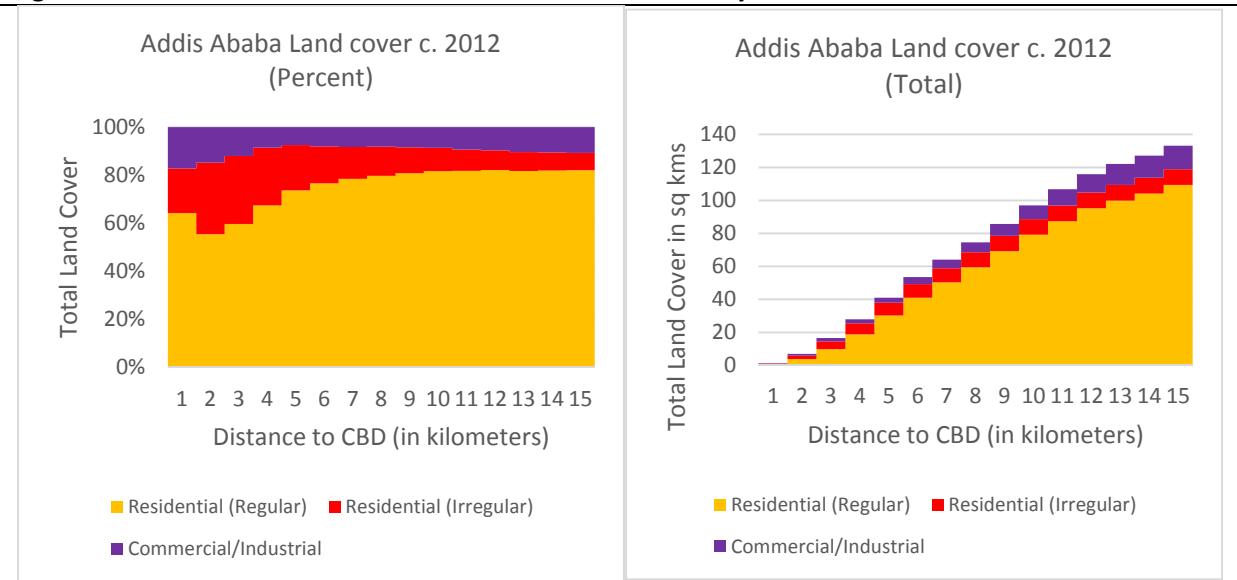
⁵¹ UN Habitat. 2007. Situation Analysis of Informal Settlements in Addis Ababa pg 28-30.

Figure 14 Land cover classification of Addis Ababa



Source: Author's classification of high resolution imagery

Figure 15 – Land Cover Classification and Distance to the City Center – Addis Ababa



Source: Author's calculations

Dakar, Senegal

Located on the Cap Vert peninsula the metro area of Dakar is home to roughly one-third of Senegal's population and 80% of the nation's economic activity. Home to the 9th busiest port in Africa, the majority of the city's economic activity is concentrated in the huge industrial zone that stretches east from the Port of Dakar to Rufisque, along Hann Bay.

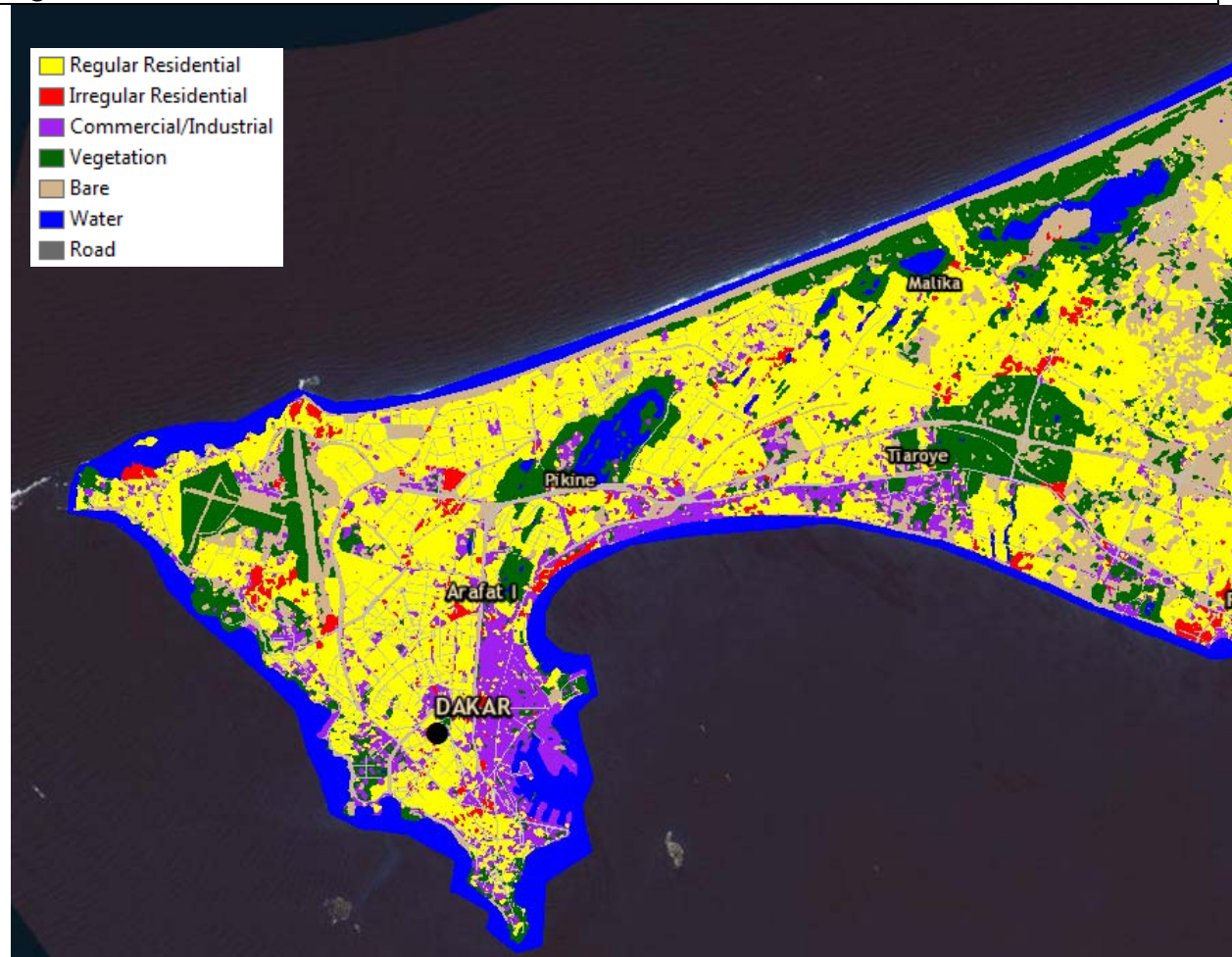
The population of Dakar has tripled since the 1970s with much of this growth occurring near the periphery of the city (in Rufisque and Pikine). The rapid urbanization of this land stems from not only natural growth, but also a considerable influx of immigrants from neighboring West African countries drawn to the city in search of economic opportunity. But prosperity is not a guarantee/ competition is stiff. Roughly one-third of Dakar's population lives under the poverty line and almost half the population is under the age of 18.⁵²

Due to the land constraints from its geographic location, the spatial distribution of the land cover in Dakar is decidedly different than the African cities previously discussed in this paper. The map in Figure 16 shows spatial distribution of Dakar's land cover. The commercial and industrial land is primarily concentrated directly in the core, and along the south coast of the peninsula. Regular residential land is located north of the city center, and extends west. Irregular residential land on the other hand, is mostly found in small pockets scattered throughout the city, particularly near the airport and near Rufisque. When plotted by distance from the city center, as shown in Figure 17, the irregular land cover classes in Dakar appear to peak at only 2 to 3 kilometers from the city <city center?>. Limited to a peninsula, the

⁵² UNEP (2014) Assessing Urban and Peri-urban Agriculture in Dakar. (http://apps.unep.org/publications/pmtdocuments/-Building_Urban_Resilience__Assessing_Urban_and_Peri-urban_Agriculture_in_Dakar-2014EN_UPA.pdf).

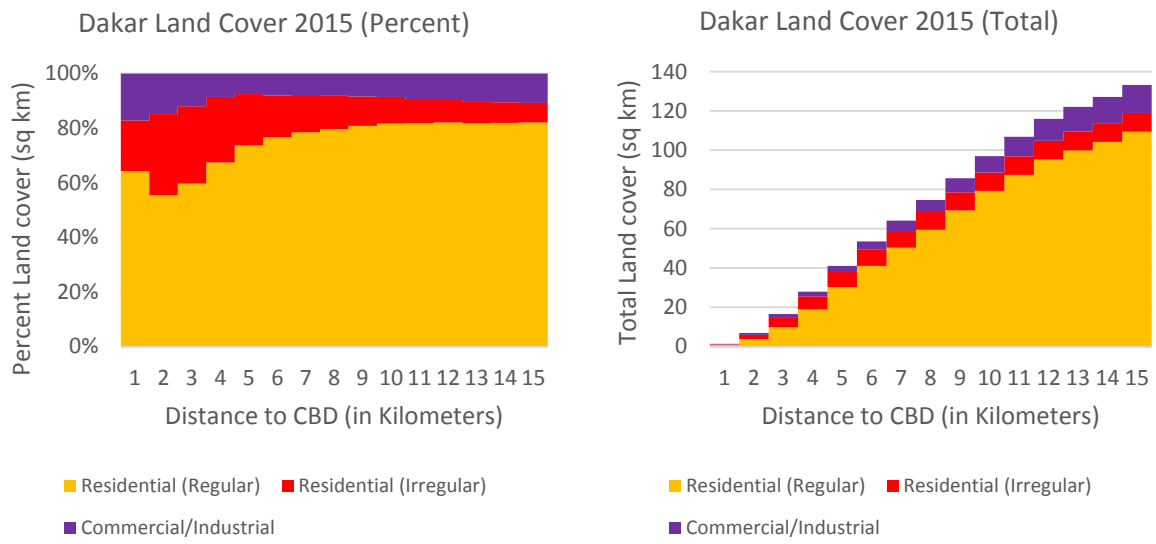
city's footprint is significantly smaller than Dar es Salaam, Kigali, Addis Ababa or Nairobi. It is important note, because any small changes in land cover classification are easily magnified when charted as a percentage. For a more accurate representation, it is important to examine the land total chart in Figure 17. This chart actually shows a fairly consistent presence of irregular settlements throughout the city's footprint.

Figure 16 – Land Cover Classification for Dakar



Source: Author's classification of high resolution imagery c 2015

Figure 17 – Land Cover Classes and Distance from City Center - Dakar



Box 2– Manual digitizing vs semi-automated approach in Dakar

Traditionally planners have relied upon manual digitizing satellite imagery to create accurate city level maps. While usually this produced very precise maps, this approach remains tedious and time intensive. A semi-automated approach presented in this study could be a time saving alternative. The screenshots below highlight the discrepancies and similarities between a land classification generated from a semi-automated approach and a land cover map that was manually digitized. On the left hand side are the layers generated by a semi-automated classification. The layer has been given a slight transparency so that the 2015 image beneath it can be seen. On the right hand side is that same area, but with a classified layer that has been manually digitized from a 2008 image. In all the maps, purple areas represent commercial/industrial land, while the yellow represents residential land, green is vegetation, beige is bare soil. The semi-automated approach clearly picks up the vegetation more accurately, and is able to identify small patches of trees. On the other hand, it appears slightly more gridded with pockets of residential within the commercial, and some minor roads being missed. In contrast the manual approach has cleaner lines that are generalized to follow roads. Overall though, it is important to note the large amount of agreement between these two layers. In both approaches the industrial area is clearly being accurately identified and the residential land is almost identical. Regardless of the methodology, it is clear the outputs are telling the same story.



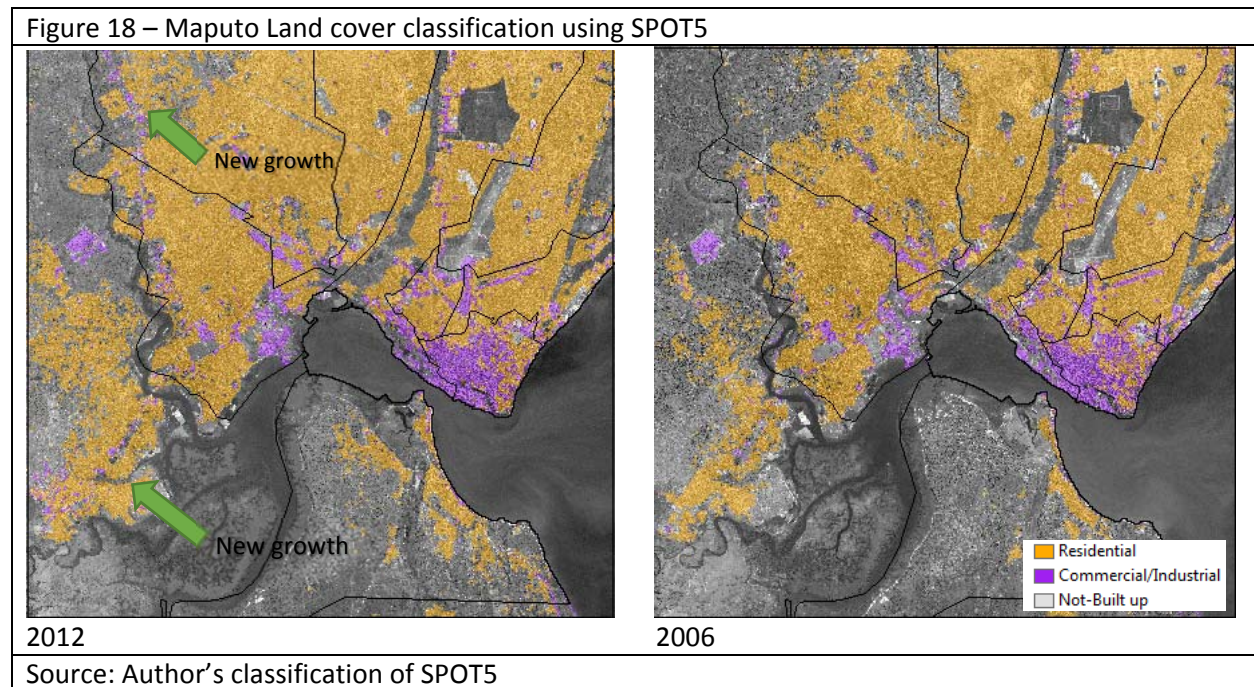
The High Resolution debate

The number of land cover classes chosen in the study was in part dictated by the spatial resolution of the imagery. In order to distinguish between residential regular, residential irregular, and commercial/industrial land, the shapes of individual rooftops and roads needed to be clearly visible in the imagery. However, the classification methodology used in this study is not scale dependent, and can be applied to imagery with various spatial resolutions, for example, if the objective is to discover the general growth of a city's footprint over time. Coarser imagery such as 30m Landsat could be classified using this semi-automated approach into land that was either urban or non-urban. Typically as the spatial resolution of the imagery decreases (i.e. becomes coarser), the number of land cover classes that can be extracted declines, as it becomes more difficult to distinguish features on the land.

Despite this trade-off, the benefits of classifying coarser resolution imagery remain high. Enticed not only by the low cost, but also the large scene size and the ability to acquire historical imagery, this team explored the classification of slightly coarser resolution imagery. More specifically, SPOT5 (2.5m pan 10m Multi-Spectral imagery) was acquired for 15 African cities at two different time periods. To learn just how much detail could be reliably extracted several different class combinations were tested in Nyala Sudan (refer to Annex II for the results). With 5 classes producing an accuracy rate of 58%, 4

classes a rate of 69.5 and 3 classes achieving a rate of 78.8% it was determined that a maximum of 3 classes could be reasonably extracted. With some manual cleanup, all 15 African cities reached an accuracy level above 85%.

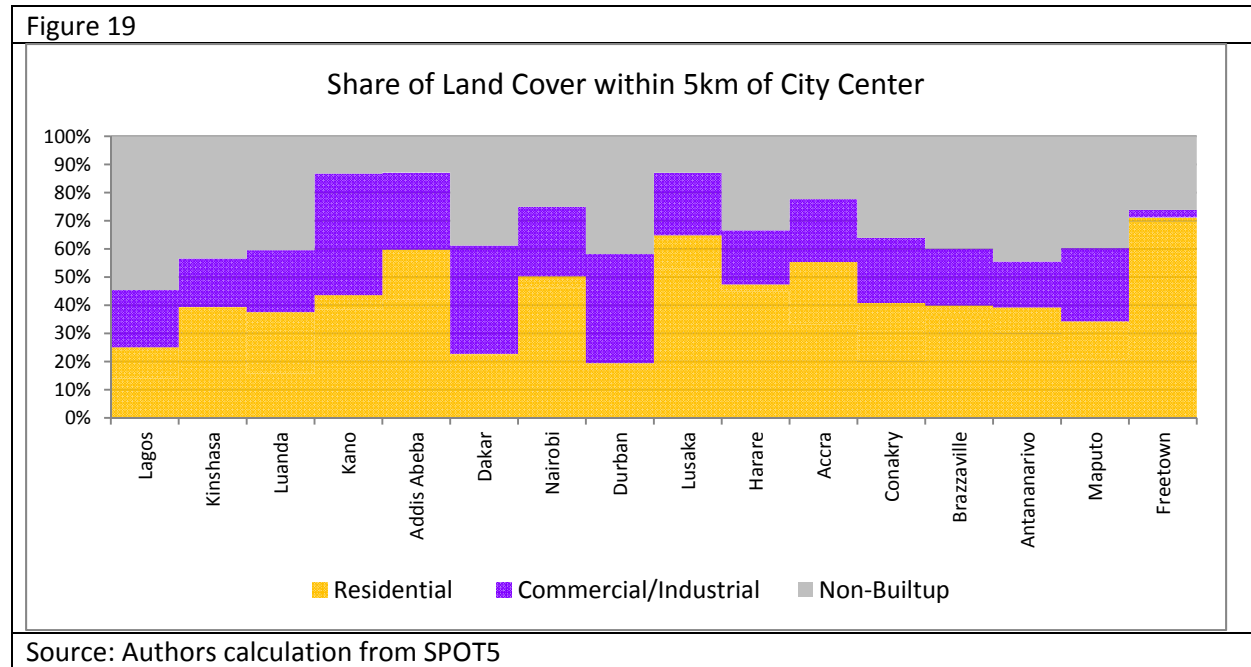
Figure 18 below shows Maputo classified into 3 classes (Commercial/industrial, Residential, and Un-built land) in 2006 and then again in 2012. These land cover maps do not merely show the urban expansion, but they also provide insight into the changes of the land cover composition (i.e. what type of land has been expanding or where has land cover remained constant. In Maputo, a noticeable amount of growth appears to be occurring the north and to the west of the city with new residential land as well as the industrial parks being built. In contrast, the downtown area near the port, remains quite unchanged. It should be noted that when conducting change detection analysis using satellite imagery, there will always be an element of uncertainty introduced by the image as well as the classification process. For example, in Maputo, the scenes were taken during different months and at different angles, the classifier was then tailored to the pixel values in each scene. As a result, buildings in the first scene might appear to have higher values than buildings in the later. The classifier must therefore adjust and identify buildings in the first scene using different criteria than the buildings in the second scene. While this source of error should be recognized, it does not invalidate the value of classifying layers and inspecting their change over time as an exploratory tool.



Although the goal of classifying SPOT5 imagery was to explore how well coarser imagery could be used to analyze urban growth over time, several interesting trends emerged through a cross city comparison. Figure 19 below summarizes the land cover within 5kms of each city's CBD. The cities have been ordered according to population size, with Kinshasa and Lagos being two of the most populated cities located near the Y-axis, and Freetown with less than 1 million inhabitants located at the very end.⁵³ Returning again to Maputo with a population of roughly 1.2 million, the chart shows that within 5 kilometers of its

⁵³ Population data taken from <http://www.citypopulation.de/>, a website that compiles national census data.

city center, 35% of its land was detected as residential, and roughly 25% of its land consists of commercial/industrial land (i.e. large buildings). Perhaps even more interestingly, almost 40% of the land within that 5km core is not built upon (i.e. is bare soil, or vegetation). Main bodies of water (rivers and ocean) have all been masked out. Upon closer inspection of the image, this non-built-up land consists primarily of parks, the airport, vacant plots, and some farmland. Figure 20 shows some high resolution imagery displayed behind the SPOT5 land cover classification. The ‘un-built’ land class has been made transparent, for better visualization, while the commercial/Industrial land has been colored purple and the residential land orange.

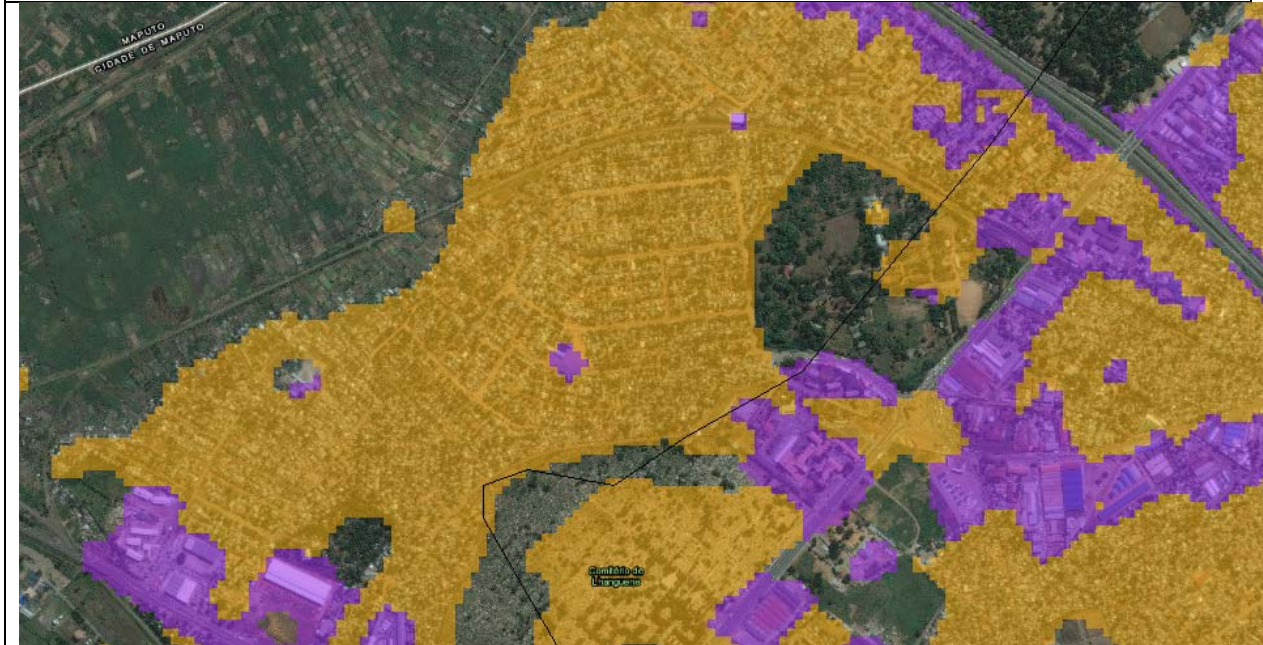


A certain amount of error will always exist when distinguishing between various land cover classes. Particularly when local land use data are not available and distinctions are being made by imagery analysts. For example, when built-up land is divided into residential and commercial/industrial, large apartment buildings will often be labeled as commercial/industrial. However this error decreases significantly when the classifier is trained to identify vegetation or bare soil, not merely because the natural environment has distinct spectral signatures (i.e. vegetation has a high Near Infrared value) but also because identifying features such as trees, grass, and bare soil involves less subjectivity. Figure 20 highlights how accurately the classifier is able to detect ‘un-built’ land, providing evidence of how un-built areas are not being equated to un-used or vacant land.

On average for these 16 cities, the land within 5 kms of the CBD consists of 33% unbuilt land, 42% residential and 24% commercial/industrial. Landlocked cities, such as Lusaka, Addis Abeba, and Kano had a much lower amount of un-built land (ranging from 12-14%), while coastal cities like Lagos, Durban, and Maputo have much higher percent of land that is not built-upon. Perhaps this is influenced by the amount of un-buildable land (such as marshes or flood prone land) in a city’s center. Antananarivo stands out as being a landlocked city with a significant amount of unbuilt land near its core. Upon further inspection, a large amount of agriculture fields and rice paddies appear very close to the city center.

While further exploration of these trends is still necessary, these initial findings with SPOT5 not only demonstrate the utility of coarser imagery but also its limitations. Lastly, conducting inter-city comparison provides valuable insight into the changing shape of African cities.

Figure 20 – Detection of un-built areas



CONCLUSION

In order to provide an assessment of the morphology of African cities, this study began by examining the spatial distribution of population within several African cities, and the structural relationship population density has with transportation. It then took a closer look at the composition of the built environment by conducting a semi-automated classification of each city using high resolution imagery. This classification broke the city down into 9 land cover classes, such as irregular residential, regular residential and commercial/industrial. This classified layer was then analyzed across space as one leaves the city center towards the periphery with variations in the composition highlighted. In conclusion this paper presents a study that relies heavily on remotely sensed data that provide insight into the internal spatial structure of a city. In an exploration of additional sources of imagery, the algorithm was also used on coarser images for 16 cities, suggesting the advantages and costs of moving to alternative sources of imagery.

Annex

Spatial Indicators

To further characterize the urban form of these 4 cities, several spatial indicators were calculated to measure each city's structure. Of concern was the amount of sprawl in each city, the degree of clustering in various land cover classes, and the relative distances between residential land and commercial/industrial land. Similar to the population density gradients discussed at the beginning of this paper, these indicators reflect the degree of monocentricity, homogeneity, and compactness in each city.

Methodology

To begin, a 0.5x0.5km grid was created over each city. This grid functioned as the base unit of measurement for all the indicator analysis. All spatial data layers were aggregated to this resolution and joined to this grid.

Urban footprints (city boundaries) were created by combining a population density layer (Landsat) with an urban footprint layer (Global Human Settlement Layer - GHSL). Created by European Commission's Joint Research Centre (JRC), the GHSL offers a systematic and detailed representation of 'built-up' areas, and classifies each 30m pixel as 'built-up' if it intersects with a building or road.⁵⁴ In order to make these datasets comparable they were overlaid and summarized to the 0.5x0.5km grid.

Grid cells comprised of more than 10% built-up land and had more than 100 inhabitants were labeled as urban. These thresholds were created from visual interpretation, and are consistent with previous urban mapping studies.⁵⁵ While the city boundary created in this study differs from the administrative border, it more accurately reflects each city's physical 'built-up' land and hence it is better suited for inter-city comparisons.

Following the creation of the city footprints, the land cover classification layers were converted to 0.5x0.5km grids. Each grid cell was labeled as a class (vegetation, residential regular, residential irregular, etc.) based on the majority land cover class contained in that cell. The following analyses use only grid cells within a 15km buffer from the CBD.

Centrality

Urban sprawl is defined as areas with low density, and scattered, discontinuous, and commercial strip development patterns.⁵⁶ Sprawl reduces inner-urban connectivity and typically places higher transportation costs on families living in these areas. However, the effects of sprawl are not just felt in the areas experiencing sprawl, but are also felt by firms and employers in the inner city. Without a competitive workforce in the vicinity, employment centers may experience the ripples of sprawl in the form of increased costs of labor. Similarly, increased infrastructure investments, such as road networks, sewage pipes, and school systems are required to service these sprawling populations, placing a monetary burden on local governments as well.⁵⁷ Additionally, non-monetary effects of sprawl include increased air pollution, loss of natural land, and ecosystem fragmentation.⁵⁸

City decentralization is a common effect of sprawl, and leads to longer travel distances and time for households. To measure the degree to which development has diffused across the city, an index

⁵⁴ Pesaresi, M.; Guo Huadong; Blaes, X.; Ehrlich, D.; Ferri, S.; Gueguen, L.; Halkia, M.; Kauffmann, M.; Kemper, T.; Linlin Lu; Marin-Herrera, M.A.; Ouzounis, G.K.; Scavazon, M.; Soille, P.; Syrris, V.; Zanchetta, L., "A Global Human Settlement Layer From Optical HR/VHR RS Data: Concept and First Results," *Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of*, vol.6, no.5, pp.2102,2131, Oct. 2013 doi: 10.1109/JSTARS.2013.2271445.

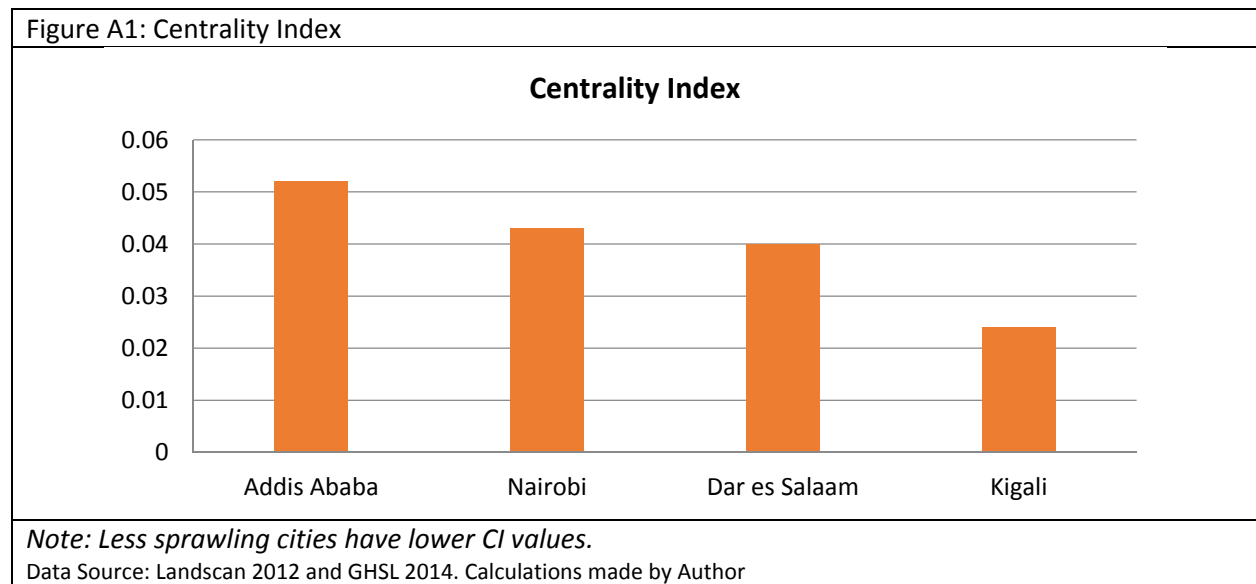
⁵⁵ Azar et al 2010. Spatial refinement of census population distribution using remotely sensed estimates of impervious surfaces in Haiti. *International Journal of Remote Sensing*. Taylor and Frances. page 5641.

⁵⁶ Ewing, Reid. 1997. Is Los Angeles-style sprawl desirable? *Journal of American Planning Association*, 63 (1): 107-126.

⁵⁷ Squires, Gregory. 2002. *Urban Sprawl: Causes, Consequences, & Policy Responses*. 2002. The Urban Institute: Washington, DC.

⁵⁸ Johnson, Michael. 2001. Environmental impacts of urban sprawl: a survey of the literature and proposed research agenda. *Environment and Planning A*, 33: 717-735.

developed by Galster et al. (2001) was adopted.⁵⁹ This Centrality Index (CI), measures the average distance of the population from the city center, normalized by the total area of the city. This measurement is slightly different than the density gradient, in that it is not influenced by the city's size, and therefore better suited to compare cities of different sizes. **Figure X** shows Nairobi and Addis having a higher level of centrality than Kigali, suggesting that Kigali is more compact and has a larger proportion of its population living close to the city center. Nairobi and Addis, on the other hand, have a slightly more polycentric population distribution. Decentralization of urban areas is often cited as a cause for longer travel distances or times and inefficiencies of land use. CI helps to understand the extent to which the urban area is characterized by a monocentric form as opposed to a polycentric form.



Clustering

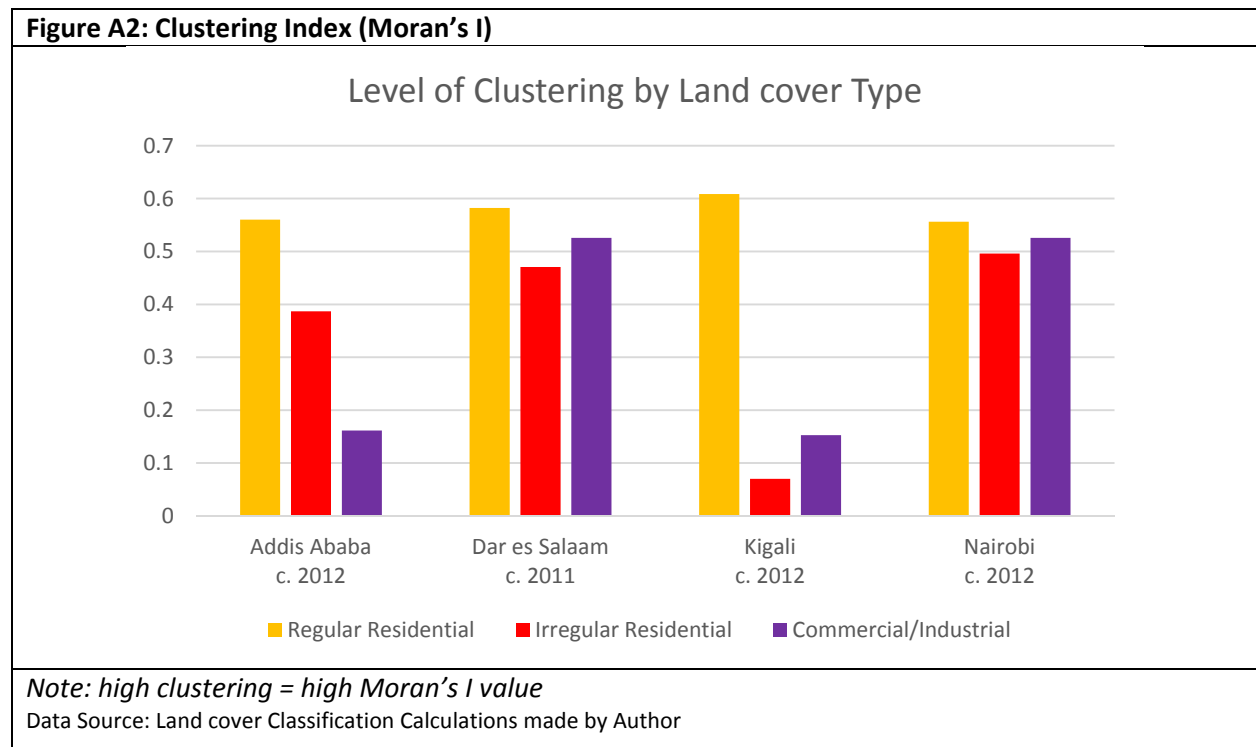
Building upon the notion of compactness, the study turns to measure the spatial clustering of land cover. Interested in understanding how disperse or clustered each land cover type was, a global Moran's I statistic was generated for Industrial/Commercial, Residential Regular, and Residential Irregular. Moran's I measures the spatial autocorrelation of features based on their location, in other words, the degree to which spatial features are similar to their neighbors. Cities where features are highly spatially correlated would have a Moran's I statistic closer to 1. A value closer to zero indicates little or no clustering.

Figure X shows the Moran's I value for each built-up land cover class in Nairobi, Dar es Salaam, Kigali, and Addis Ababa. Generally speaking from a land planning perspective, a high Moran's I value is seen as advantageous, as it suggests there are significant concentrations of land cover. A low Moran's I, in contrast, is often observed in decentralized, sprawling urban areas, as they experience strip and more discontinuous development.⁶⁰

⁵⁹ Galster, George, Hanson, Royce, Ratcliffe, Michael, Wolman, Harold, Coleman, Stephen, and Freihage, Jason. 2001. Wrestling Sprawl to the Ground: Defining and measuring an elusive concept. *Housing Policy Debate*, 12 (4), 681-717.

⁶⁰ Tsai, Yu-Hsin. 2005. Quantifying Urban Form: Compactness versus 'Sprawl'. *Urban Studies*, 42 (1): 141-161.

In this study, Nairobi and Dar es Salaam were found to have relatively medium levels of clustering in all three land classes, while Kigali and Addis have a wide range of dispersion (see figure X). Commercial and Industrial appear to be the most clustered in Dar es Salaam and Nairobi, which is not surprising given the large industrial park that traverses Dar es Salaam, and the large commercial area in the center of Nairobi. In Addis Ababa, the commercial/Industrial clustering is quite low, and much lower than its irregular residential land. This is likely due to the high percentage of irregular residential land found in the city center, and the small pockets of industrial/commercial land spread throughout the city. In Kigali, the clustering of the commercial and irregular residential land is quite low, which is reflective of the lack of any large central irregular residential neighborhoods or commercial/industrial land.



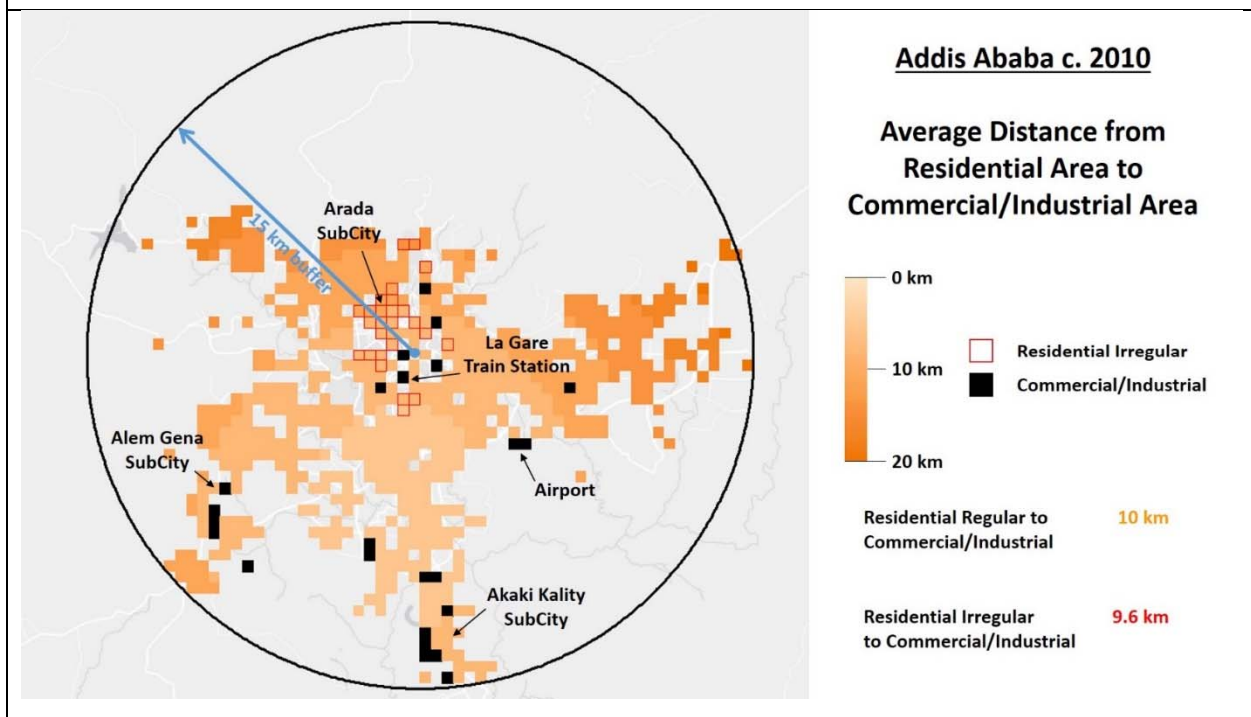
Euclidian Distance from Residential to Commercial/Industrial

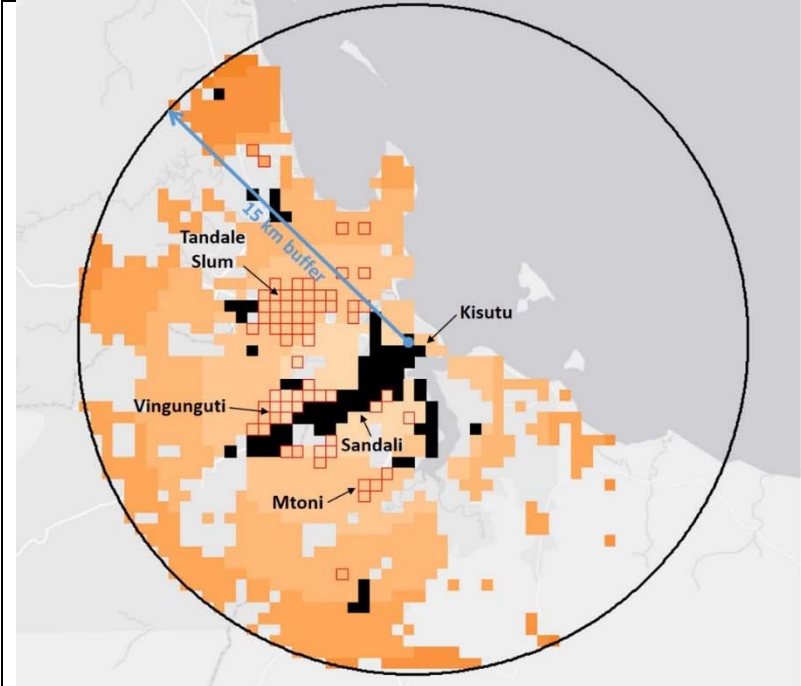
To study the spatial relationships between land cover classes, an average neighborhood distance indicator was developed. Using the land cover 0.5x0.5km grid, the distance from each residential grid cell to each commercial/industrial area was calculated. The distances were then averaged, producing a single value for each grid cell which represented the average distance between residential areas and commercial/industrial areas. Finally, all distances for residential regular and irregular neighborhoods were summarized as two values, showing the difference between the locations of regular and irregular residential areas relative to commercial activity.

In all four cities, the average distance from residential irregular to commercial/industrial areas was less than that to regular residential areas. This spatial pattern indicates that people living in residential regular neighborhoods have longer commutes to economic activity (i.e. commercial buildings and industrial zones), while people living in irregular residential neighborhoods are closer to such areas and do not travel as far.

The average distance from residential irregular to commercial/industrial in Addis Ababa is quite high, presumably due to the scattered pockets of commercial land cover, and the 'urban village' environment previously discussed. In contrast Kigali, has the shortest distances, which is probably due to its smaller size. Nairobi and Dar es Salaam have similar distances, with Dar es Salaam having only a slightly tighter distribution of residential to commercial/industrial.

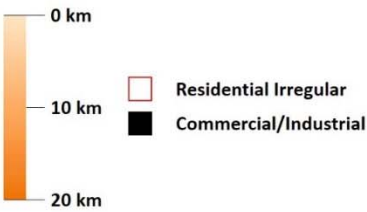
Figure A3: Average Distance from Residential Neighborhoods to Commercial/Industrial Areas





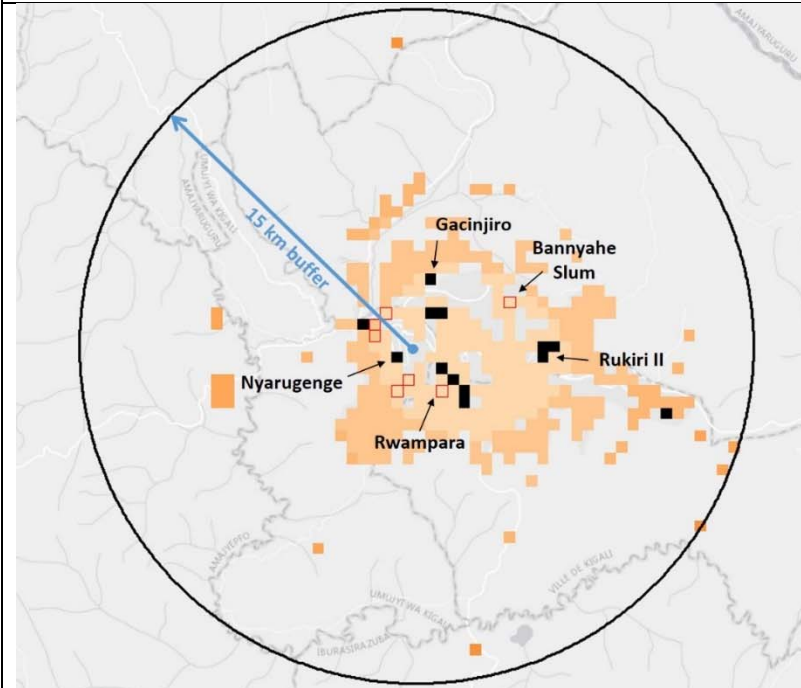
Dar es Salaam c. 2010

Average Distance from Residential Area to Commercial/Industrial Area



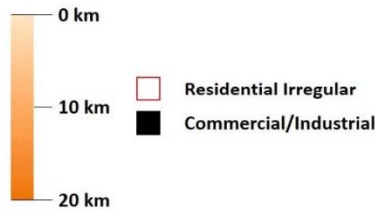
Residential Regular to Commercial/Industrial **8.9 km**

Residential Irregular to Commercial/Industrial **5.7 km**



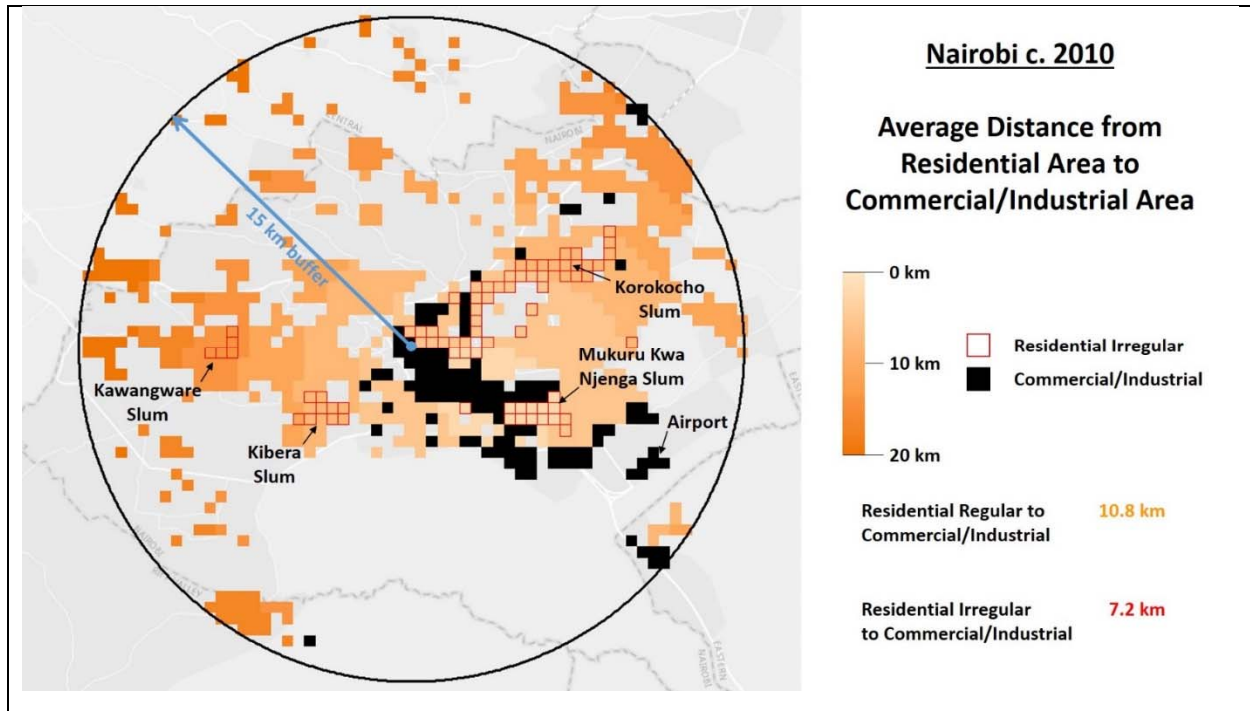
Kigali c. 2010

Average Distance from Residential Area to Commercial/Industrial Area



Residential Regular to Commercial/Industrial **5.8 km**

Residential Irregular to Commercial/Industrial **4.6 km**



Annex II

Figure A4: Accuracy Assessment Results

Addis Ababa c. 2000		Reference Data									Producer's Accuracy	User's Accuracy
		Regular Residential	Irregular Residential	Commercial/ Industrial	Vegetation	Bare Ground	Water	Paved Roads	Clouds/ Shadows	Total		
Classified Data	Regular Residential	42	0	0	1	7	0	0	0	50	76.36%	84.00%
	Irregular Residential	8	40	2	0	0	0	0	0	50	100.00%	80.00%
	Commercial/ Industrial	1	0	46	1	2	0	0	0	50	93.88%	92.00%
	Vegetation	1	0	0	44	4	0	1	0	50	81.48%	88.00%
	Bare Ground	0	0	0	6	44	0	0	0	50	66.67%	88.00%
	Water	0	0	0	0	3	47	0	0	50	100.00%	94.00%
	Paved Roads	3	0	1	2	6	0	38	0	50	97.44%	76.00%
	Clouds/ Shadows	0	0	0	0	0	0	0	50	50	100.00%	100.00%
	Total	55	40	49	54	66	47	39	50	400		
Overall Accuracy	0.878											
Kappa	0.860											

Addis Ababa c. 2010		Reference Data										
		Regular Residential	Irregular Residential	Commercial/Industrial	Vegetation	Bare Ground	Water	Paved Roads	Clouds/Shadows	Total	Producer's Accuracy	User's Accuracy
Classified Data	Regular Residential	46	0	1	1	2	0	0	0	50	76.67%	92.00%
	Irregular Residential	4	46	0	0	0	0	0	0	50	97.87%	92.00%
	Commercial/Industrial	3	0	44	0	3	0	0	0	50	97.78%	88.00%
	Vegetation	1	0	0	49	0	0	0	0	50	94.23%	98.00%
	Bare Ground	0	0	0	0	48	0	2	0	50	81.36%	96.00%
	Water	0	0	0	2	6	42	0	0	50	100.00%	84.00%
	Paved Roads	6	1	0	0	0	0	43	0	50	95.56%	86.00%
	Clouds/Shadows	0	0	0	0	0	0	0	50	50	100.00%	100.00%
	Total	60	47	45	52	59	42	45	50	400		
Overall Accuracy	0.920											
Kappa	0.909											

Dar es Salaam c. 2000		Reference Data										
		Regular Residential	Irregular Residential	Commercial/Industrial	Vegetation	Bare Ground	Water	Paved Roads	Clouds/Shadows	Total	Producer's Accuracy	User's Accuracy
Classified Data	Regular Residential	47	0	0	0	3	0	0	0	50	71.21%	94.00%
	Irregular Residential	9	41	0	0	0	0	0	0	50	100.00%	82.00%
	Commercial/Industrial	0	0	44	1	5	0	0	0	50	95.65%	88.00%
	Vegetation	4	0	0	38	8	0	0	0	50	86.36%	76.00%
	Bare Ground	1	0	1	2	46	0	0	0	50	68.66%	92.00%
	Water	0	0	0	0	0	50	0	0	50	100.00%	100.00%
	Paved Roads	5	0	1	3	5	0	36	0	50	100.00%	72.00%
	Clouds/Shadows	0	0	0	0	0	0	0	50	50	100.00%	100.00%
	Total	66	41	46	44	67	50	36	50	400		
Overall Accuracy	0.880											
Kappa	0.863											

Dar es Salaam c. 2010		Reference Data										Producer's Accuracy	User's Accuracy
		Regular Residential	Irregular Residential	Commercial/ Industrial	Vegetation	Bare Ground	Water	Paved Roads	Clouds/ Shadows	Total			
Classified Data	Regular Residential	43	1	1	2	3	0	0	0	50	71.67%	86.00%	
	Irregular Residential	2	47	0	1	0	0	0	0	50	94.00%	94.00%	
	Commercial/ Industrial	0	1	40	0	4	0	5	0	50	93.02%	80.00%	
	Vegetation	3	0	0	46	1	0	0	0	50	83.64%	92.00%	
	Bare Ground	1	0	0	3	45	0	1	0	50	77.59%	90.00%	
	Water	0	0	0	1	4	45	0	0	50	100.00%	90.00%	
	Paved Roads	11	1	2	2	1	0	33	0	50	84.62%	66.00%	
	Clouds/ Shadows	0	0	0	0	0	0	0	50	50	100.00%	100.00%	
	Total	60	50	43	55	58	45	39	50	400			
	Overall Accuracy	0.873											
Kappa	0.854												

Kigali c. 2000		Reference Data										Producer's Accuracy	User's Accuracy
		Regular Residential	Irregular Residential	Commercial/ Industrial	Vegetation	Bare Ground	Water	Paved Roads	Clouds/ Shadows	Total			
Classified Data	Regular Residential	44	0	0	3	3	0	0	0	50	80.00%	88.00%	
	Irregular Residential	8	40	2	0	0	0	0	0	50	97.56%	80.00%	
	Commercial/ Industrial	1	0	45	0	3	0	1	0	50	93.75%	90.00%	
	Vegetation	0	0	0	47	3	0	0	0	50	69.12%	94.00%	
	Bare Ground	0	0	0	6	44	0	0	0	50	75.86%	88.00%	
	Water	0	0	0	2	2	46	0	0	50	100.00%	92.00%	
	Paved Roads	2	1	1	10	3	0	33	0	50	97.06%	66.00%	
	Clouds/ Shadows	0	0	0	0	0	0	0	50	50	100.00%	100.00%	
	Total	55	41	48	68	58	46	34	50	400			
	Overall Accuracy	0.873											
Kappa	0.854												

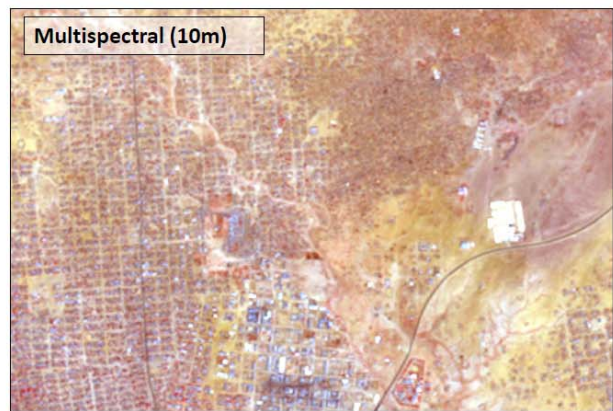
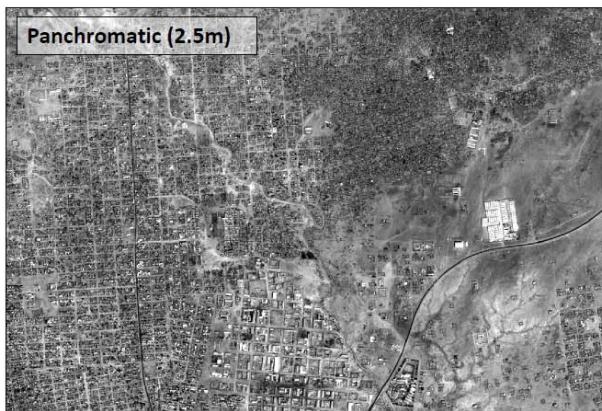
Kigali c. 2010		Reference Data										
		Regular Residential	Irregular Residential	Commercial/Industrial	Vegetation	Bare Ground	Water	Paved Roads	Clouds/Shadows	Total	Producer's Accuracy	User's Accuracy
Classified Data	Regular Residential	41	0	0	4	5	0	0	0	50	78.85%	82.00%
	Irregular Residential	6	41	2	0	1	0	0	0	50	100.00%	82.00%
	Commercial/Industrial	0	0	45	0	5	0	0	0	50	90.00%	90.00%
	Vegetation	0	0	0	45	5	0	0	0	50	69.23%	90.00%
	Bare Ground	0	0	0	7	43	0	0	0	50	72.88%	86.00%
	Water	0	0	0	2	0	48	0	0	50	100.00%	96.00%
	Paved Roads	5	0	3	7	0	0	35	0	50	100.00%	70.00%
	Clouds/Shadows	0	0	0	0	0	0	0	50	50	100.00%	100.00%
	Total	52	41	50	65	59	48	35	50	400		
	Overall Accuracy	0.870										
Kappa	0.851											

Nairobi c. 2000		Reference Data										
		Regular Residential	Irregular Residential	Commercial/Industrial	Vegetation	Bare Ground	Water	Paved Roads	Clouds/Shadows	Total	Producer's Accuracy	User's Accuracy
Classified Data	Regular Residential	46	0	2	1	1	0	0	0	50	83.64%	92.00%
	Irregular Residential	2	45	3	0	0	0	0	0	50	95.74%	90.00%
	Commercial/Industrial	3	0	41	2	3	0	1	0	50	85.42%	82.00%
	Vegetation	1	0	0	46	3	0	0	0	50	80.70%	92.00%
	Bare Ground	0	0	0	2	48	0	0	0	50	84.21%	96.00%
	Water	0	0	0	1	2	47	0	0	50	100.00%	94.00%
	Paved Roads	3	2	2	5	0	0	38	0	50	97.44%	76.00%
	Clouds/Shadows	0	0	0	0	0	0	0	50	50	100.00%	100.00%
	Total	55	47	48	57	57	47	39	50	400		
	Overall Accuracy	0.903										
Kappa	0.889											

Nairobi c. 2010		Reference Data										
		Regular Residential	Irregular Residential	Commercial/Industrial	Vegetation	Bare Ground	Water	Paved Roads	Clouds/Shadows	Total	Producer's Accuracy	User's Accuracy
Classified Data	Regular Residential	49	1	0	0	0	0	0	0	50	79.03%	98.00%
	Irregular Residential	2	45	3	0	0	0	0	0	50	93.75%	90.00%
	Commercial/Industrial	7	0	39	0	4	0	0	0	50	90.70%	78.00%
	Vegetation	0	0	0	49	1	0	0	0	50	89.09%	98.00%
	Bare Ground	0	0	0	1	49	0	0	0	50	90.74%	98.00%
	Water	0	0	0	3	0	47	0	0	50	100.00%	94.00%
	Paved Roads	4	2	1	2	0	0	41	0	50	100.00%	82.00%
	Clouds/Shadows	0	0	0	0	0	0	0	50	50	100.00%	100.00%
	Total	62	48	43	55	54	47	41	50	400		
	Overall Accuracy	0.923										
Kappa	0.911											

Annex III

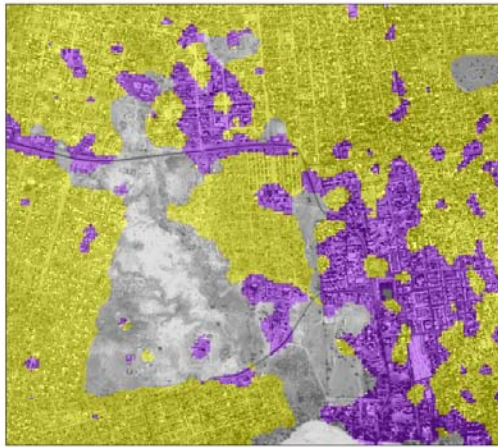
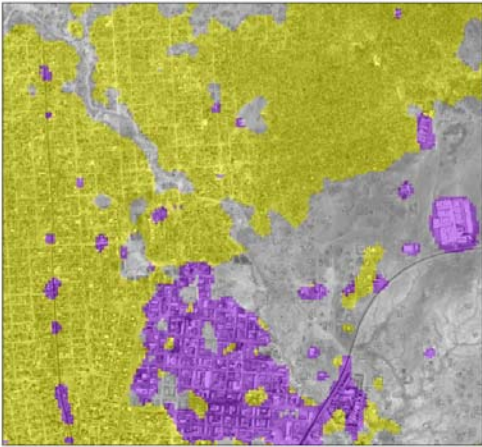
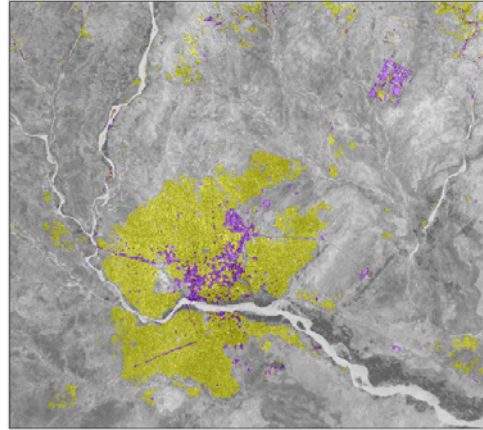
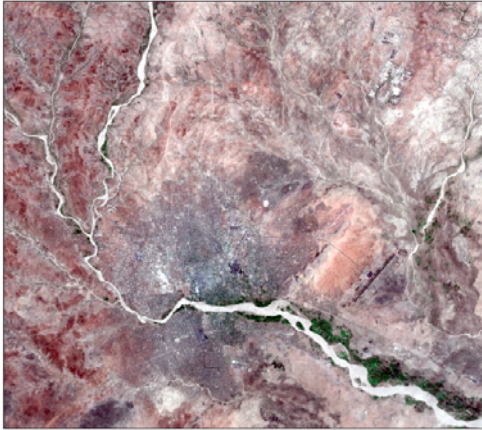
Spot 5 Imagery



3 Classes

- Residential (Small Buildings)
- Commercial/Industrial (Large Buildings)
- Natural (Vegetation, soil, water)

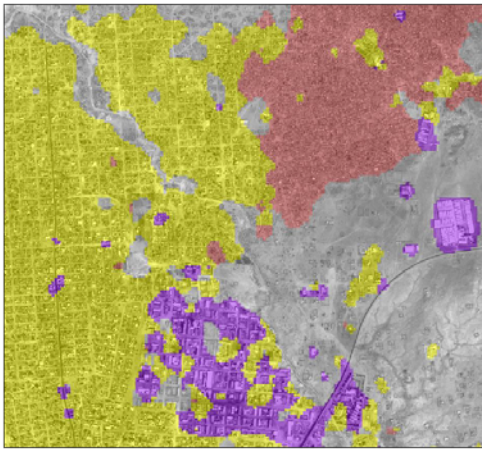
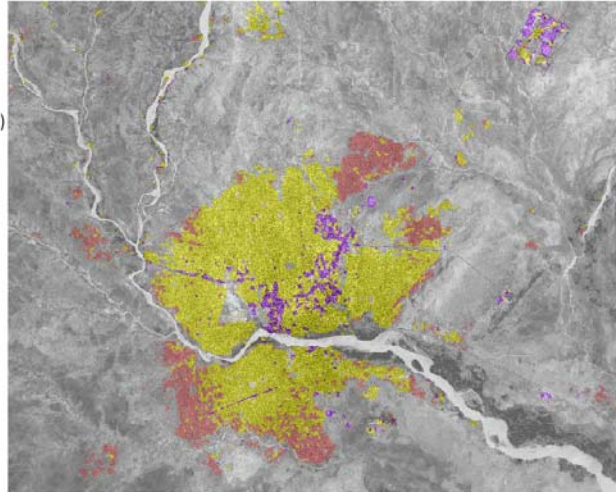
Overall Accuracy: 78.67%



4 Classes

- Residential Regular (Small Buildings)
- Residential Irregular (Small Buildings)
- Commercial/Industrial (Large Buildings)
- Natural (Vegetation, soil, water)

Overall Accuracy: 69.50%

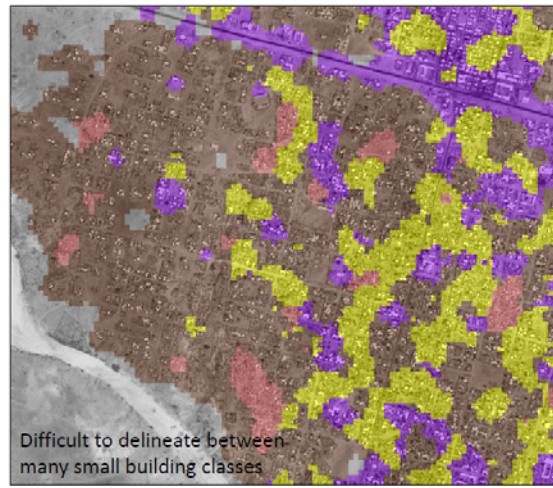
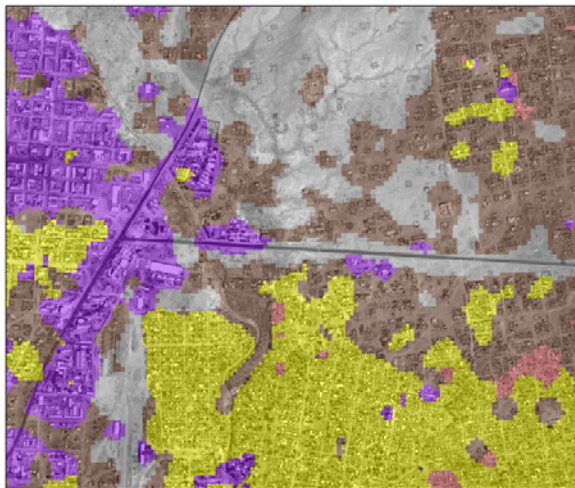
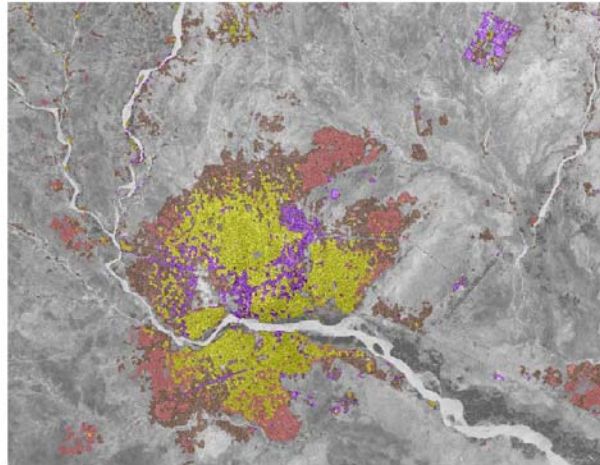


Misclassifies the gridded sparse residential land as irregular residential

5 Classes

- Residential Regular (Small Buildings)
- Residential Irregular (Small Buildings)
- Residential Sparse (Small Buildings)
- Commercial/Industrial (Large Buildings)
- Natural (Vegetation, soil, water)

Overall Accuracy: 58.00%



Annex IV

Population Density Gradients

