ACC DAR Adapting to Climate Change in Coastal Dar es Salaam

INVESTIGATING THE RELATIONSHIP BETWEEN LAND COVER AND VULNERABILITY T0 CLIMATE CHANGE IN DAR ES SALAAM

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Acronyms and Abbreviations

ACC Dar – Adapting to Climate Change in Coastal Dar es Salaam
AHS – Average Household Size
GIS – Geographic Information System
GPS – Global Positioning System
IHH – Interviewed Household
LC – Land Cover
LCC – Land Cover Change
NDVI – Normalized Difference Vegetation Index
UDEM – Urban Development and Environment Management

Glossary

Land Cover – The "physical material at the surface of the earth. It is the material that we see and which directly interacts with electromagnetic radiation and causes the level of reflected energy that we observe as the tone or the digital number at a location in an aerial photograph or satellite image. Land covers include grass, asphalt, trees, bare ground, water, etc." (Fisher et al., 2005, p.89).

Land Cover Change – The detection of changes in Land Cover, usually through analysis of multitemporal data; in remote sensing, Land Cover Change will result in changes in reflectance values (Lu et al., 2011).

Land Use – The "description of how people use the land. Urban and agricultural land uses are two of the most commonly recognised high-level classes of use. Institutional land, sports grounds, residential land, etc. are also all land uses" (Fisher et al., 2005, p.89).

Remote Sensing – The measurement of the energy emanating from the earth's surface, using a sensor mounted on an aircraft or spacecraft platform, in order to obtain an image of the landscape beneath the platform (Richards & Jia, 2006).

Urban Sprawl – The unplanned, low-density urban expansion, characterized by a mix of land uses on the urban fringe (EEA, 2006), which "happens when population growth and the physical expansion of a city are misaligned" (UN-HABITAT, 2010, p.10).

Vulnerability – The "degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes" (IPCC, 2001, p.21).

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1. Introduction, Scope, and Motivation

1.1 Background

The ACC Dar project aims to improve the effectiveness of municipal initiatives in Dar es Salaam for supporting the efforts of coastal peri-urban dwellers, who are partially or totally dependent on natural resources, to adapt to Climate Change (CC) impacts. More specifically, the action will enhance the capacities of Dar's municipalities by increasing their understanding of adaptation practices and by providing them with enhanced methodologies for mainstreaming adaptation into their Urban Development and Environment Management (UDEM) strategies and plans. The achievement of these objectives will contribute to the overall goal of improving implementation of the National Adaptation Programme of Action (NAPA) of the United Republic of Tanzania.
The present report presents the results of Activity 2.1 of the Project, which focuses on the development of methodologies for monitoring Land Cover Changes (LCC) in the Dar es Salaam region. In fact, LCC in the form of urban sprawl is considered a non-climatic factor that could amplify climate change impacts while reducing people's adaptive capacity in coastal peri-urban areas of Dar es Salaam, thus worsening the vulnerability of the growing population living there.
Activity 2.1 draws upon the results from the household survey conducted in 2011 (Activity 1.2) and the participatory workshops held at the community level in 2012 (Activity 1.3), both aiming at exploring the peri-urban lifestyles of people living within the coastal plain as well as their strategies for coping with major changes in their living environment. Meanwhile, the activity reported here represents the first step in the process of developing a methodology for the participatory design of institutional adaptation initiatives, which is the ultimate goal of Work Package 2 of the Project.

1.2 Goals and Scope

The overall objective of the research study undertaken in Activity 2.1 of the Project is to advance LCC assessment methods and an understanding of its drivers in the Dar es Salaam region, with a special focus on peri-urban development within the coastal plain.

The specific goals pursued by the working team based at Sapienza University of Rome are as follows:

- development and validation of a methodology for monitoring Land Cover (LC) that allows for observation of the urban sprawl phenomenon and can be adapted to the needs of the Local Authorities in the Dar es Salaam region. More specifically, the monitoring technique must be: i) economical, in order to guarantee practicability for municipal services; ii) simple, in order to allow for regular updating of land use information; iii) quick to execute, in order to reveal the land cover changes in a very dynamic area;
- analysis of the urban development dynamics occurring in the Dar es Salaam region over the last decade in order to assess the change patterns which prevailed, leading to either the densification or the sprawling of peri-urban areas. This analysis will also provide the opportunity for testing LCC indicators from the literature in order to select an easy-to-use indicator of urban sprawl to be adopted by municipal services for further assessment;
- investigation of the relationships between urban sprawl and population growth, two phenomena which are usually considered misaligned but nevertheless seem to be highly correlated in the Dar es Salaam region. A deeper knowledge of the actual correlation linking them will pave the way to the development of new methods for estimating the regional population from LC classification datasets, which is crucial for the management of fast growing cities like Dar es Salaam, especially for interim years between two censuses.

1.3 Motivation

In climate change adaptation literature it is widely acknowledged that the assessment of vulnerability should be based on the analysis of the interaction of climatic, environmental, and human factors. In fact, reducing vulnerability also means addressing its underlying drivers, which include, besides climate change effects, those non-climatic factors that play an important role in determining impacts and shaping adaptive capacity.

The relevance of non-climatic factors is especially evident in urban areas, notwithstanding the differences among regions and countries. Settlement patterns, urbanization, and changes in socioeconomic conditions all influence the three key components of vulnerability, i.e. exposure, sensitivity, and adaptive capacity. As a special feature of developing countries, rapid urbanization and the growth of megacities have led to the emergence of highly vulnerable urban communities, particularly through informal settlements and inadequate land management.
This is even truer for coastal cities like Dar es Salaam, because the physical environment there is more exposed and sensitive to climate change than elsewhere, thus resulting in more serious impacts (Nicholls et al., 2007). A typical example is the reduced access to water for people relying on the coastal watershed due to the seawater intrusion phenomenon, which is expected to be exacerbated by the combined effects of climate change (rainfall decrease, temperature and sea-level rise) and urban sprawl (increase in soil sealing and groundwater extraction rates).
Urbanization itself is not always a driver of increased vulnerability. Instead, the type of urbanization and the context in which urbanization is embedded defines whether these processes contribute to an increase or decrease in people's vulnerability. Development planning, including land use and urban planning, river basin and land management, hazard-resistant building codes, and landscape design are all activities that can reduce exposure and vulnerability to hazards and change (Cardona et al., 2012). The ability to carry these activities out in an effective way is part of local capacity for adaptation, but all of them need time to produce significant effects and require a significant effort to develop future scenarios under conditions of climate change and continuous urban sprawl.
The research reported here seeks to contribute to this effort through the enhancement of knowledge of the relationship between LCC and climate change vulnerability in coastal Dar es Salaam.

2. Approach and Methods

2.1 Overall Approach

LC is the description of the materials at the Earth's surface, with a focus on the physical characteristics thereof, for example: vegetation, soil, water, and asphalt. LC differs from land use, which is the way people use the territory and is defined according to categories such as: residential, agricultural, industrial, or sporting (Fisher et al., 2005).
LC is changed by human activities (i.e. LCC), which alter the soil surface according to need. According to the IPCC (2001, p.26), LCC is a non-climatic driver of environmental change, and it influences climate change for three reasons:

1. Soil plays a role in carbon fluxes and greenhouse gas emissions;
2. The characteristics of land surfaces indirectly affect climate processes;
3. LCC can alter the vulnerability of ecosystems to climate change.

Dar es Salaam's coastal plain is intensely suffering from a particular kind of LCC, namely urban sprawl, which is characterized by low-density development at the urban fringe that consists of a mixture of agricultural and urban land uses.
This study assumes that in the Dar es Salaam region, as in most fast-growing Sub-Saharan cities,

- firstly, urban sprawl represents the major non-climatic factor influencing the vulnerability to climate change of people living in peri-urban areas. As such, the assessment of land cover changes over time is crucial to the preparation of adaptation measures by Local Authorities
- secondly, population growth is the major driver for urban sprawl, even if the correlation between these two phenomena requires must be further analyzed for the relationship linking them to be better understood. Urban sprawl "happens when population growth and the physical expansion of a city are misaligned" (UN-HABITAT, 2010, p.10).

Urban sprawl involves a process of soil sealing, where natural surfaces are converted to impervious ones, which in turn has a series of consequences for the environment, local climate, and water balance (Scalenghe & Marsan, 2009). Those consequences lead to an increase in people's vulnerability to climate change, due to the vicious circle that ties urban sprawl, environmental change, and people's adaptation strategies. A conceptual framework of the relationship between LCC and climate change vulnerability is shown in Figure 1.

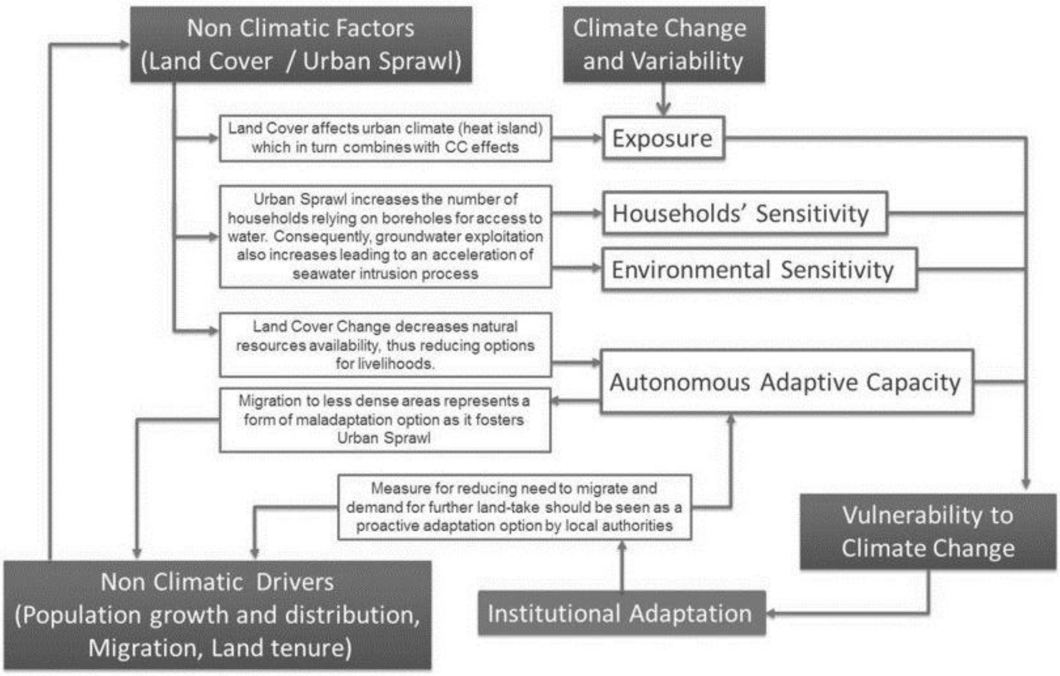

Figure 1: Relationship between LCC and climate change vulnerability in coastal Dar es Salaam

Urban sprawl affects urban climate (e.g. heat island), which in turn combines with Climate Change effects on temperature and rainfall patterns, leading to an increase in expected exposure to Climate Change. Urban sprawl can also increase the number of households relying on boreholes for access to water (human sensitivity), as it entails a growing number of households living in new and underserviced peri-urban neighbourhoods. Consequently, groundwater exploitation also rises, leading to an acceleration of seawater intrusion processes (natural sensitivity). The decrease in groundwater availability results in a reduction of livelihood options and, consequently, of people's adaptive capacity. People may also decide to adapt to changes in environmental conditions by moving further away from the city, thus accelerating the sprawling process (maladaptation).
Therefore, a better understanding of the factors driving urban sprawl dynamics is required in order to design institutional adaptation measures that will be effective in slowing the process of vulnerablization.
A tentative list of those drivers includes the following:

- population growth and distribution;
- migration (internal and external);
- a lack of legal frameworks and land controls;
- land speculation;
- the livelihood strategies of households.

Dar es Salaam's population rose from 870,000 inhabitants in 1978 to about 1.4 million in 1988 (Briggs, 1991), and to 2.5 million in 2002 (United Republic of Tanzania, 2006a). Figures from the 2012 census are not yet available, but local media have estimated a total population of more than 5 million people to date.
Such demographic growth is mainly the result of migration flows from upcountry. External migration is acknowledged as the major cause of Dar's urban sprawl, as migrants have predominantly purchased inexpensive houses in poor areas (Kombe, 2005), which has led to rapid expansion in unplanned areas of the city. It is worth mentioning that migration is a common strategy for adaptation to environmental change in Sub-Saharan Africa (FORESIGHT, 2011). People living in deteriorating areas migrate to other zones, altering the environment (e.g. deforestation, urbanization) and actually increasing vulnerability at the regional level through LCC and the effects thereof.
External migration aside, the contributions of internal migration to urban sprawl should not be overlooked. People from the city centre have moved towards more affordable and/or suitable areas of the periphery for a series of reasons that have changed over time. According to Briggs and Mwamfupe (2000), during the 1980's, households bought land in the periphery to produce their own food, while in the '90's they also did so as an investment in commercial agriculture.
In light of the population growth rate, legal frameworks and land control also represent important drivers of urban sprawl, as they motivate people to move away from already developed urban areas. In fact, the unofficial system of land delivery seems to be faster than the official one at providing plots (Kironde, 1997). Informal development has happened independently of whether areas were planned or not because the land tenure regime tends to slow down the purchase and sale of land (Kironde, 2006).
Land speculation is another driver of urban sprawl. In the 1980s, land assumed monetary value (Briggs, 1991) notwithstanding the fact that it was considered public (Kironde, 1997), and trade liberalization allowed for investments and rent-seeking activities in the peri-urban areas (Briggs & Mwamfupe, 2000). The relatively recent policy of land formalisation "Property and Business Formalisation Programme" (known as MKURABITA), seems to have encouraged investment in the peri-urban due to the additional value gained by registered land; registered land located in the city centre is sold by the owner in order to then buy other land in the periphery (where prices are lower), thereby earning a profit (Briggs, 2011).
Lastly, urban sprawl dynamic also pushes people whose livelihoods rely, in whole or in part, on agriculture towards the periphery of the urban region. This is reflected by the mix of urban and rural features that characterize the peri-urban areas and play an important role in the livelihood strategies of the people living there (Ricci et al., 2012). When their urban neighbourhoods become too densely built-up, such people tend to move to new areas where the natural resources they rely on are still available.

2.2 Data Collection and Methodology

The assessment of LCC in the present study is based on LC classification through remote sensing and GIS techniques. LC classification only requires information about the reflected electromagnetic

radiation (i.e. radiance), provided by satellite imagery. Land use classification, on the other hand, requires data about the planned and unplanned uses of territory, which are not always available (especially for informal settlements).
The research consisted of the following phases:

1. Assessment of data sources and software for image analysis, and development of the methodology for semi-automatic LC classification;
2. Image acquisition and data analysis for the production of multi-temporal LC maps;
3. Validation of Land Cover maps (accuracy assessment);
4. Change assessment of built-up areas over time (urban sprawl);
5. Investigation of the links between LC and people's vulnerability to climate change.

The developed methodology for LC classification has focused on urban development patterns, and is intended to be affordable, rapid, and reliable. As such, the research has emphasized the use of freely available data as well as the definition of tools and methods for LC classification and LCC assessment that are especially reliable for urban areas, available at little cost, and easy to use.

LC classifications were produced using Landsat data, which are provided for free by the United States Geological Survey. Landsat is a family of multispectral satellites. The images used in this study were acquired by Landsat 5 and Landsat 7 sensors over the period 1999-2011. These Landsat satellites sense several bands of the electromagnetic spectrum and have a spatial resolution of 30m, which corresponds to a 900m^2 pixel.

Besides Landsat data, SPOT imagery provided for free by the European Space Agency was also taken into consideration. SPOT satellite images have a spatial resolution of 10m, which would allow for more detailed LC analysis than is possible using Landsat ones. Nevertheless, Landsat imagery was chosen for the present study because it was available over a longer period, and because a 900m^2 pixel is small enough to capture the required detail while large enough to ensure computer storage and analysis to be performed efficiently.

The whole activity was performed using a computer with the following specifications: Intel Core 2 Duo CPU E8500 @ 3.16 GHz; 4GB of RAM; NVIDIA GeForce 9600GT graphic card; Windows 7 64bit operating system. The above system characteristics are quite affordable at present, and they are also compatible with the software used, namely ERDAS IMAGINE 2011 and ArcGIS 10.0.

An LC classification methodology was developed using data from both sources (Congedo & Munafò, 2012a, 2012b), and based on algorithms for a semi-automatic identification of materials that labelled image pixels according to the spectral characteristics of the covering materials (Richards & Jia, 2006).

The reflected solar energy bands in the visible and infrared spectrum were used for LC classification. The image processing workflow is shown in Figure 2. The main advantage of the developed methodology is the rapidity and affordability of LC classification, particularly for a large area like Dar es Salaam (Congedo & Munafò, 2013).

In order to further decrease the costs of the methodology, a plugin for the open-source software QGIS (free and usable on free operating systems such as Linux) was developed that allows for the semi-automatic classification of remote sensing images.

LC classifications focused on the identification of dense urban patterns (i.e. "Continuously Built-up"), and low-density development patterns (i.e. "Discontinuously Built-up"). This allowed for the assessment of changes in developed urban land over the period 2002-2011. Also, an indicator was calculated for the purpose of providing a reliable tool for the assessment of urban sprawl over time.

As part of the investigation of the links between LC and people's vulnerability to climate change, a method of population estimation was also developed, based on an integrated GIS spatial analysis of the LC classifications and a dataset of household locations drawn from a survey conducted in the coastal plain of Dar es Salaam in 2011. In order to evaluate the reliability of this method, the 2002 estimates were compared with 2002 census data (United Republic of Tanzania, 2006a).

The main findings regarding LCC in Dar es Salaam, as well as the method and results of population estimation, are explained in the following chapter.

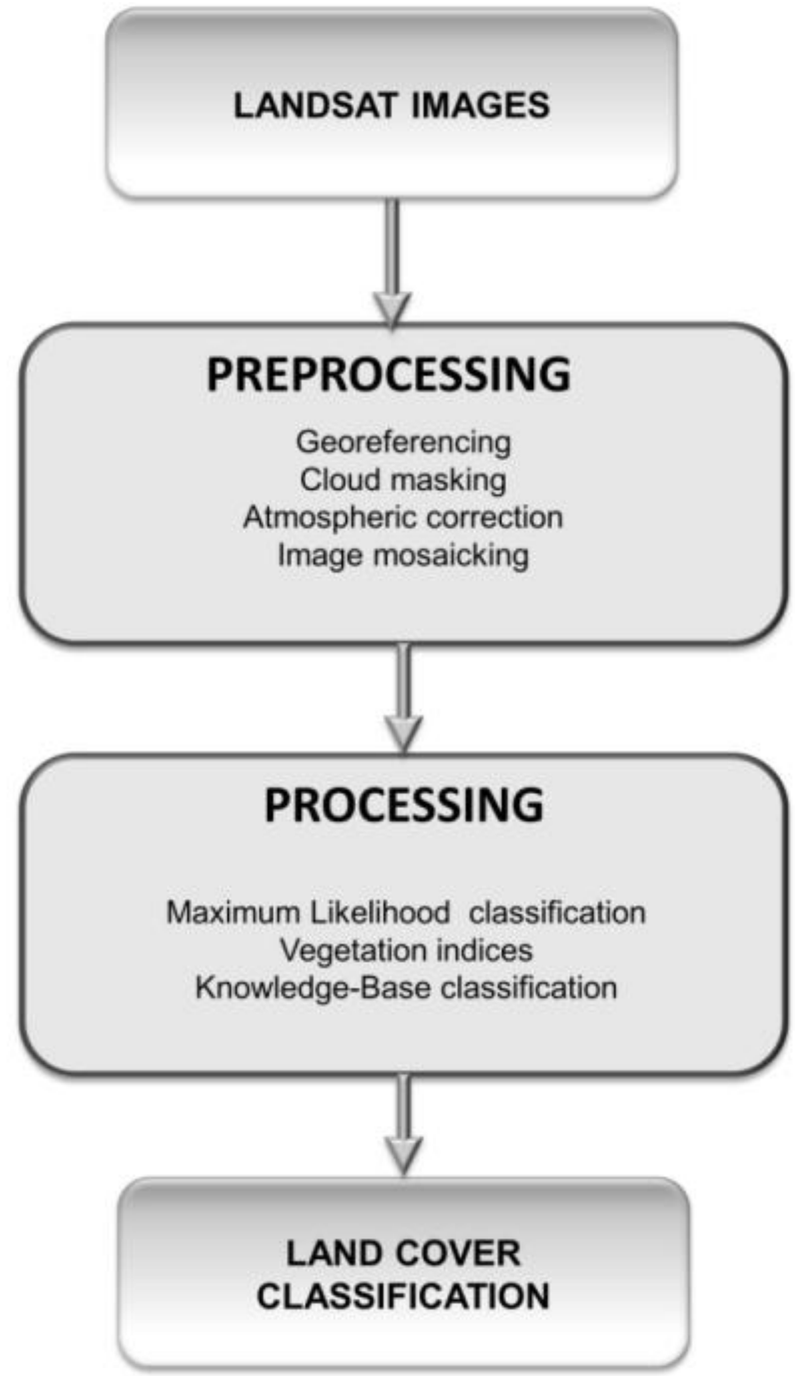

Figure 2: Image processing workflow

3. Findings

The overall findings consist of the following:

- a methodology for land cover classification based on remote sensing and GIS technologies, which has been used to prepare Land Cover maps for years 2002, 2004, 2007, 2009, and 2011;
- assessment of LCC occurring in the Dar es Salaam region over the period 2002-2011, with a special focus on urban development dynamics observed through analysis of LC classifications;
- analysis of the correlation between demographic growth and urban sprawl, including the development of a method for estimating the population and its spatial distribution.

The findings related to the second and third points above are fully reported in the present papers, while those concerning the first point are reported in a summary fashion, as a number of detailed papers on that topic have been already published on the Project website (Congedo & Munafò, 2012a, 2012b, 2012c, 2013).

As a general conclusion, it is worth noticing that the results demonstrate that LC monitoring through remote sensing allows for an affordable and reliable production of data related to LC in the Dar es Salaam region. In addition, by drawing on these data, understanding of urban development dynamics can easily be enhanced, and some useful information produced (as is the case for demographic projections), thus providing Dar's Local Authorities with the tools necessary for improved planning processes. Lastly, better knowledge of urban sprawl as the major driver of change in the Dar es Salaam region enhances the capacity for proactive institutional adaptation, since urban sprawl and climate change will combine their effects on the natural resources that peri-urban populations rely upon.

3.1 Land Cover Change Assessment

3.1.1 Technical notes on LC classifications

Applying the methodology described in Congedo and Munafò (2012a), LC classifications were produced from Landsat images for the years: 2002, 2004, 2007, 2009, and 2011.

The whole Dar es Salaam region (i.e. 1,690 km^2) was categorized according to six LC classes, as described in Table 1.

Table 1: Description of the six LC classes identified

Class	Description	Example Profile
Continuously Built-up	densely developed class whose pixels are characterized by homogeneity of urban cover	Figure 11, Appendix 1
Discontinuously Built-up	low-density development class, whose mixed pixels are characterized by a variety of land cover types, including urbanized, vegetation, and bare soil	Figure 12, Appendix 1
Soil	bare soil class, or sparse vegetation (including dry grass)	Figure 13, Appendix 1
Full Vegetation	very green and abundant vegetation class (mainly trees and forests), whose pixels have a high NDVI value	Figure 14, Appendix 1
Mostly Vegetation	vegetation class that is less green than “Full Vegetation” (typically grass and brush), whose pixels have a medium NDVI value	Figure 15, Appendix 1
Water	surface water class	

LC classifications have a spatial resolution of 30m, which corresponds to a certain number of pixels (specifically, 1,877,725 pixels) a size that ensures computer storage and analysis can be performed efficiently. The accuracy assessment undertaken for the 2011 classification (Congedo & Munafò, 2012c) has demonstrated the reliability of these classifications in identifying the above classes, especially as concerns the two LC classes related to urban development (continuously and discontinuously built-up classes) which is the main focus of the activity. In fact, the fuzzy overall accuracy of the 2011 classification is 72%, and the accuracies of urban classes range between 93-98% for the “Continuously Built-up” and 72-77% for the “Discontinuously Built-up”.

The resulting LC maps are freely available at the ACC Dar website. A low-resolution version highlighting urban development classes is presented in Appendix 2 – Land Cover Classifications.
It should be noted that the areas related to other LC classes, such as “Soil” and “Mostly Vegetation”, are dependent on the season during which the remote sensing image is acquired (due to different states of vegetation). As a result, the proportions of these classes fluctuate from year to year, since LC classifications were produced using images acquired in several seasons (due to the lack of usable images caused by high cloud cover).

The datasets generated by the LC classifications have been analysed using a variety of techniques. The main results from these analyses are described in paragraphs 3.1.3 to 3.1.6. But first, a tool for improving the performance of open-source software products for semi-automatic LC classification is introduced in paragraph 3.1.2.

3.1.2 Semi-Automatic Classification Plugin for QGIS

LC monitoring through remote sensing requires specific software products, particularly for the semi-automatic classification of multispectral images, the methodology applied in this project.
Most software products are commercial and their purchase costs might be unaffordable for the technical services of local authorities in LDCs. A few open-source (and free) programs could be used as an alternative – like Orfeo Toolbox (http://www.orfeo-toolbox.org/otb/) and SAGA (http://www.saga-gis.org/en/index.html) – , but they lack some of the features that make classification easier.
In order to close this gap, a plugin (i.e. a program that adds features to another one) has been developed for Quantum GIS (http://www.qgis.org/), which is open-source software.
This plugin (Figure 3) relies on other open-source software (SEXTANTE plugin, Orfeo Toolbox, and SAGA), and allows for the collection of training areas through a region-growing algorithm (i.e. the selection of homogeneous pixels around a seed pixel of the image). The collected training areas have the advantage of being spectrally homogeneous, and therefore allow for a better definition of LC classes.

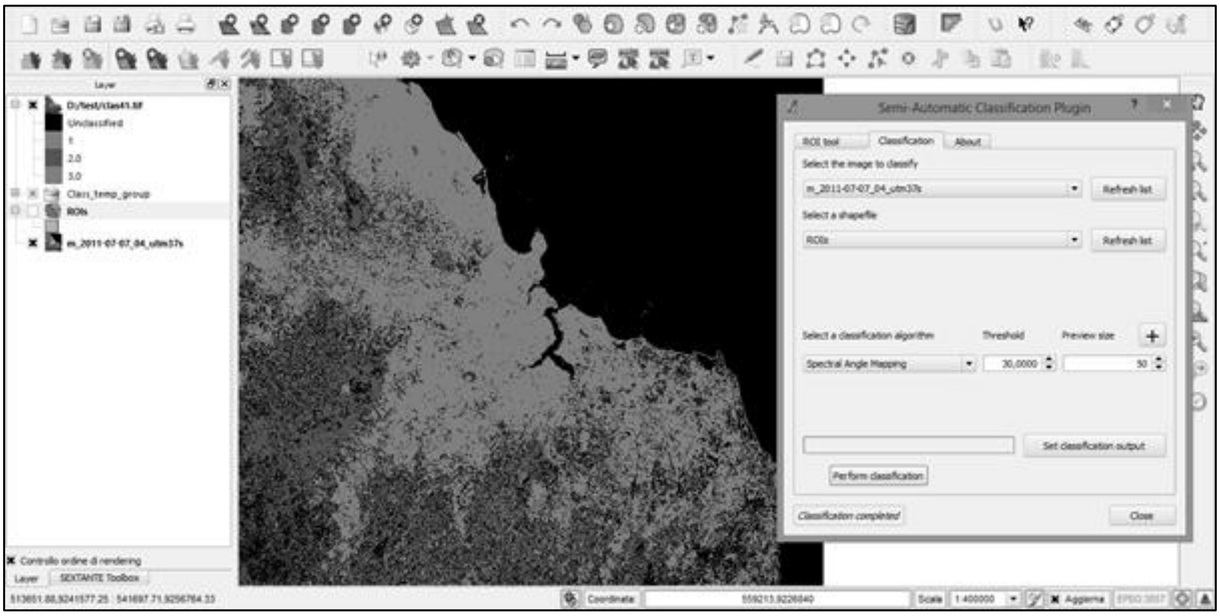

Figure 3: Screenshot of the Semi-Automatic Classification Plugin for QGIS

The plugin also allows for image classification using one of the following algorithms:

- Maximum Likelihood;
- Minimum Distance;
- Spectral Angle Mapping.

The Semi-Automatic Classification Plugin can satisfactorily replace commercial software for LC classification, making LC monitoring more affordable.
It is freely available at http://plugins.qgis.org/plugins/SemiAutomaticClassificationPlugin/, and an overview of its functionalities is available on the ACC Dar website (Congedo, 2013).

3.1.3 Analysis of built-up LC classes

The areas (in hectares) calculated for built-up LC classes are shown in Table 2, below, and in the charts in Figure 9 (Appendix 1). Table 3 then outlines the percentage increase of built-up LC classes since 2002.

Table 2: Area in hectares of built-up land cover classes

Class	2002	2004	2007	2009	2011
Continuously Built-up	8,415	10,025	10,447	12,370	14,808
Discontinuously Built-up	8,098	9,134	12,509	17,318	23,678

Table 3: Percentage increase of built-up land cover classes since 2002

Class	2004	2007	2009	2011
Continuously Built-up	19	24	47	76
Discontinuously Built-up	13	54	114	192

The “Continuously Built-up” class has grown from 8,415ha to 14,808ha in the period 2002-2011 (+76%), indicating the development of over 6,000ha of new built-up areas. In the same time period, the “Discontinuously Built-up” class grew even more, climbing from 8,098ha to 23,678ha (+192%), an increment of 15,580ha of new discontinuously built-up areas.
The increase of urban developed areas in the landscape is also reflected in the pie charts of Figure 10 (Appendix 1). In 2002, 5% of the total landscape was “Continuously Built-up”, while another 5% was “Discontinuously Built-up”. The progressive increase of urban development in 2011 had covered 23% of the total landscape, with 9% “Continuously Built-up” and 14% “Discontinuously Built-up”.

The estimate of impervious surfaces based on LC classification is influenced by the spatial resolution of the images used, which in this case is 30m, corresponding to a pixel size of 900m^2. Consequently, small and isolated buildings that are smaller than a pixel are not recognized. Moreover, only a portion of a pixel classified as built-up will correspond to a real impervious surface, while the rest could be vegetation or soil. Due to these elements of uncertainty, two ranges of accuracy have been defined for the built-up LC classes, according to the classification methodology. The impervious surface of a “Discontinuously Built-up” pixel is between 20% and 60% of the area thereof, while the impervious surface of a “Continuously Built-up” pixel is between 60% and 100%.
The impervious surface has been calculated for 2011 according to the above ranges (see Table 4). Results indicate that the total impervious area was approximately 14,000ha to 29,000ha (or between 8% and 17% of the total landscape area).

Table 4: Estimated impervious surface for 2011

Land Cover Class	**Estimated Impervious Surface** [ha]
Continuously Built-up	9,000 to 15,000
Discontinuously Built-up	5,000 to 14,000
	Total: 14,000 to 29,000

3.1.4 Assessment of Urban Development Dynamics

In order to provide an overall assessment of the urban development dynamics occurring from 2002 to 2011, two different analyses of the LC classifications were performed.
First, changes to urban developed land have been calculated for every period between available LC maps. Each LC classification was compared with the previous one and the increase in urban developed land was calculated.
Table 5 shows that the growth rate of the "Discontinuously Built-up" areas has been accelerating in every period from 2002 to 2011, with over 6000ha developed in the 2009-2011 period alone. The growth of the "Discontinuously Built-up" class has become preponderant since 2004 (Figure 4).

Table 5: Increase of land cover size (in hectares)

Land Cover Class	**2002-2004**	**2004-2007**	**2007-2009**	**2009-2011**
Continuously Built-up	1,609	422	1,924	2,438
Discontinuously Built-up	1,036	3,374	4,809	6,360

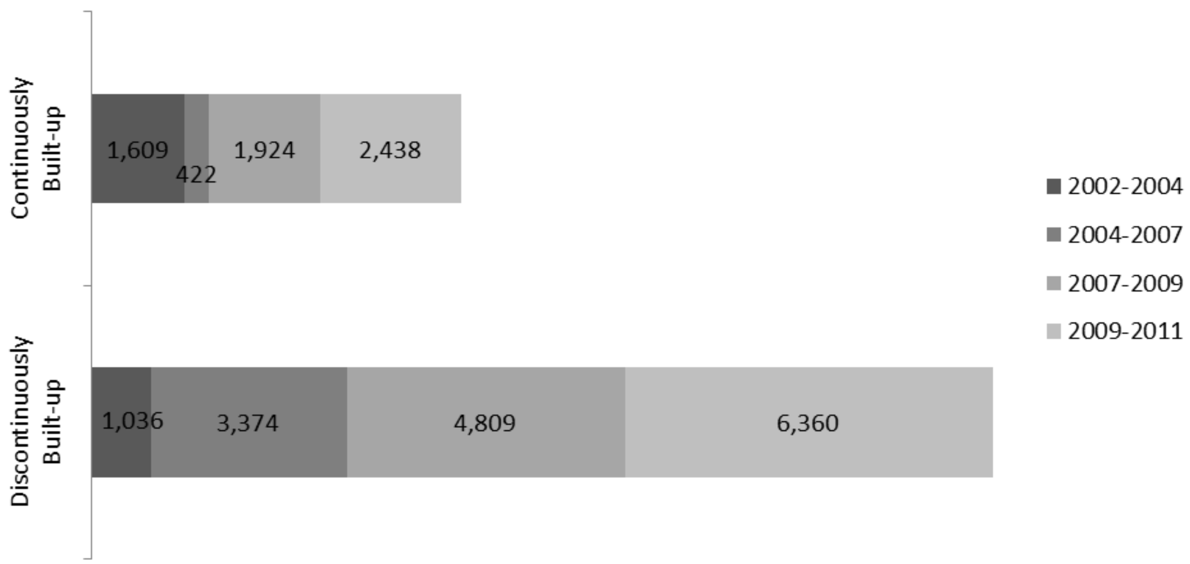

Figure 4: Chart of the increase in land cover (in hectares) from 2002 to 2011

Second, a comparison between the LC classifications for years 2002 and 2011 has been conducted. The map in Figure 5 highlights the main LC changes that occurred during that period. As shown in Table 6, 2,856ha of "Discontinuously Built-up" areas and 5,550ha classified as non-urban (i.e. vegetation or soil) in 2002 were converted to "Continuously Built-up" by 2011, effectively doubling the "Continuously Built-up" land. The increase in "Discontinuously Built-up" areas from 2002 to 2011 is even more striking, up from 8,098ha to 23,678ha.
These dynamics indicate that processes of densification are occurring in low-density areas, and processes of sprawling are occurring in new peri-urban areas.

Table 6: Land cover change from 2002 to 2011, focused on urban classes

Land Cover Change Class	**Area** [ha]
Continuously Built-up in 2002	6,402
Discontinuously Built-up converted to Continuously Built-up (2002-2011)	2,856
Non-urban converted to Continuously Built-up (2002-2011)	5,550
Non-urban converted to Discontinuously Built-up (2002-2011)	15,580

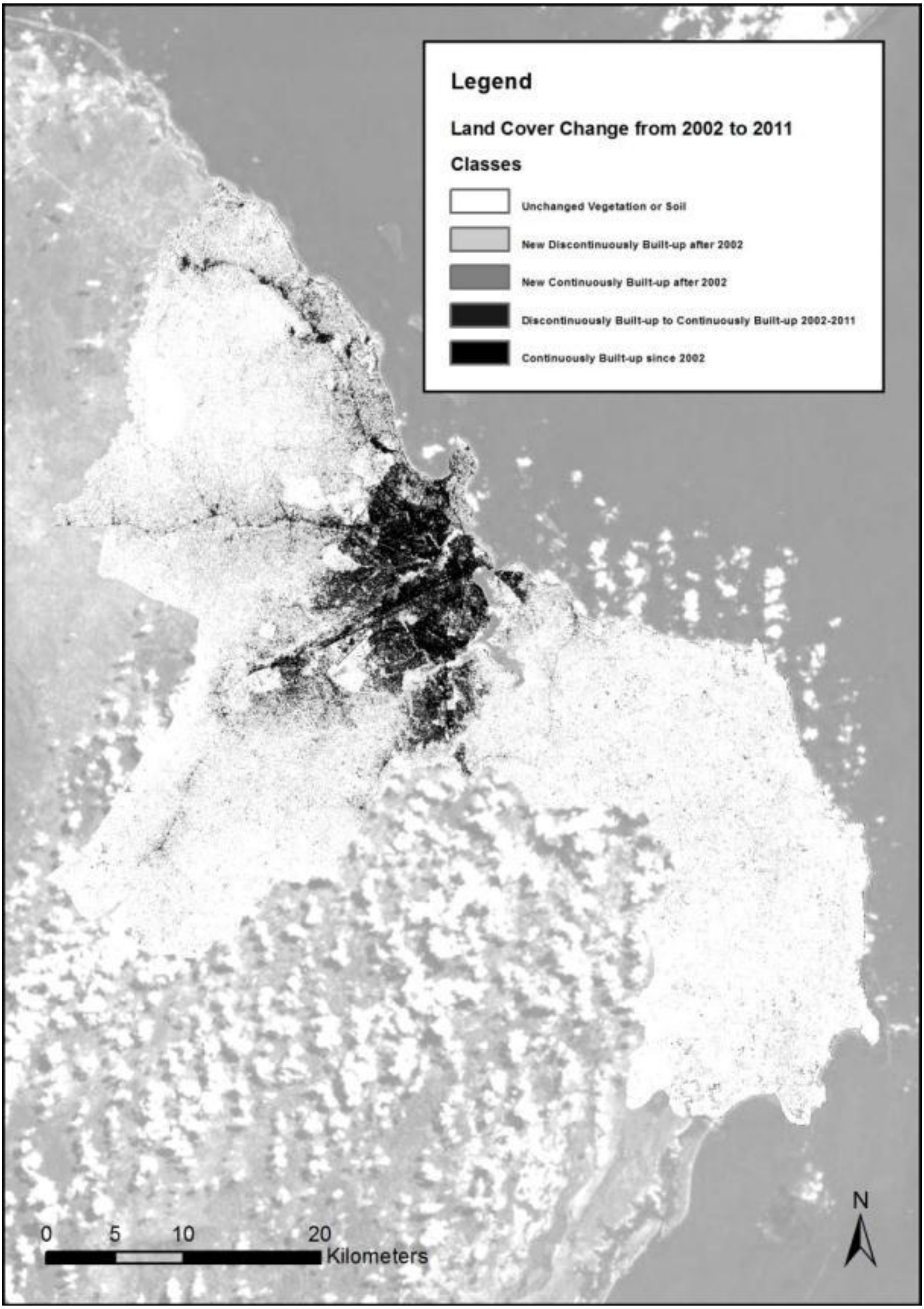

Figure 5: Land cover change of Dar es Salaam from 2002 to 2011

3.1.5 Landscape Metrics

LCC statistics are useful for assessing the quantitative changes from one specific LC class to another. However, in order to assess urban form, it is also useful to understand how the composition of LC classes changes within the landscape.

There are numerous definitions of landscape, depending on the situation under consideration or the study objective. Broadly defined, a landscape is a land mosaic, a mix of local ecosystems or land use types repeated over the land (Forman, 1995).

Focusing on urban landscape, urban form is influenced by several variables, including topography, economic and demographic development, and spatial planning (Schwarz, 2010).

Landscape Metrics, originally developed for ecological studies, are measures that describe the characteristics of landscape patches related to their structure, function, and changes thereof in the space (McGarigal & Marks, 1995).

Several studies have used LC classifications to calculate Landscape Metrics for the assessment of urban sprawl and spatial heterogeneity (Tang et al., 2008) and for the assessment of the effects of rapid urban expansion on the landscape of coastal areas (Li et al., 2010). Landscape Metrics have also been used to assess future urban growth scenarios (Aguilera et al., 2011).

However, the interpretation of certain Landscape Metrics can be difficult and not always straightforward, because it depends on the scale of data and the boundaries of the landscape (McGarigal & Marks, 1995).

An ESPON study (2011, p.15) has provided a reliable and easy to understand metric of urban sprawl, defined as “the percentage of disperse urban land over the total of urban land”, which has been adapted to built-up LC classes for the purposes of the present study, as described in the following paragraph.

3.1.6 An Urban Sprawl Indicator

In the Dar es Salaam region, the increase in built-up areas is the result of both sprawling and densification processes. In order to assess which of these two processes prevails over the other, an indicator of urban dynamicity has been defined as:

$$Urban\ Sprawl\ Indicator = \frac{Discontinuously\ Built-up\ area}{Total\ Urban\ area} * 100$$

Where $Total\ Urban\ area$ is the sum of the “Continuously Built-up” and “Discontinuously Built-up” areas.

This indicator is related to urban sprawl, and highlights the proportion of low-density urbanization over high-density urbanization (ESPON, 2011). Increasing values over time show that the city is sprawling rather than becoming more compact.

The Urban Sprawl Indicator has been calculated for every LC classification (Table 7) and values are depicted in chart form in Figure 16 (Appendix 1). These values highlight that prior to 2004 the city was more compact, while after 2004 it has been sprawling with an increasing rate. The 2011 value (61.5%) indicates that low-density urban development has become the major pattern in Dar es Salaam.

Table 7: The Urban Sprawl Indicator calculated for every classification

Year	2002	2004	2007	2009	2011
Urban Sprawl Indicator [%]	49.0	47.7	54.5	58.3	61.5

3.2 Urban Sprawl and Demographic Growth

As an additional consideration, we were interested to know if and to what extent the LC classification work described above could help in estimating population growth and its spatial distribution. In light of UN-Habitat’s description of urban sprawl as the misalignment of population growth and the physical expansion of a city, the idea arose of verifying whether any correlation existed between demographic growth and urban sprawl in the present case. Previous field surveys suggest that, even if they are misaligned, the two phenomena are not completely independent. Calculation of spatial distribution was particularly feasible for the year 2011, thanks to the particular methodology used for selecting the 5%

household sample of peri-urban neighbourhoods within the coastal plain that was interviewed during that same year under Activity 1.1. of this Project.
The following paragraphs describe the method developed and the main results achieved.

3.2.1 Estimation Method

Given the availability of data on household density for 2011, collected through the household survey performed during Activity 1.1, spatial density could be estimated for that year using the 2011 LC classification based on Landsat images.
The workflow in Figure 6 outlines the steps involved in population estimation, which are:

1. Calculate the average household density for each LC class, based on the spatial location of households participating in the survey;
2. Estimate the number of households for each LC class, according to the average household density and area thereof;
3. Estimate the total population using the average household size provided by the Tanzanian National Bureau of Statistics.

Once the average household density of each LC class had been calculated for 2011, population was estimated for several other years between 2002 to 2011 (according to LC classification availability), assuming that average household densities had remained constant.

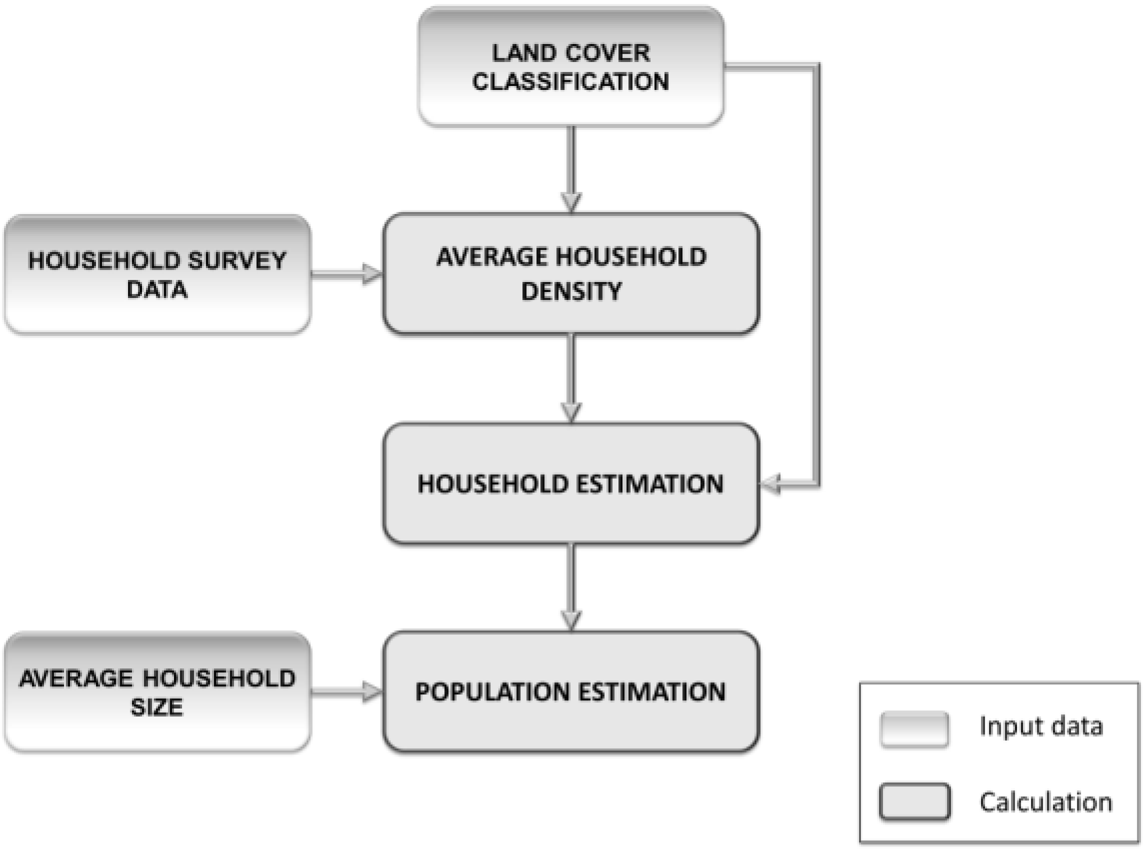

Figure 6: Workflow of the population estimate

Estimation of Number of Households

In 2011, a questionnaire was administered to a sample of 5,860 households in the coastal plain of Dar es Salaam, for the purpose of analyzing people's adaptive capacity (Ricci et al., 2012). Interviewers selected sample households in the field simply by counting 20 households from the last one interviewed (Figure 17, Appendix 1).
As all interviewed households (IHHs) were georeferenced with a GPS, a GIS shapefile (a point vector file) was created using their coordinates in the reference system WGS 1984 UTM Zone 37S. Applying

several GIS spatial analyses, it was possible to calculate the distance between the IHHs, which is approximately the distance of 20 households. Thus, average household density was estimated in relation to the IHH distance.
This method of household estimation is based on the assumption that household density around a given IHH is inversely proportional to the distance between that IHH and the next one in the sample. Therefore, the greater the distance between two IHHs, the fewer households there are in the neighbourhood (Figure 7, Appendix).

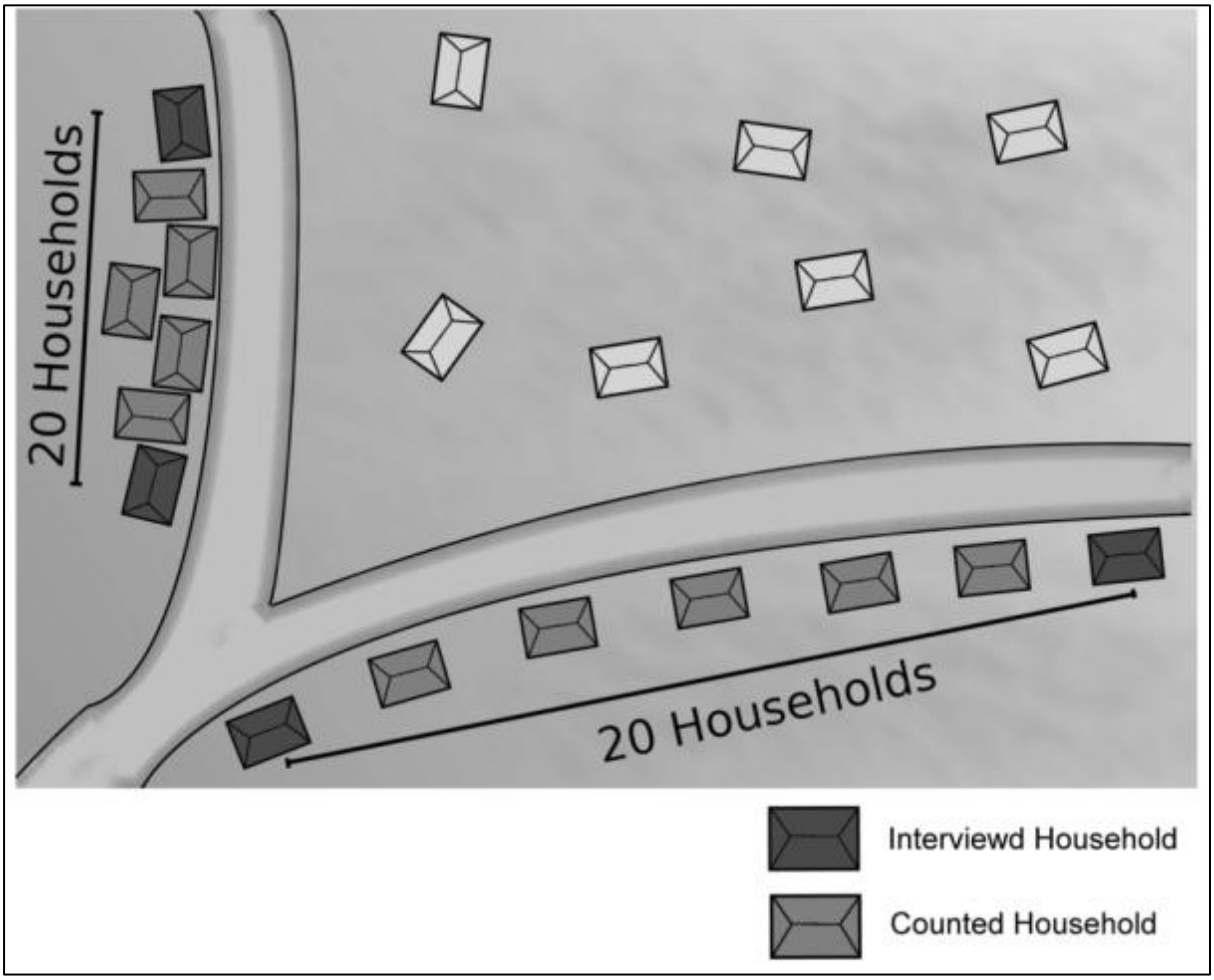

Figure 7: Illustration of the proportionality of the distance between interviewed households and the number of households in the neighbourhood

Household interviewers followed parallel paths and consequently several IHHs are very close (there are less than 20 households between them). In this analysis, IHHs less than 20m apart were considered too close together, and were excluded to avoid overestimation of household density. Thus, only 4,300 of the 5,860 IHHs were considered in the analysis.
Average household density was then calculated for each LC class using the method described in Appendix 3 – Method for Calculating Average Household Density.
Two classes of urban developed land ("Continuously Built-up" and "Discontinuously Built-up") were identified through LC classification. However, as explained above, the spatial resolution of Landsat images (30m) precludes classification of small isolated buildings. Thus, there may be households in pixels classified as soil or vegetation. According to the household survey, excluding the urban developed areas, most of the IHH were in the "Soil" class, and very few in the other classes.
The surface of the "Soil" class is very large, and obviously there are households only in a small portion thereof. Households for the "Soil" class were estimated based on the assumption that the area they cover is the same as in the "Discontinuously Built-up" class.
Because the non-urban classes have very low household densities, households in the "Soil", "Full Vegetation", "Mostly Vegetation", and "Water" classes were estimated as a group using the values for the "Soil" class. As such, only the "Continuously Built-up", "Discontinuously Built-up", and "Soil"

classes are considered for the total estimate.
The formulas used for the household estimates of each LC class considered are described in Table 8.

Table 8: Household estimates by LC class

Land Cover Class	Household Estimate
Continuously Built-up	$\bar{\rho}_{\text{Continuously Built-up}} * Area_{\text{Continuously Built-up}}$
Discontinuously Built-up	$\bar{\rho}_{\text{Discontinuously Built-up}} * Area_{\text{Discontinuously Built-up}}$
Soil	$\bar{\rho}_{\text{Soil}} * Area_{\text{Discontinuously Built-up}}$
Full Vegetation	
Mostly Vegetation	
Water	

The spatial resolution of the classifications used and the assumptions upon which estimations are based considerably limit the accuracy of the estimates produced. The method described above is therefore appropriate for household estimation of larger samples, such as the entire Dar es Salaam region, or single municipalities. However, the number of households of the single ward cannot be properly estimated. Data from the 2012 census will be useful in refining this methodology.

Estimation of Population

After estimating the number of households, the approximate population can be calculated by multiplying the number of households by the average household size (AHS).
The most recent census available was conducted in 2002 (data from the 2012 census are not yet public). According to the 2002 census (United Republic of Tanzania, 2006a), the AHS varied by region as follows:

- Tanzania: 4.7 persons per household;
- Tanzania, urban area: 4.2 persons per household;
- Tanzania, rural area: 4.9 persons per household;
- Dar es Salaam: 4.1 persons per household.

For ease of computation, only one AHS value was considered for all LC classes. The value for urban areas of Tanzania (4.2) was chosen as the AHS for all areas. The accuracy of this choice will be verified against 2012 census data, once it becomes available.
The expected margin of error (which should be ±20% of total population, given the accuracy of LC classifications and household estimates) should also comprise the variability of the AHS over multiple years.
LC classifications for 2002 allowed for a comparison between the calculated estimates and the 2002 census, the results of which are described in the following section.

3.2.2 Estimation Results

Estimated average household density by LC class

The average household density was calculated on the basis the LC classification of 2011 and the IHH shapefile, as described above. The results are reported in Table 9:

Table 9: Average household density for each Land Cover class

Land Cover Class	**Average Household Density** [households/ha]
Continuously Built-up	31.11
Discontinuously Built-up	17.56
Soil	13.78

By applying these density values to the LC classifications, an estimate of the number of households living in Dar's region was calculated for each year for which LC classification had been performed.

Estimated number of households in Dar es Salaam

The numbers of households in the Dar region were estimated for the years 2002, 2004, 2007, 2009, and 2011. In addition, the same household estimates were performed for three municipalities (Figure 18, Appendix 1), the coastal plain, and the "existing city" (Figure 19, Appendix 1).
The Table 10 shows an example of household calculation based on LC class, while Figure 20 and Figure 21 (Appendix 1) contain charts of the estimates.

Table 10: 2002 household estimates

Land Cover Class	**Area** [ha]	**Average Household Density** [households/ha]	**Estimated Number of Households**
Continuously Built-up	8,365.5	31.11	260,251
Discontinuously Built-up	8,032.0	17.56	141,043
Soil	8,032.0	13.78	110,682
			Total: 511,975

It is worth pointing out that the LC areas used for these calculations differ slightly from the LC areas reported in the previous paragraphs, due to minor differences in administrative boundaries (i.e. Dar es Salaam shapefile and shapefiles of municipalities).
It order to assess estimation accuracy, the 2002 estimate was compared to the 2002 census, according to which there were 596,264 households in Dar es Salaam (Mwakaje, 2010). Our estimate is about 84,000 households lower than the census, a difference of about 14% (see Table 12).
Estimates at the municipal level have also been compared to the census. Because of the unavailability of household data at the municipal level, the number of households was calculated as the ratio of municipal population and average household size, using the data from the United Republic of Tanzania (2004). Table 11 reports the number of households calculated at municipal level.

Table 11: Households per municipality according to the 2002 census

	Ilala	**Kinondoni**	**Temeke**
2002 Population	634,924	1,083,913	768,451
Average Household Size	4.2	4.1	4.1
Estimated Number of Households	151,172	264,369	187,427

In Table 12, the estimated number of households and the number report in the 2002 census are compared at the municipal level. The differences range between 11.1 and 18.7, which is inside the expected margin of error (±20%).

Table 12: Comparison of household estimates and 2002 census data at the city and municipal level

	Dar es Salaam	**Ilala**	**Kinondoni**	**Temeke**
Calculated based on the 2002 Census	596,264	151,172	264,369	187,427
Estimate	511,975	122,888	235,142	153,945
Difference (Census - Estimate)	84,289	28,284	29,227	33,482
Difference (Census - Estimate) [%]	14.1	18.7	11.1	17.9

The lowest difference is for the Kinondoni Municipality, probably because the interviewed households were mostly located in this municipality. The higher difference for Ilala and Temeke is probably due to LC classification errors and the higher variability of household density.
The sum of household estimates for each municipality, approximated using the calculations described above, is about 6,700 households more than the official total for Dar es Salaam for 2002. Although

household counts per municipality were not included in the 2002 census, they would likely have been slightly lower than each of the above estimates.
The 2011 estimate will be compared with the 2012 census (when available) in order to determine whether the general underestimation of households in 2002 is caused by LC classification errors, or by a bias in the estimation method (which therefore should be confirmed in 2011). This will allow for a refinement of the estimation.

Estimated Population for Dar es Salaam

Population has been estimated for the years 2002, 2004, 2007, 2009, and 2011 (Figure 22, Appendix 1), using the defined AHS. In the same way, the population has been estimated for the coastal plain and within the "existing city" boundary (Figure 23, Appendix 1).
In order to verify the reliability of the estimates, they have been compared to 2002 census data at the municipal level, as illustrated in Table 13.

Table 13: Comparison of population estimates and 2002 census data at the municipal level

Municipality	2002 Census	Estimated Population	Difference (Census - Estimate)	Difference [%]
Kinondoni	1,083,913	987,595	96,318	8.9
Ilala	634,924	516,132	118,792	18.7
Temeke	768,451	646,569	121,882	15.9

The difference between estimates and census data at the municipal level is always lower than 20%, confirming the reliability of the estimation based on the selected AHS (i.e. 4.2). As predicted, given the household estimate, population estimates are lower than the census.
According to the margin of error of household estimates, all population estimates are expected to be correct within an error range of ±20%. The 2011 estimate (5,034,559) is consistent with the provisional data from the 2012 census, according to which population should range between 5 and 6 million.
While the official 2012 census will provide useful indications about the estimation accuracy and the choice of the AHS parameter, results already confirm a direct relationship between urban sprawl and demographic growth, at least at regional and municipal levels.
The estimated increase in population is particularly high for the periods 2007-2009 (about 900,000 people) and 2009-2011 (about 1.2 million people) as shown in Figure 24 (Appendix 1). Total population increase from 2002 to 2011 was about 2.5 million.
According to these estimates, the population in Dar es Salaam has almost doubled from 2002 to 2011 (Figure 25, Appendix 1). In addition, the percentage of relative growth (i.e. growth as a percentage of the previous year's estimated population) has been continuously increasing. As such, the low growth rate from 2002 (census) to 2004 (estimate) likely indicates that the 2004 estimate is lower than the real population.
In the period 2009-2011, relative growth was similar to that of 2007-2009, suggesting a stabilization of the annual growth rate at around 14.8%.

In order to assess the limits of the developed method, it has been tested at ward level and compared to 2002 census data. The result of this comparison (Figure 26, Appendix 1) indicates that most wards were estimated incorrectly (with an error of more than 25%), particularly the Temeke Municipality, though there were a few exceptions.
This inconsistency with census data demonstrates that there are several constraints preventing estimation at the ward level, like:

- the spatial resolution of LC classifications (i.e. 30m), which limits detection of small isolated houses;
- the thematic accuracy of LC classifications, which affects estimate accuracy;
- the assumptions of this estimation method, which generalizes some features (e.g. the average household density per LC class), while each ward seems to have its own urban development pattern and household characteristics.

However, estimates at the regional and municipal level confirm the existence of a relationship between LCC and population growth in Dar es Salaam.

ArcGIS Model for Estimating the Population

In order to automate the process of estimating the population, a model has been developed with the software ArcGIS. The workflow of the model, which is shown in Figure 27 (Appendix 1), has two inputs:

- the boundary of the area of estimation (e.g. municipal boundary), which is a shapefile;
- the LC classification, which is a raster.

Therefore, the software calculates the area, for each LC class, belonging to the input boundary (i.e. "Tabulate Area" command), and joins this information to the attribute table of the input boundary (i.e. "Join Field" command. In particular, two fields are added: the "Continuously Built-up" area and the "Discontinuously Built-up" area.

Then, two fields are created in the attribute table of the input boundary (i.e. "Add Field" command):

- "Estimated HH", which is a field that will contain the household estimate;
- "Estimated Pop", which is a field that will contain the population estimate.

The number of households is estimated through using the following expression:

Estimated HH = [Continuously Built-up area] * 31.11 + [Discontinuously Built-up area] * 17.56 + [Discontinuously Built-up area] * 13.78

Where 31.11, 17.56, and 13.78 are the average household densities by LC class. The result of the calculation is written in the "Estimated HH" field.

In the end, the population estimate is performed through the following calculation:

Estimated Pop = [Estimated HH] * 4.2

Where 4.2 is the AHS. The result is written in the "Estimated Pop" field.

Therefore, after the execution of the model, the input shapefile will contain the estimated households and population, as shown in the following Table 14.

Table 14: Example of attribute table produced for the 2002 estimate at the municipal level

MUNICIPALITY	Continuously Built-up area	Discontinuously Built-up area	Estimated HH	Estimated Pop
Kinondoni	3,583	3,946	235,142	987,596
Ilala	2,107	1,830	122,889	516,134
Temeke	2,676	2,256	153,945	646,569

3.2.3 Comparison with Demographic Projections

The census is the main reference for assessing population estimates. However, predicting demographic growth is useful for several reasons, from administrative to health issues. Several institutions attempted demographic projections following the 2002 census, basing on census data and other socio-economic variables.

The developed method of estimation is not appropriate for demographic projections, but it could be used as reference for updating the base data, thus improving projection accuracy.

In the following paragraphs, the population estimates are compared with demographic projections produced by other sources, in particular:

- the National Bureau of Statistics of Tanzania;
- the AfriPop project.

The National Bureau Projections

The National Bureau of Statistics of Tanzania published the regional and district projections for Dar es Salaam in 2006 (United Republic of Tanzania, 2006b).
The base population for projections was calculated according to the 2002 population and several other inputs (e.g. death rate, fertility rate, and migration) and assumptions about those inputs (United Republic of Tanzania, 2006b, pp.4-9).
Those projections, compared to this study's estimates, are shown in Figure 28 (Appendix 1).
Both the National Bureau of Statistics' projection and the present study's estimate started with a base population of 2,500,000, as indicated in the 2002 census, and the projected and estimated values for 2004 are quite similar. However, the gap between projection and estimate grows from 2007 to 2011 (Table 15); and in 2011 the projection is about 1.8 million people lower than the estimated population.
Rumours about the 2012 census, suggest that population was found to be between 5 and 6 million in 2012, indicating that the 2011 projection has highly underestimated demographic growth.
This comparison confirms that projections far into the future can differ considerably with real data (which at the moment is the provisional 2012 census).

Table 15: Difference between population projections and estimates from 2004 to 2011

Year	Population Projections (National Bureau of Statistics, 2006)	Estimated Population	Difference (Projection - Estimate)
2004	2,642,708	2,493,828	148,880
2007	2,881,548	3,000,882	-119,334
2009	3,040,118	3,882,610	-842,492
2011	3,194,903	5,034,559	-1,839,656

The AfriPop project

AfriPop is a project that aims to model population distributions and densities for the entire African continent, based on the assumption that there is a relationship between LC and population (Linard et al., 2012a).
The project has produced maps of population density for African countries. AfriPop data, which are raster files with a spatial resolution of about 100m (i.e. 0.000833 decimal degrees), are freely available at http://www.clas.ufl.edu/users/atatem/index_files/AfriPop.htm.
The AfriPop data is for 2010, and population densities are based on available census data. If the most recent available census is from prior to 2010, population is projected to that year with an exponential equation (using urban and rural growth rates estimated by the UN Population Division), as described by Linard (2012b, p.6).
It was possible to download the AfriPop data for Tanzania, which was used to calculate the population of Dar es Salaam. Total population was calculated through GIS analysis (i.e. "Zonal Statistics"), using AfriPop data and the city boundary shapefile.
The 2010 population calculated using AfriPop data is 3,378,935, which should correspond to the projection calculated by the AfriPop project for Dar es Salaam.
In order to compare the AfriPop projection to the estimates of this study, an estimate for 2010 was needed. Since LC-based estimates were only available for 2009 and 2011, the average of the two was calculated, which is 4,458,585.
The AfriPop projection, based on the 2002 census and several assumptions regarding growth rates, is quite different from the population estimate of this study.
The difference between the AfriPop projection and the estimate is: -1,079,650.
Although AfriPop data refers to 2010, the AfriPop projection is 2million people lower than provisional 2012 census. It can therefore be reasonably inferred that the AfriPop 2010 population is underestimated.

3.2.4 Comparison Between Urban Growth and Demographic Growth

The population estimates (and the household estimates) indicate considerable growth from 2002 to 2011, which is expected to prove consistent with census data, once 2012 figures are available, as the method used for estimation has provided results within the expected margin of error (±20%) with

respect to the 2002 census value.
The line graph in Figure 8 represents the evolution of “Continuously Built-up” and “Discontinuously Built-up” areas as compared with the estimated demographic growth and population projections based on the 2002 national census (United Republic of Tanzania, 2006b).

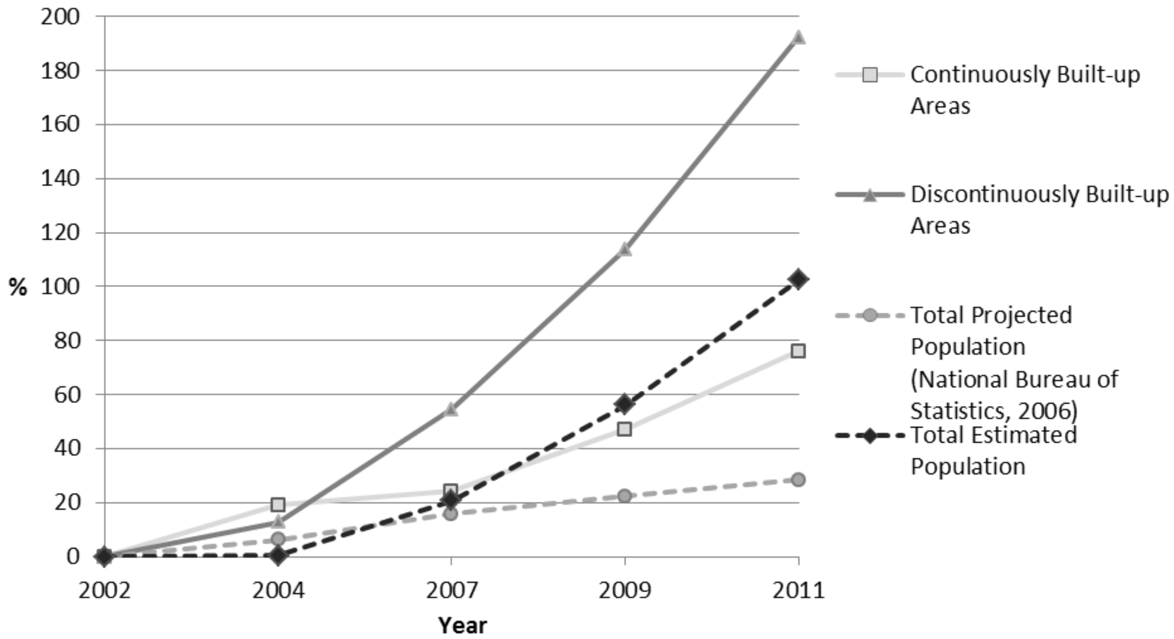

Figure 8: Percentage of population growth (estimates and projections) according to the 2002 census, compared to built-up growth from 2002 to 2011

This comparison indicates that projected population follows a trend similar to the growth of the “Continuously Built-up” area, while the estimated population tendency is more similar to the growth of the “Discontinuously Built-up” area.
That leads to the following conclusions.
Firstly, population growth and the physical expansion of Dar es Salaam are correlated, although not directly proportional. The misalignment between the two phenomena, which characterizes urban sprawl according to UN-Habitat (2010), seems to be the more marked where the discontinuously built-up areas grow at a faster rate than the continuously built-up areas. In other words, a correlation between demographic growth and physical expansion exists, but it is mediated by the settlement pattern that dominates in new urban developed areas, and it is the discontinuously built-up pattern that dominates in Dar es Salaam. Secondly, the integration of LCC scenarios into demographic projection methods could considerably improve the reliability of population predictions for the Dar es Salaam region. In the context of ACC Dar Project goals, such improved reliability is crucial in assessing future scenarios of people’s vulnerability for a number of reasons, including the need to estimate the rate of groundwater extraction, which is correlated with the number of households located in peri-urban areas.
In both respects, if the trends observed in Dar es Salaam are confirmed in the other fast growing Sub-Saharan cities, these conclusions could be generalized, with important consequences for urban studies in Sub-Saharan countries.

4. Conclusions and Recommendations

4.1 Conclusions

Dar es Salaam is suffering the effects of growing urbanization, which results in the rapid and unplanned expansion of low-density settlements. This phenomenon, which is termed Urban Sprawl, has several impacts on the environment, which will combine with expected climate change effects. It is therefore fundamental that LCC (and urban sprawl) be assessed in order to develop vulnerability scenarios for people who rely on natural resources for their livelihoods, which in turn will enhance local institutions' capacity for adaptation.

The contributions of the present study to the investigation of the relationships between LCC and vulnerability to climate change in Dar es Salaam are twofold. Methods for assessing LCC and understanding its drivers have been advanced. Moreover, knowledge of urban development patterns and spatial population distribution has been improved, thus providing a valuable background for assessing LCC impacts on the three key components of vulnerability: exposure, sensitivity, and adaptive capacity.

As regards LCC assessment, a methodology for the monitoring of LC has been developed and validated (Congedo & Munafò, 2012a). This methodology is economical, simple, and quick to execute, as it uses freely available satellite imagery with a resolution that is small enough to capture the required detail while large enough to ensure computer storage and analysis can be performed efficiently. Also, a plugin for the open-source software QGIS has been developed in order to provide a cost-free classification tool and render the methodology more affordable (Congedo, 2013).

LC maps of the Dar es Salaam region for the years 2002, 2004, 2007, 2009, and 2011 were produced using Landsat images with a spatial resolution of 30m. Adopting the density of urban development as a criterion for classification, six LC types were identified, ranging from completely natural areas (Full Vegetation and Water) to built-up areas (Continuously Built-up and Discontinuously Built-up, depending on the observed urban development pattern).

The considerable number of LC classifications performed allowed for the assessment of LCC occurring in Dar es Salaam from 2002 to 2011, which were conducted with a special focus on the evolution of the built-up classes. The results described in this paper confirm a fast pace of urban development and provide an estimate of the amount of land involved. In less than ten years, the "Continuously Built-up" areas have expanded by more than 6,000ha, while the "Discontinuously Built-up" class has increased by 15,580ha.

The considerable increase in low-density areas is related to the urban sprawl phenomenon, particularly along the main thoroughfares. It should be noted that the "Discontinuously Built-up" class does not necessarily represent urban sprawl areas, since all low-density settlements are included under this class with no regard for whether they are planned (like the Msasani Peninsula) or unplanned. However, planned low density settlements are more stable over time and cover a smaller land area as compared with unplanned ones. Therefore, most of the "Discontinuously Built-up" areas that developed in the period under study can be labelled as urban sprawl.

A comparison of trends occurring in the two urban development classes considered during 2002-2011 indicates densification processes in existing low-density areas and sprawling processes in new peri-urban areas. In order to assess the magnitude of these dynamics, an Urban Sprawl Indicator has been calculated (i.e. the ratio of low-density built-up surfaces over the total urban surface) for every LC classification. The results show that Dar es Salaam's urban form has become ever more sprawled since 2004, and since 2007 the "Discontinuously Built-up" areas prevail over the "Continuously Built-up" ones and cover more than 50% of the urban developed land.

The classification methodology also allowed for a rough estimate of the impervious surface area of the Dar es Salaam region. Estimates indicate that 20-60% of land classified as "Discontinuously Built-up" and 60-100% of land classified as "Continually Built-up" can be considered an impervious surface. This means that between 14,000ha and 29,000ha was sealed as of 2011.

Understanding of the role of population growth as a driver of urban sprawl has been improved thanks to the development of a method of demographic estimation that integrates LC classifications from satellite images with household density observed during the on-site survey conducted under the Activity 1.1 of this Project (Ricci et al., 2012).

The population of Dar es Salaam was estimated for 2002, and then compared to census data. The comparison confirmed the reliability of the estimation method at the city and municipal levels, as the estimate proved to have a margin of error of ±20% with respect to census data, which indicated a population of 2.4 million inhabitants for 2002.

Population was then estimated for all years for which LC classifications were performed (2002, 2004, 2007, 2009, and 2011). Estimates highlight rapid population growth, which in 2011 reached 5 million inhabitants. The 2011 estimate is consistent with provisional data from census 2012, according to which between 5 and 6 million people live in Dar es Salaam.

Estimates also show that the majority of Dar's inhabitants live within the coastal plain, even though ever more settlements have arisen outside the plain. Moreover, the yearly rate of population growth seems to have reached an impressive 14.8% since 2007, which testifies to a high rate of immigration.

The major innovation of the developed estimation method is that the required parameters (i.e. average household densities per LC class, and average household size) need to be calculated for just one year; estimations for subsequent or previous years (preferably not more than 10 years) can be based on the related LC classification only.

This study seems to confirm the hypothesis that LCC (especially urban sprawl) in Dar es Salaam is highly related to demographic growth. Such hypothesis could be confirmed for all cities where household density does not vary substantially within individual basic urban development patterns (i.e. continuously or discontinuously built-up patterns). In other words, the proposed method is not likely to be applicable to cities where the same LC class includes areas with very different household densities, due to a variety of building heights and/or land uses, as it is the case for most cities in the Global North.

Considering the low frequency of census taking (once every ten years), and the growth rate of Dar es Salaam, this estimation method represents a valuable and affordable way for updating demographic information between two census years at the regional and municipal levels. However, it has proven to be unreliable at ward level, as the accuracy and spatial resolution of LC classifications limit the spatial scale at which it is applicable.

Moreover, the proposed method could be used to improve the accuracy of projections by updating base data, thus recalibrating projection parameters. In fact, the estimations calculated using this methodology have proven to be decidedly more reliable than projections by the National Bureau of Statistics or AfriPop in the case of Dar es Salaam, which is probably true for all cities where population growth is rapid and unexpected and/or census data are largely out-dated.

The study also provides valuable knowledge for the assessment of the bearing that LCC has on the vulnerability to climate change of people living in the peri-urban areas of coastal Dar es Salaam.

The rising dominance of sprawling over densification in urban development dynamics is likely to lead to an increase in the number of people whose livelihoods rely on natural resources, because of poor urban infrastructure and facilities but also because of their rural activities. This means that a growing number of Dar's inhabitants will become sensitive to environmental changes (like, for instance, groundwater salinization, which is being investigated by the ACC DAR Project), while increasing the pressure on natural cycles and thus resulting in increased environmental sensitivity. This influence of urban sprawl on both human and natural sensitivity to climate change has also been highlighted in similar studies conducted on European cases (ESPON, 2011). The method developed in the present study for estimating population growth and its spatial distribution could help in assessing the magnitude of both effects in cities like Dar es Salaam.

Moreover, urban sprawl involves an increase in the amount of land take per inhabitant, with an increase in the total amount of impervious land surface over the region. Imperviousness related to LC affects local climate (heat island), surface runoff, and groundwater recharge, thus amplifying the expected effect of climate change in terms of environment alteration. These phenomena are largely accounted for in European urban studies, though it still is not clearly stated whether densification or sprawling processes have worse consequences. In the case of Dar es Salaam, there are reasons to hypothesize that the effects of densification are worse than those related to sprawling, but further research efforts will be necessary in order to settle such a question.

Lastly, examination of the relationship between population growth and physical expansion of the city has demonstrated a strong correlation linking the two phenomena. This knowledge may facilitate the development of scenarios of future vulnerability to climate change as it allows for a translation of migration scenarios at the national level into urban sprawl scenarios at the city level.

4.2 Recommendations

Diffusion of the various tools presented here to local authorities' technical units, in Dar es Salaam and other similar cities, is strongly advised in order to enhance their capacity to deal with adaptation to climate change as well as more general urban development and environmental management issues. In particular, thanks to the affordability and simplicity of the methods proposed for LC classification, those units are expected to become more independent from national services and the donor community in developing their own LC maps and monitoring LCC over time. It is worth noting that, given the rapidity of population growth and related urban expansion, LC maps should be regularly updated - preferably every 2 years, image availability permitting – in order to perform an effective monitoring of on-going urban sprawl. Such monitoring activity seems to be crucial to ensuring the flexibility in decision making that is a prerequisite for effective adaptation. Obviously, the feasibility of sharing these tools with local authorities should be further assessed by introducing their staff to the technologies and methods developed in the present study. A first opportunity to do so will be provided by the training course currently being implemented as part of Work Package 3 of this Project. Outcomes from that testing exercise should also provide useful suggestions for further enhancement of the developed LC classification methodology, which could also be adapted for higher spatial resolution input data (if available) in order to increase the accuracy of LC mapping.

Moreover, it is recommended that local authorities become more aware of the relationship between LLC and the various dimensions of people's vulnerability so that they can more effectively direct adaptation initiatives. It is worth recalling that there are at least two noticeable links connecting urban sprawl to the adaptive capacity of people in Dar es Salaam. As a general assumption, migration represents an important adaptation strategy to environmental change (FORESIGHT, 2011) and in fact urban sprawl in Dar es Salaam seems to be fuelled by both internal and external migration. Also, the mix of uses that characterizes peri-urban areas is an important source of income diversification, which is crucial to ensuring more resilient livelihoods (Ricci et al., 2012). Therefore, the role of LCC in determining people's vulnerability to climate change is twofold: on the one hand, it is a cause of environmental change and increases people's sensitivity to climate change, while on the other, LCC is the output of a form of autonomous adaptation. In order to break the vicious circle of LCC and people's vulnerability, adaptation measures should support people in a manner that allows them to remaining where they are, thus discouraging further migration to the urban fringe.

As regards the proposed method of demographic estimation, it has the potential to be of great value in urban planning and environmental management. But before it can become fully applicable, this method requires further testing, in particular through comparison with the 2012 census, once it becomes available, in order to better calibrate the parameters to be adapted. The use of LC classifications with higher resolution may also improve estimation accuracy.

Future research under this Project will include assessment of the role of LCC in specific environmental phenomena (for instance, seawater intrusion into the coastal aquifer) and local urban climate. Understanding the specific relationships between LCC and vulnerability to climate change in Dar es Salaam should provide valuable indications for developing scenarios of future vulnerability to climate change, which are indispensable for strategically addressing institutional initiatives for adaptation.

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Appendix 1 – Figures

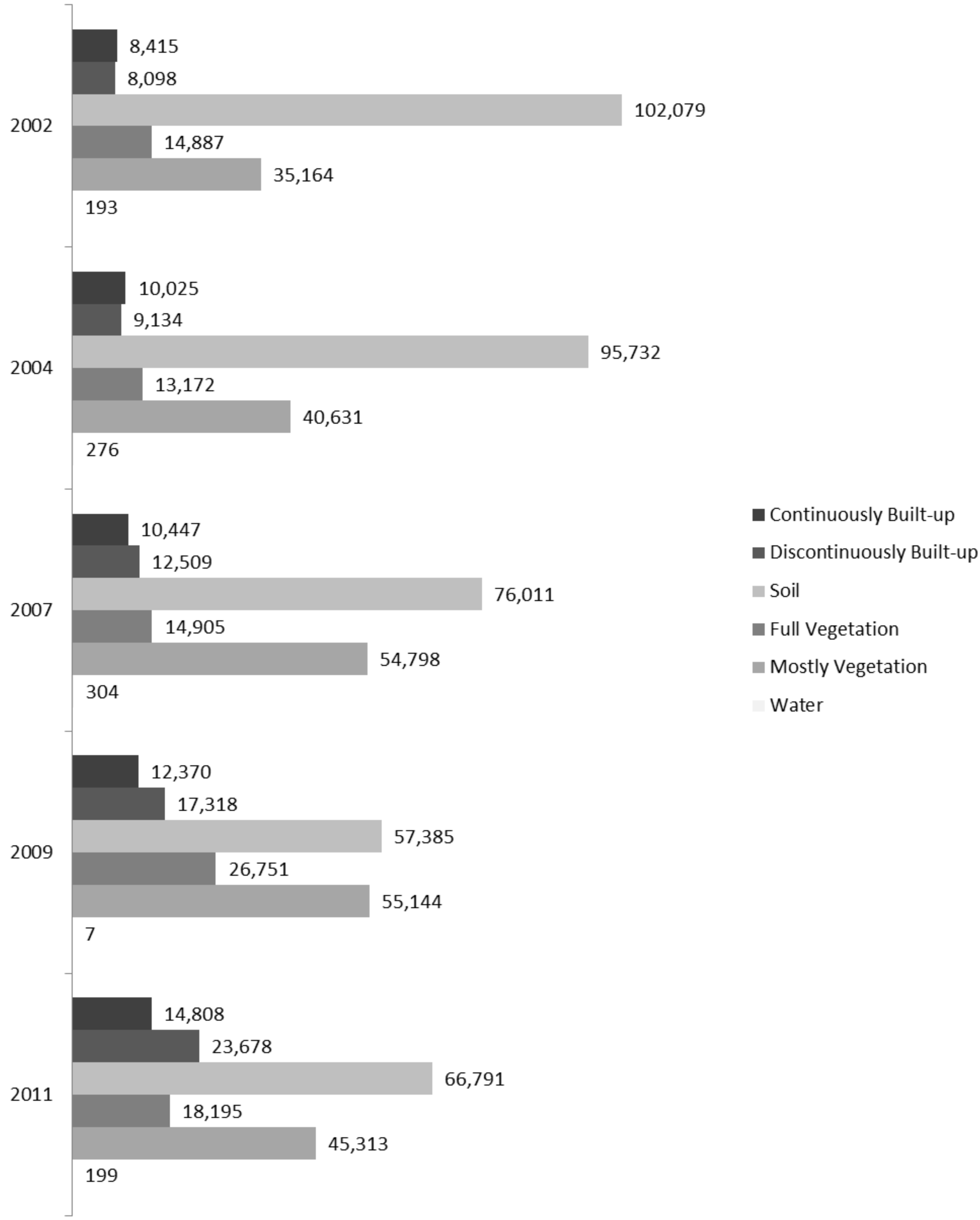

Figure 9: Areas of land cover classes in hectares

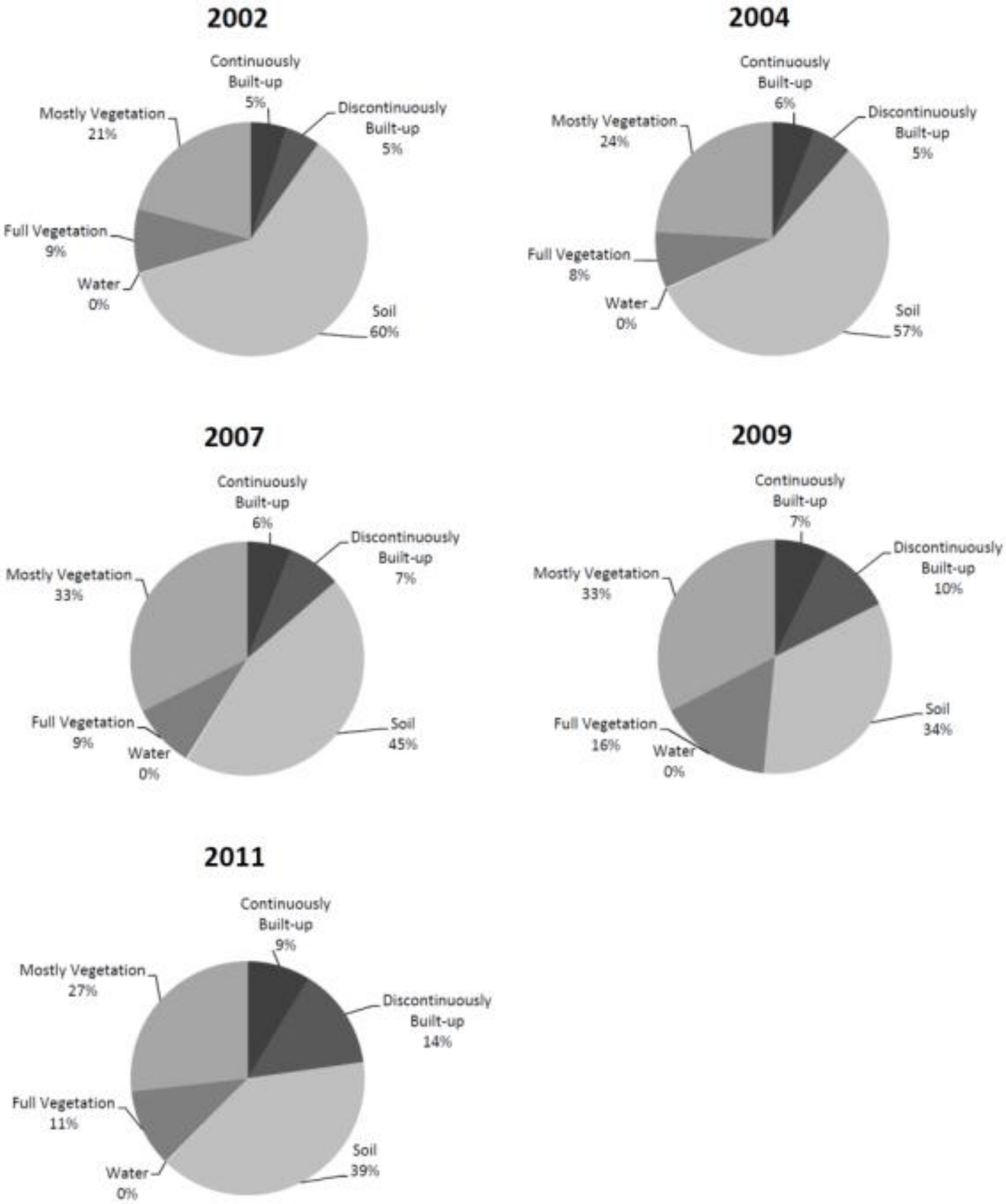

Figure 10: Charts of land cover classes

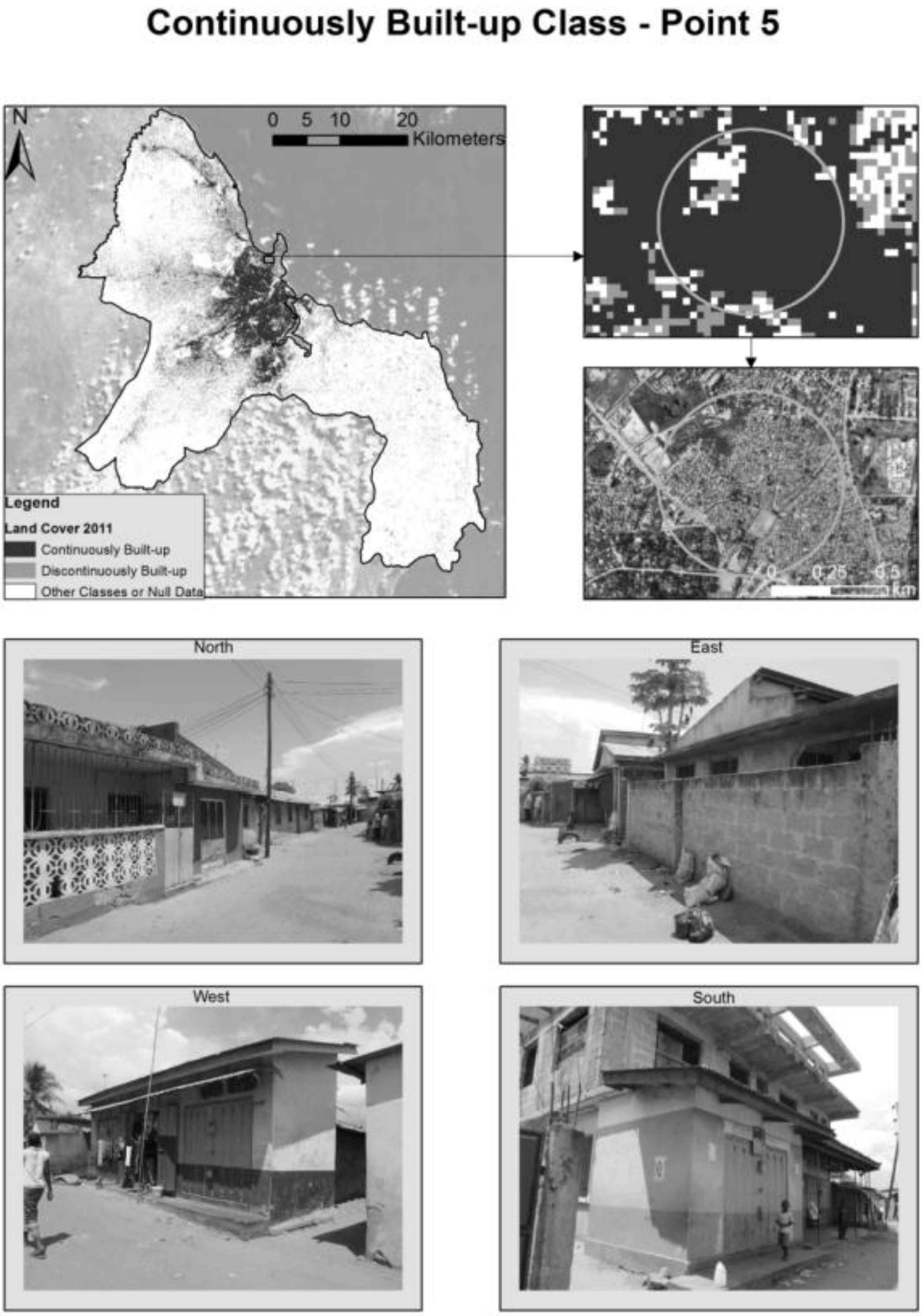

Figure 11: Example profile of an area classified as “Continuously Built-up”, produced during the LC validation activity

Discontinuously Built-up Class - Point 3

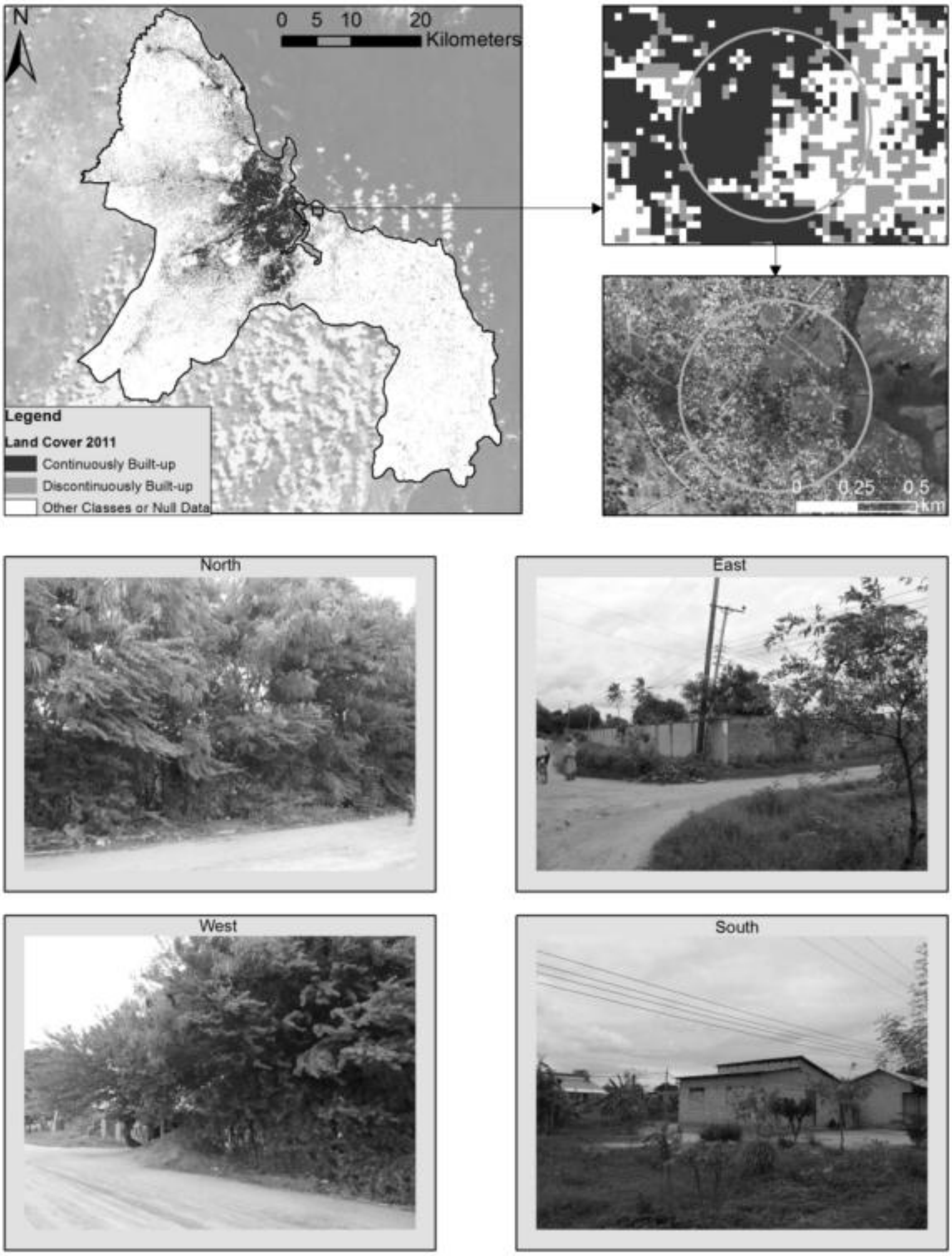

Figure 12: Example profile of an area classified as “Discontinuously Built-up”, produced during the LC validation activity

Soil - Point 12

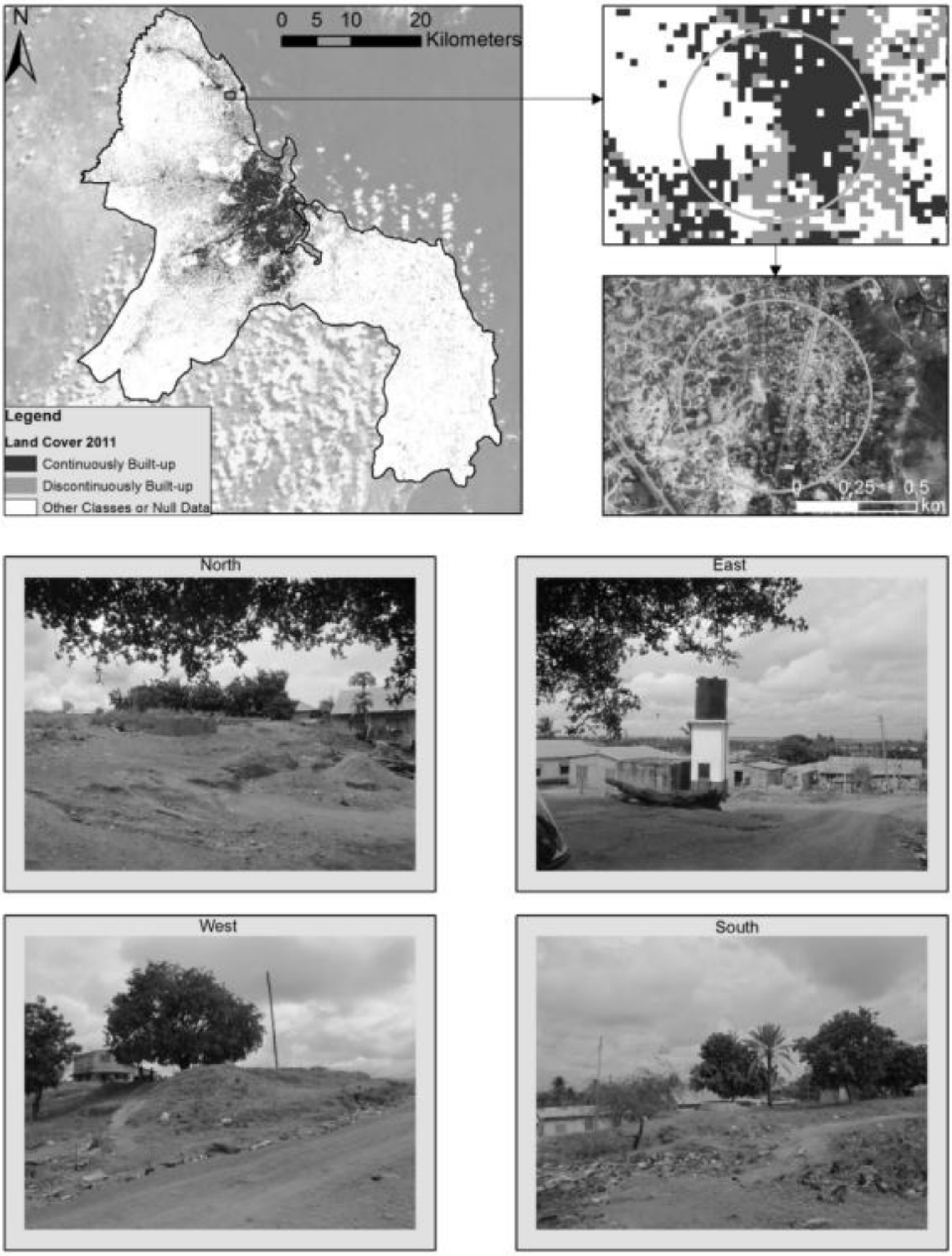

Figure 13: Example profile of an area classified as “Soil”, produced during the LC validation activity

Full Vegetation Class - Point 20

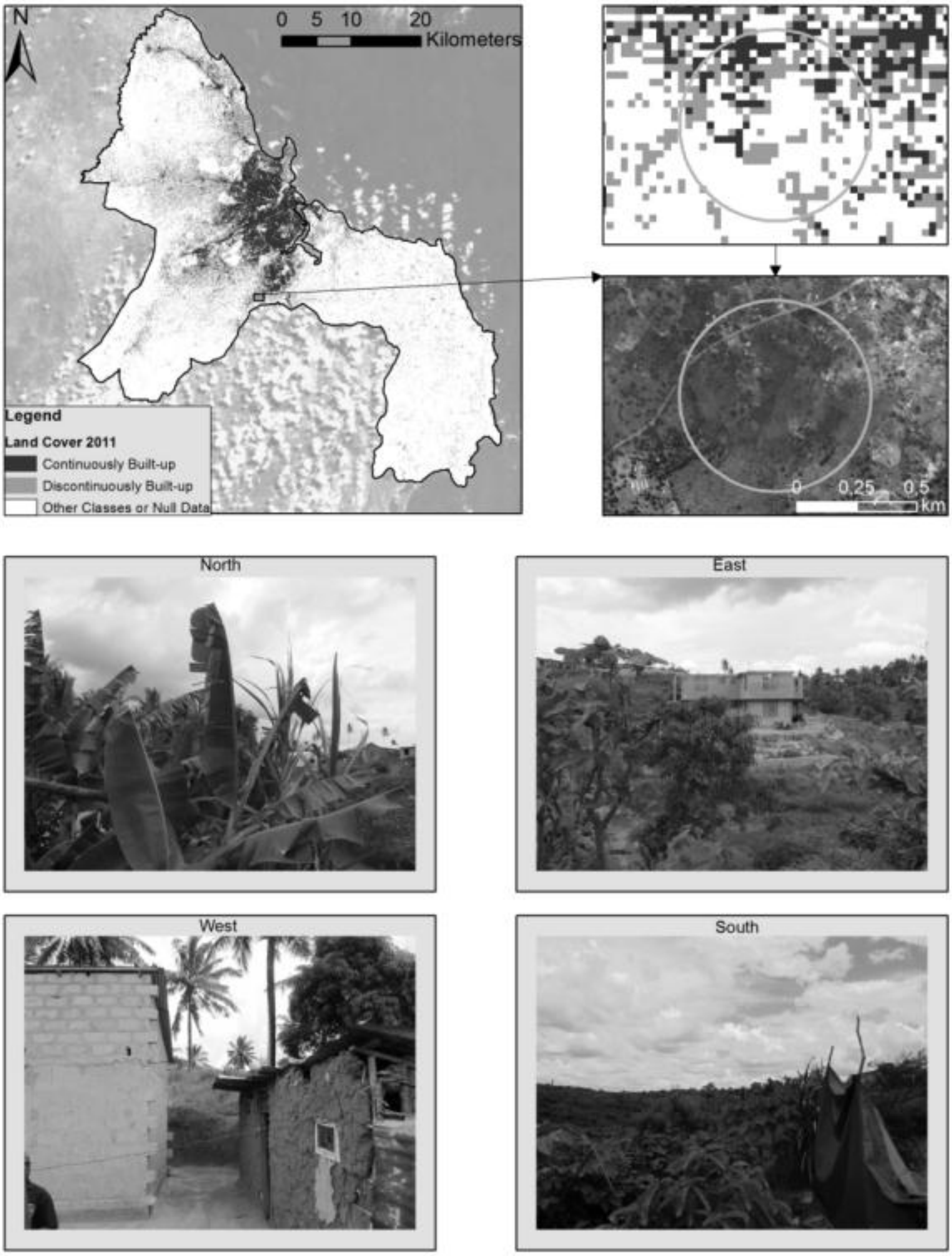

Figure 14: Example profile of an area classified as “Full Vegetation”, produced during the LC validation activity

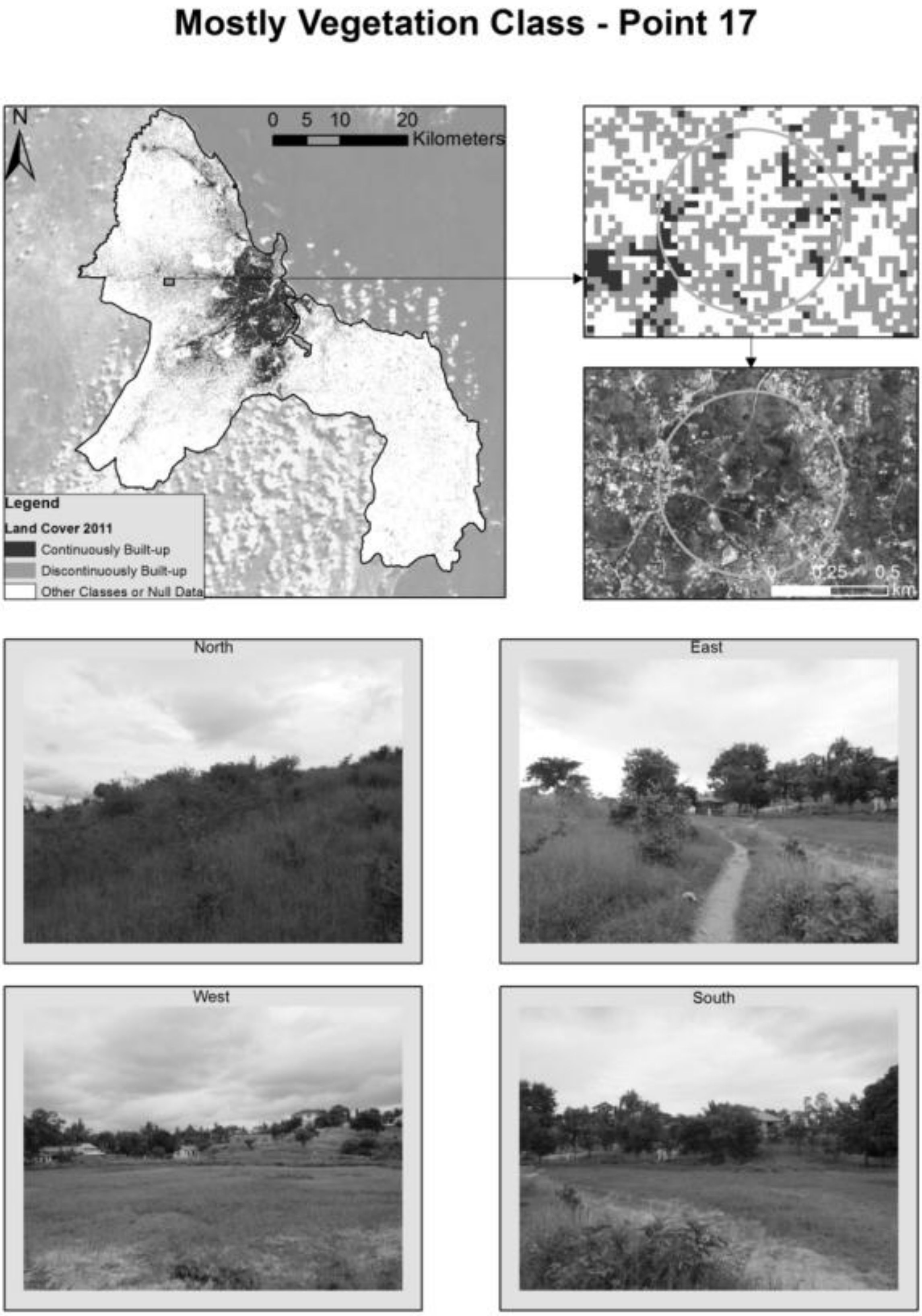

Figure 15: Example profile of an area classified as “Mostly Vegetation”, produced during the LC validation activity

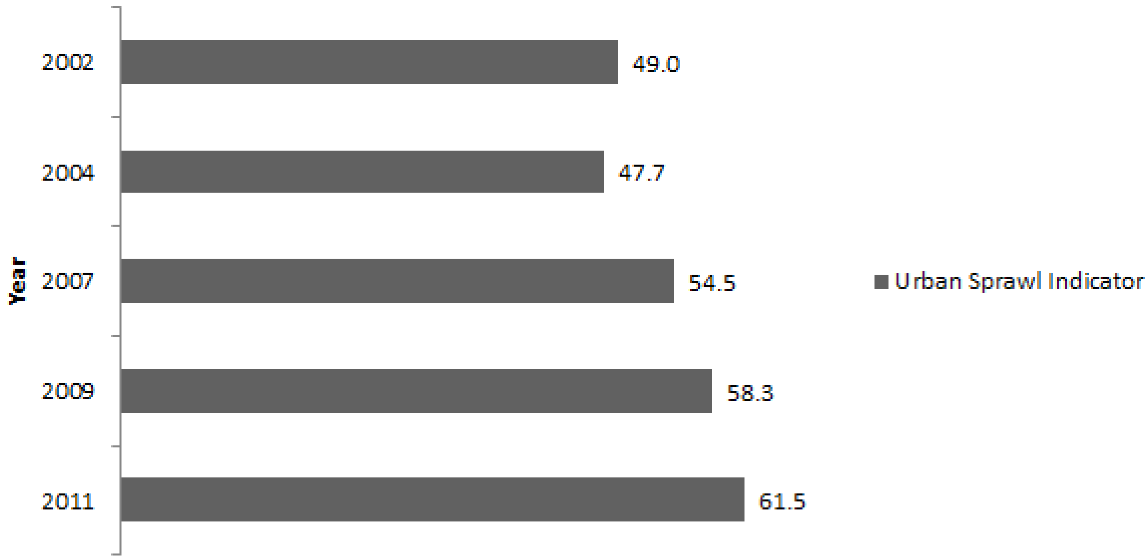

Figure 16: Chart of the Urban Sprawl Indicator

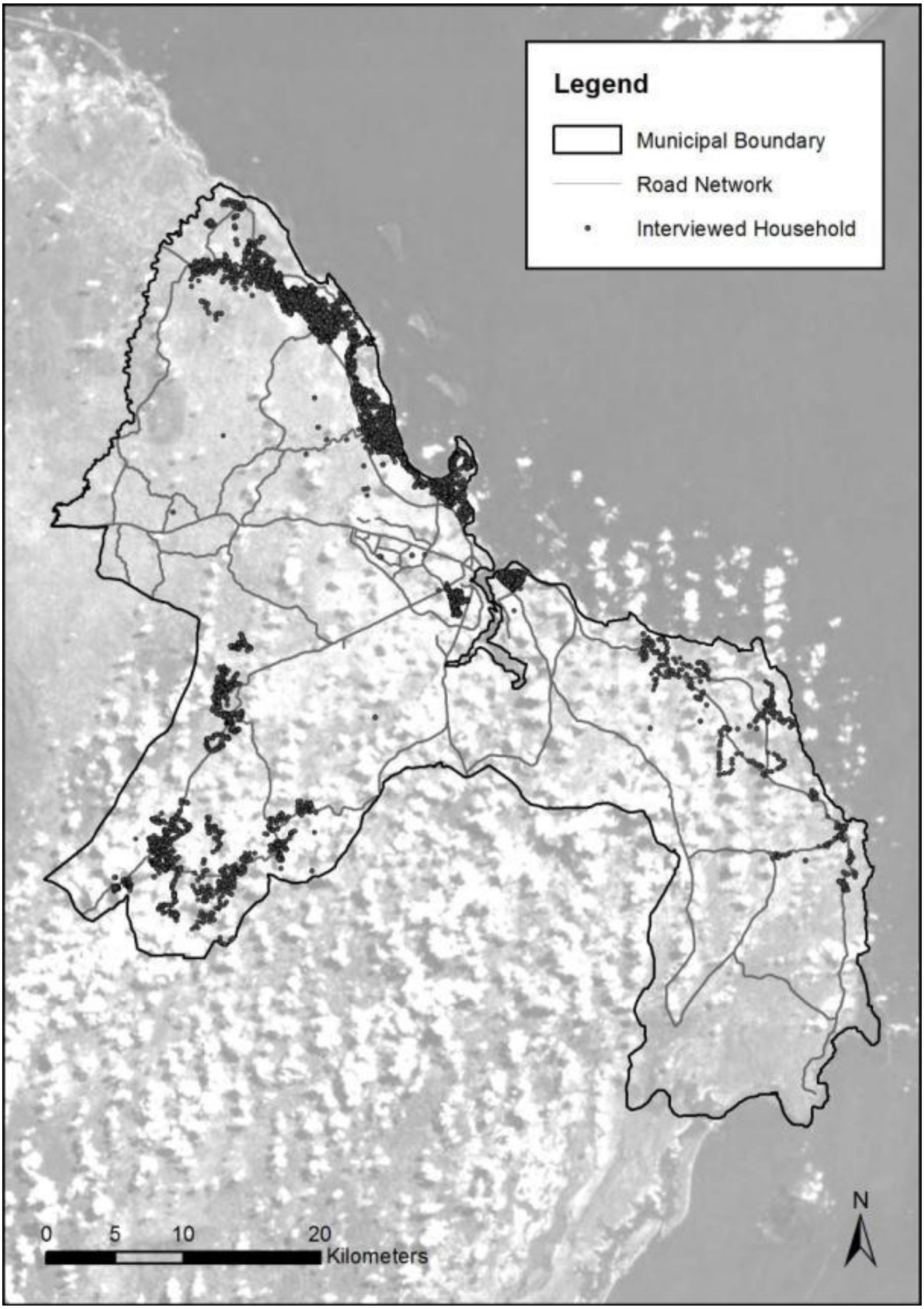

Figure 17: Interviewed households in Dar es Salaam

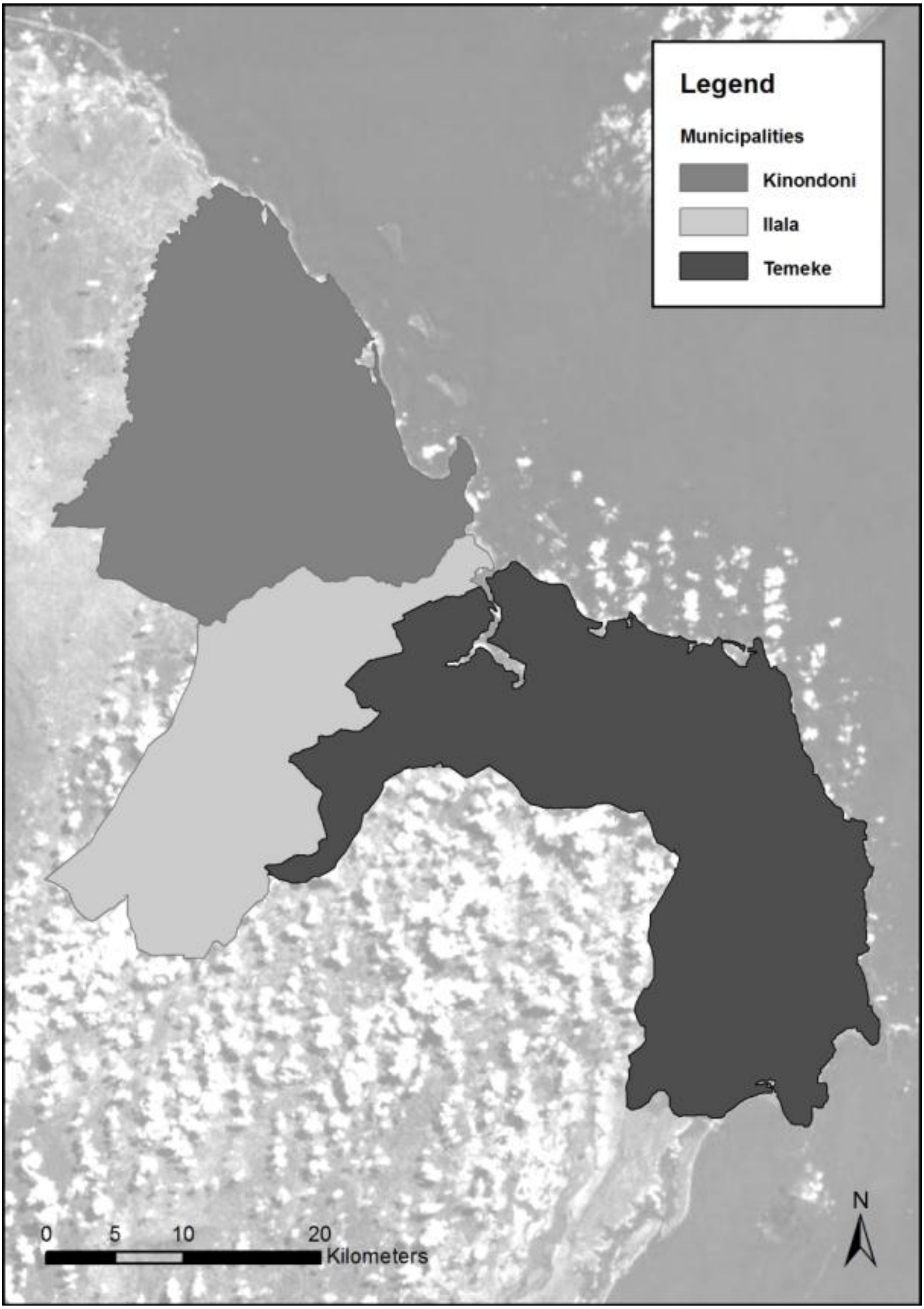

Figure 18: Dar es Salaam's municipalities

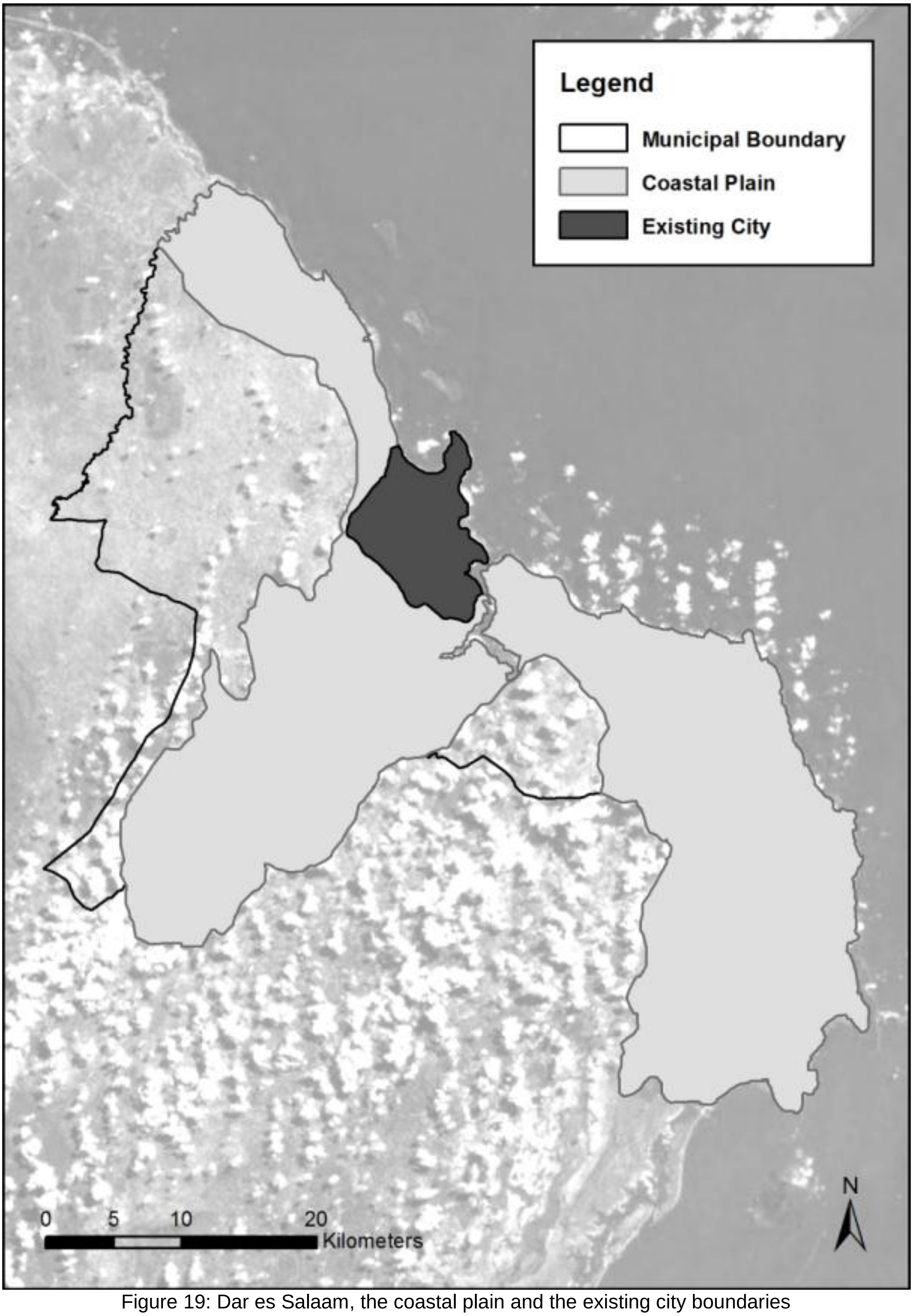

Figure 19: Dar es Salaam, the coastal plain and the existing city boundaries

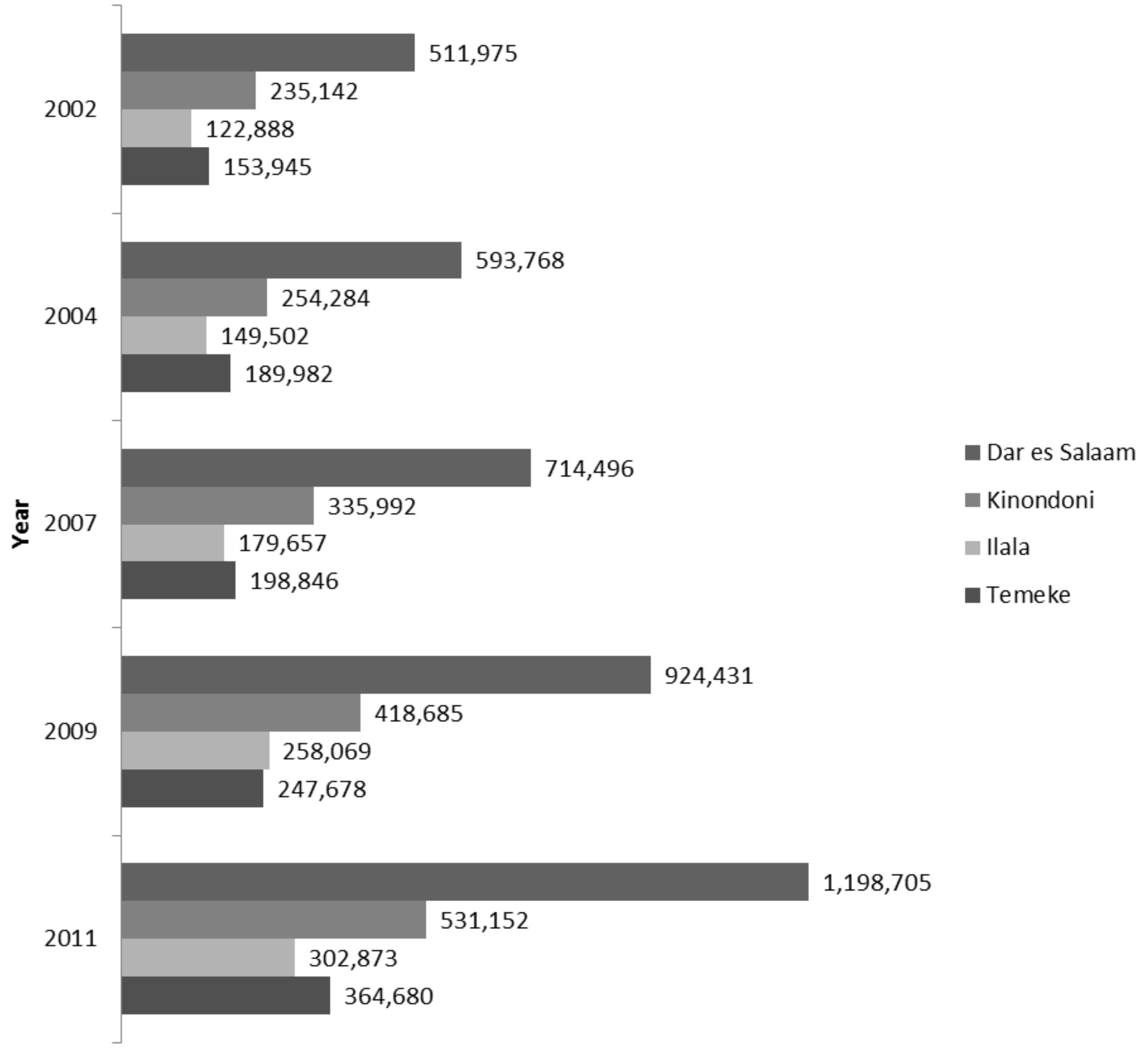

Figure 20: Household estimates for Dar es Salaam and its municipalities

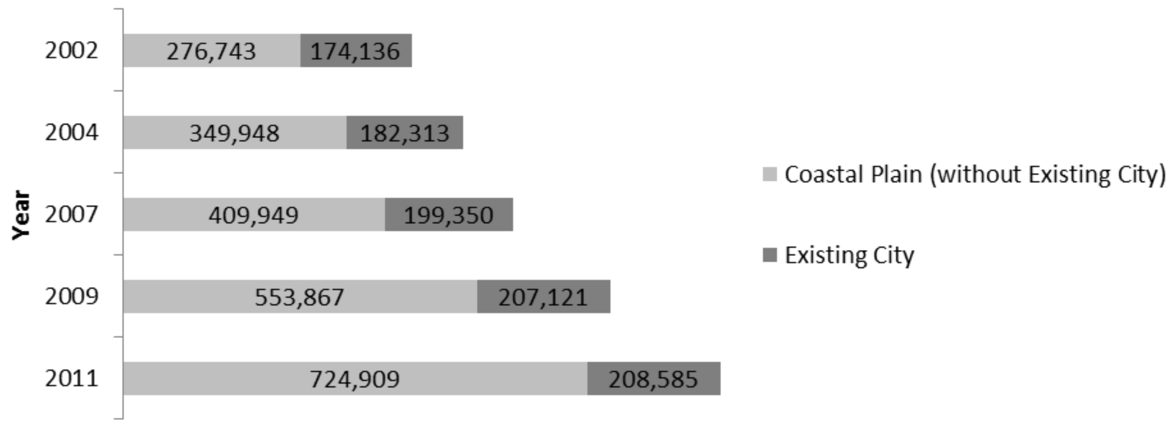

Figure 21: Household estimates for the coastal plain and the “existing city”

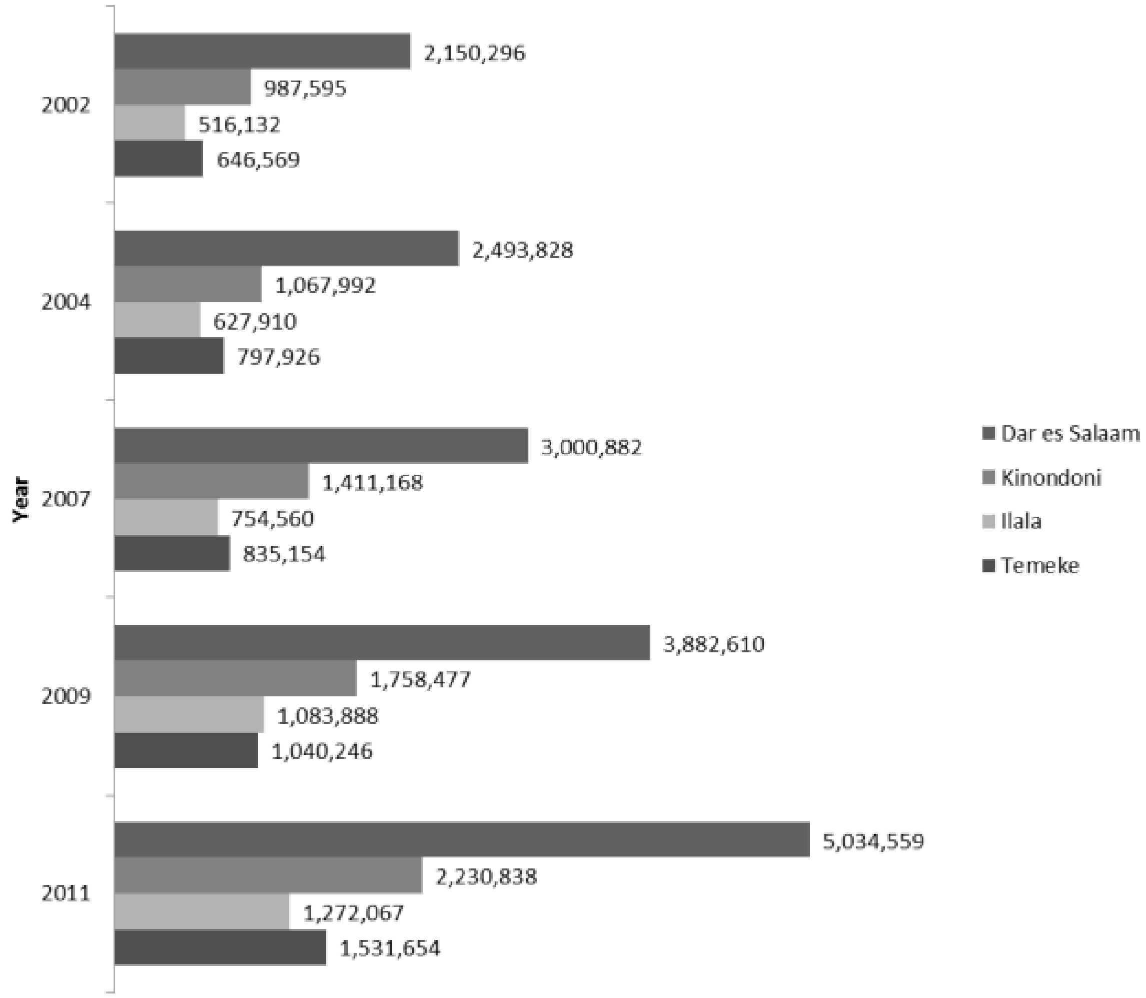

Figure 22: Population estimates for Dar es Salaam and its municipalities

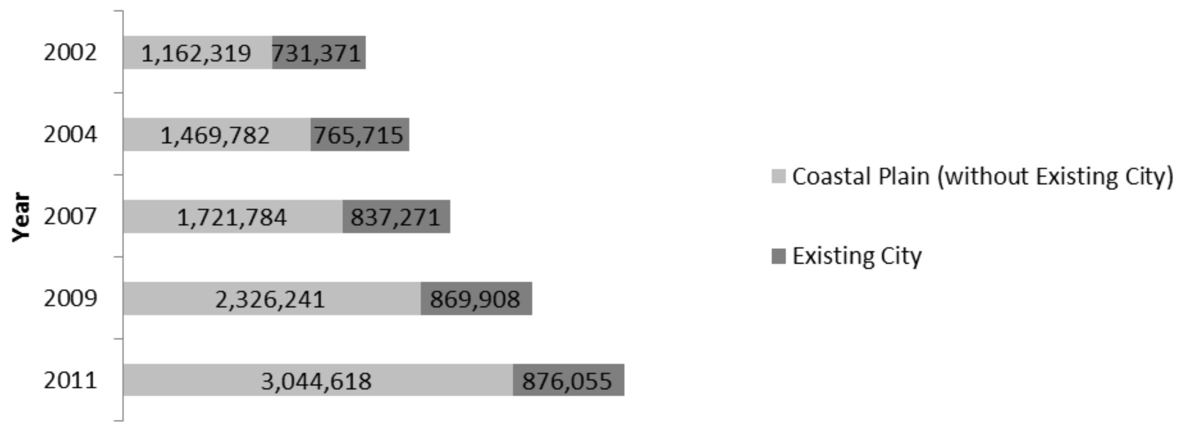

Figure 23: Population estimates for the coastal plain and the “existing city”

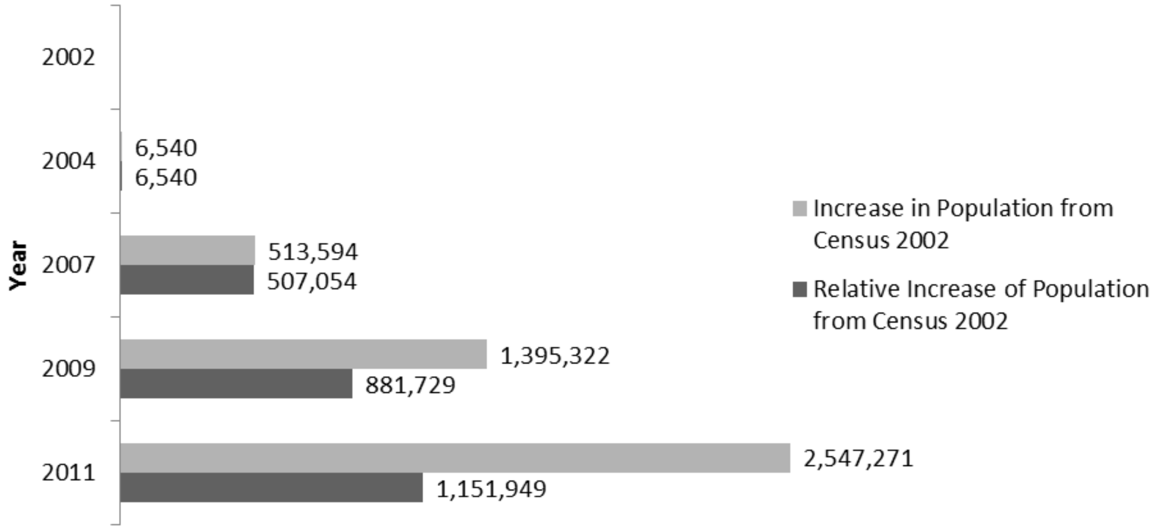

Figure 24: Increase in population from 2002 to 2011 and relative increase for individual periods

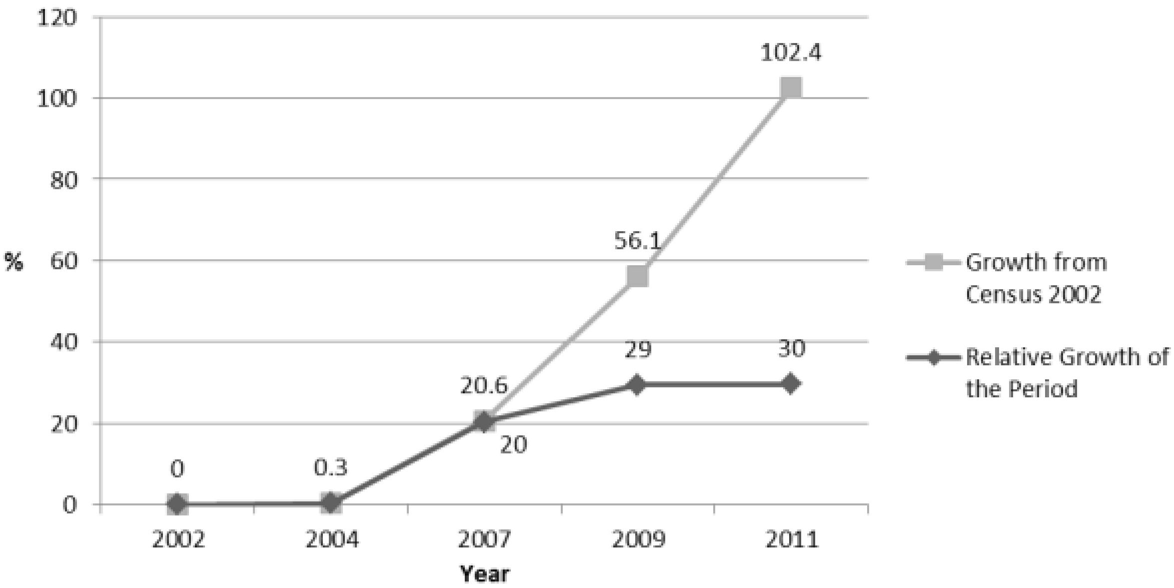

Figure 25: Estimated population growth from 2002 to 2011 (from 2002 census) and relative growth for individual periods

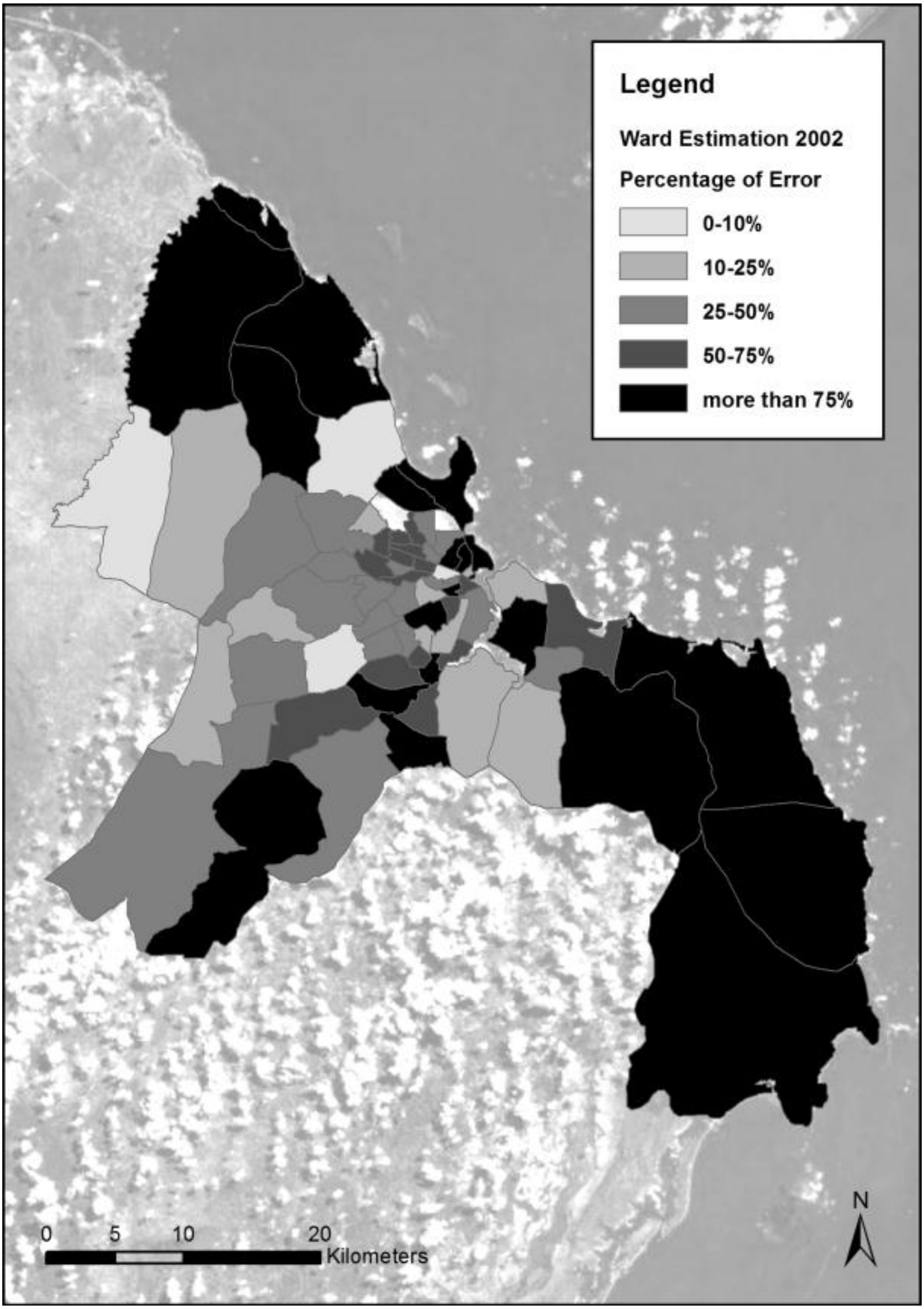

Figure 26: Population estimate at ward level compared to 2002 census

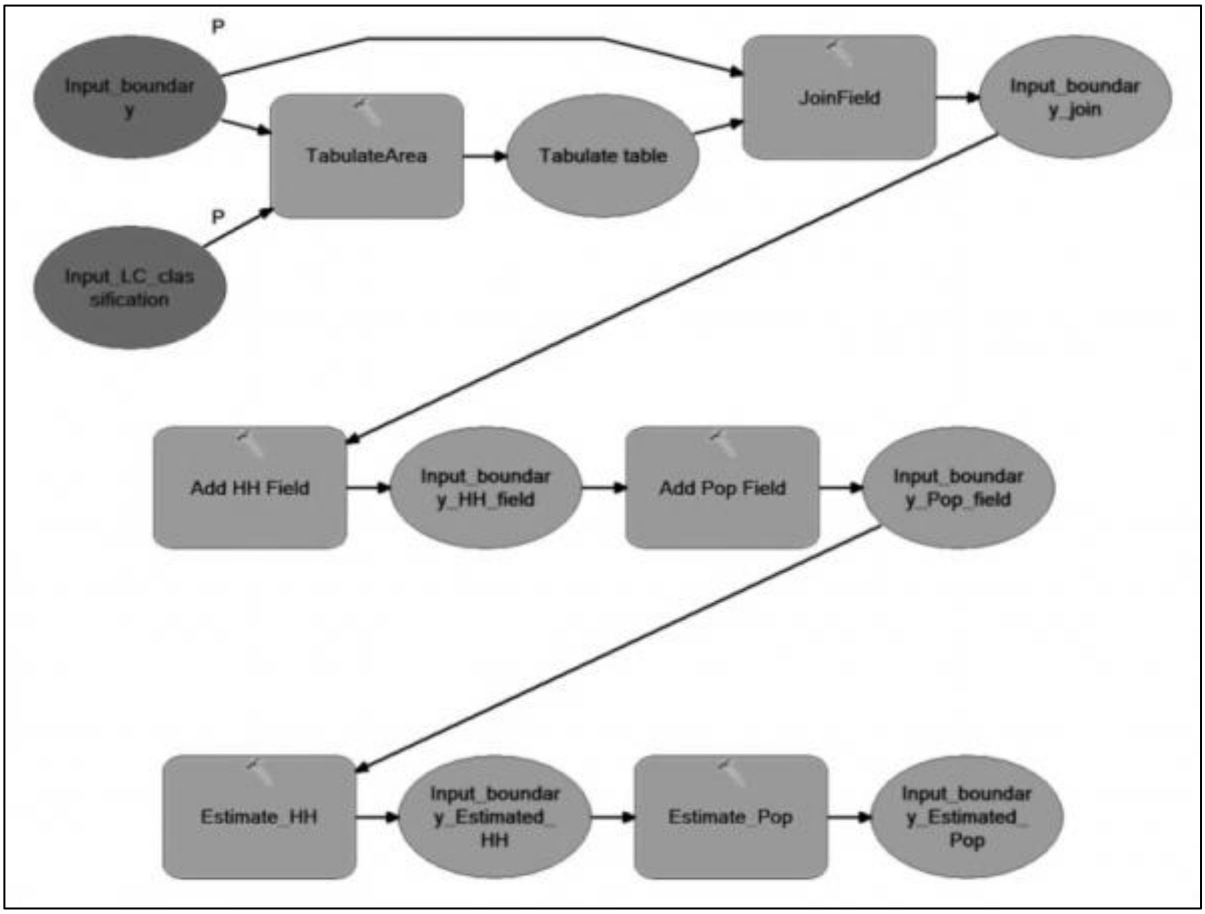

Figure 27: ArcGIS model for population estimation

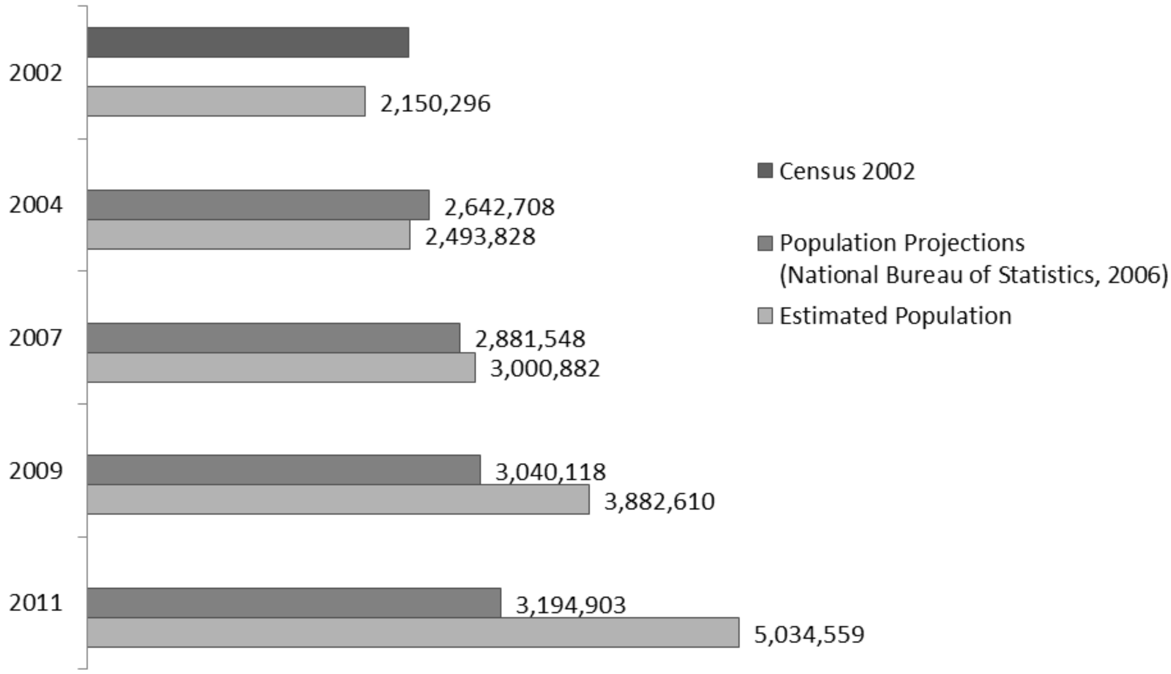

Figure 28: Comparison of estimated population to census data and projections of the National Bureau of Statistics

Appendix 2 – Land Cover Classifications

This appendix contains the LC maps from 2002 to 2011, with a focus on urban classes.

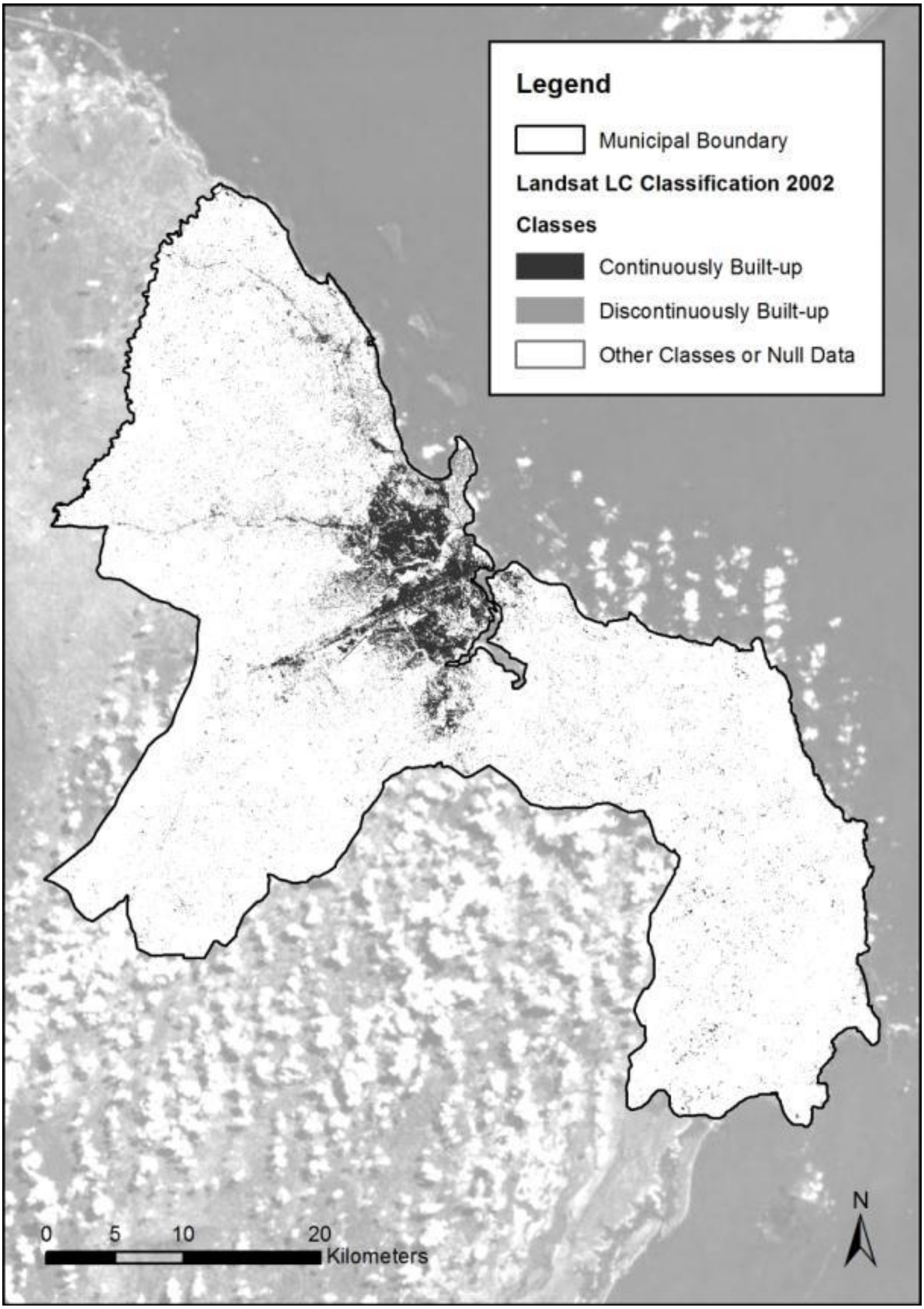

Figure 29: 2002 land cover classification

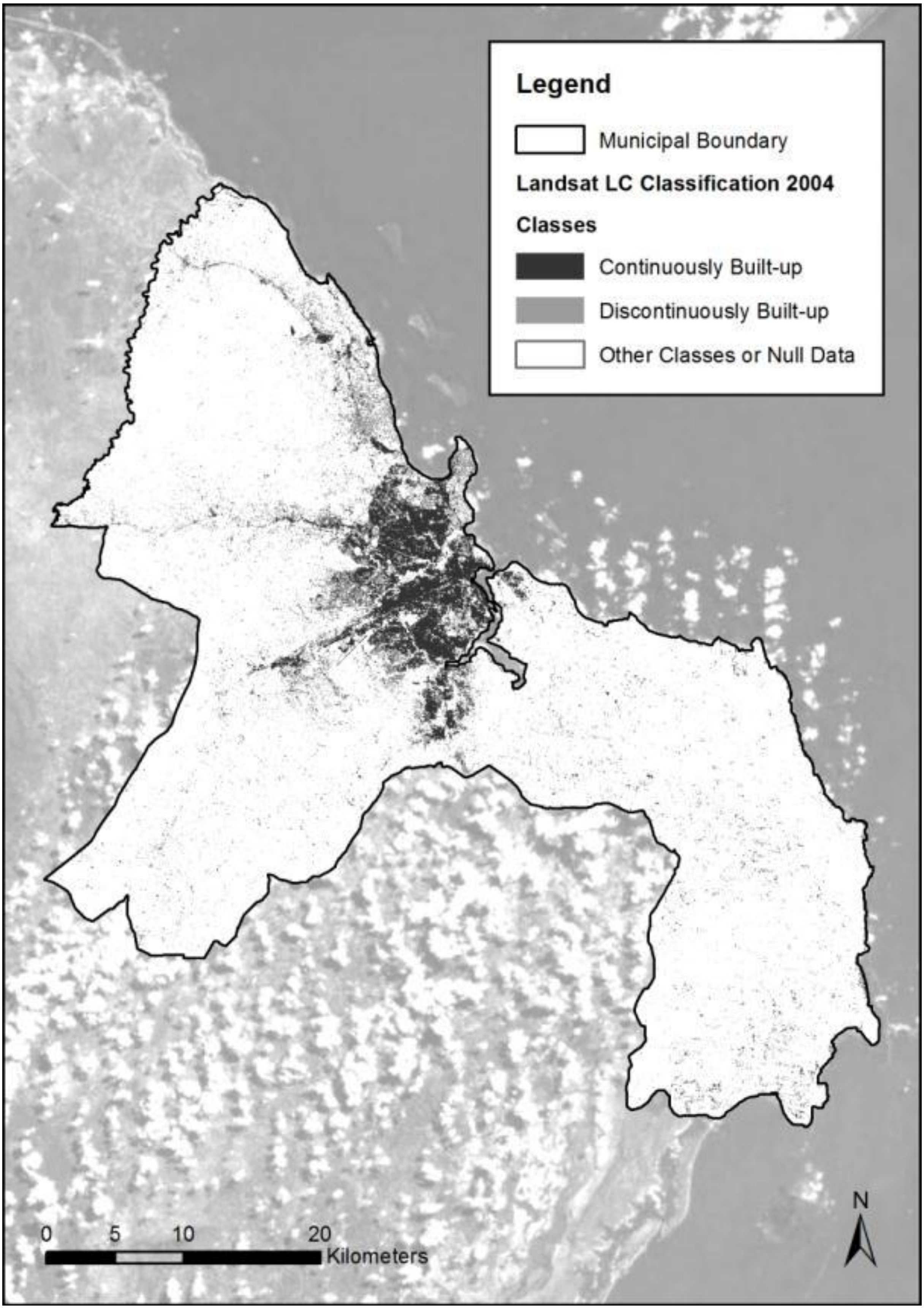

Figure 30: 2004 land cover classification

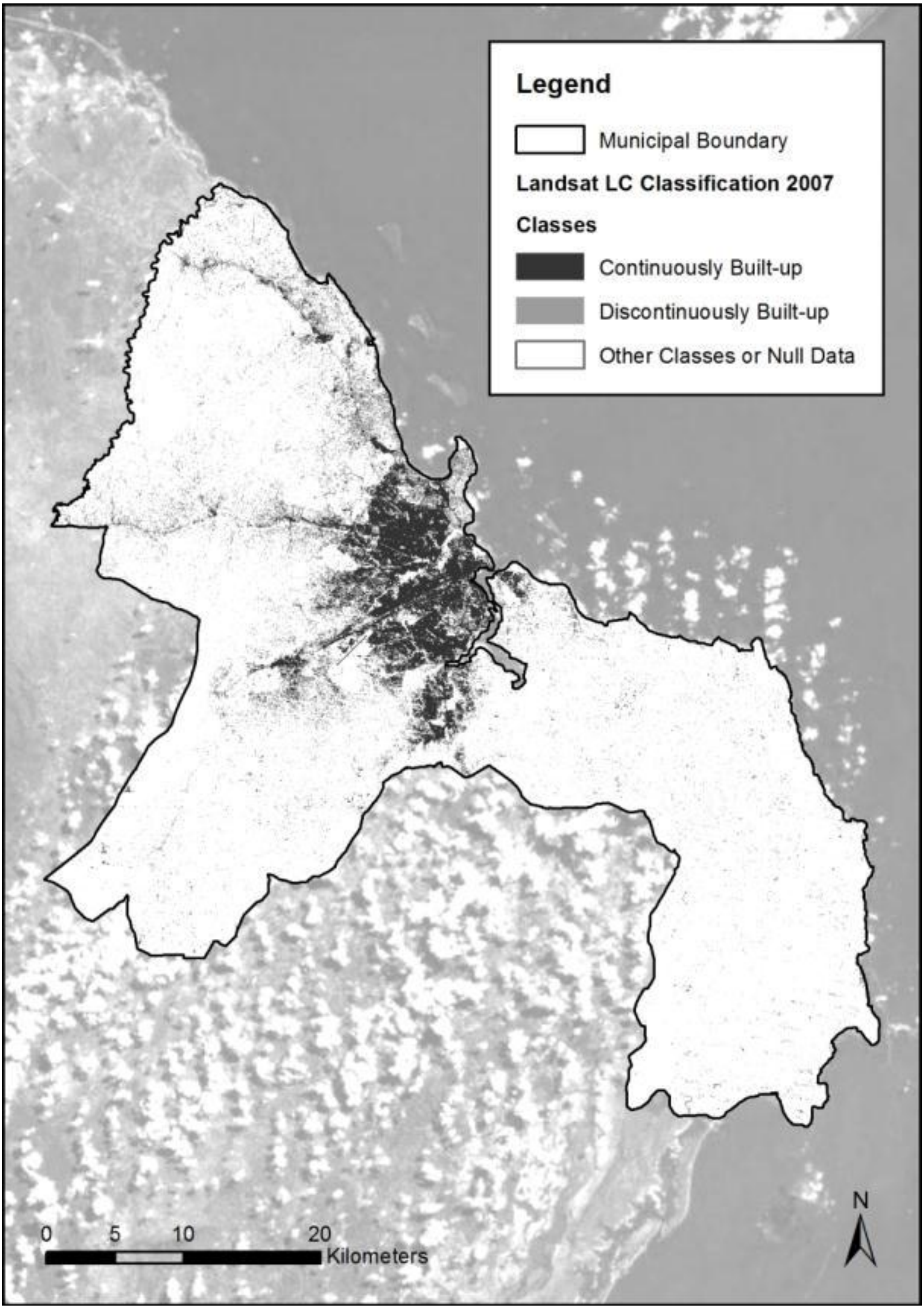

Figure 31: 2007 land cover classification

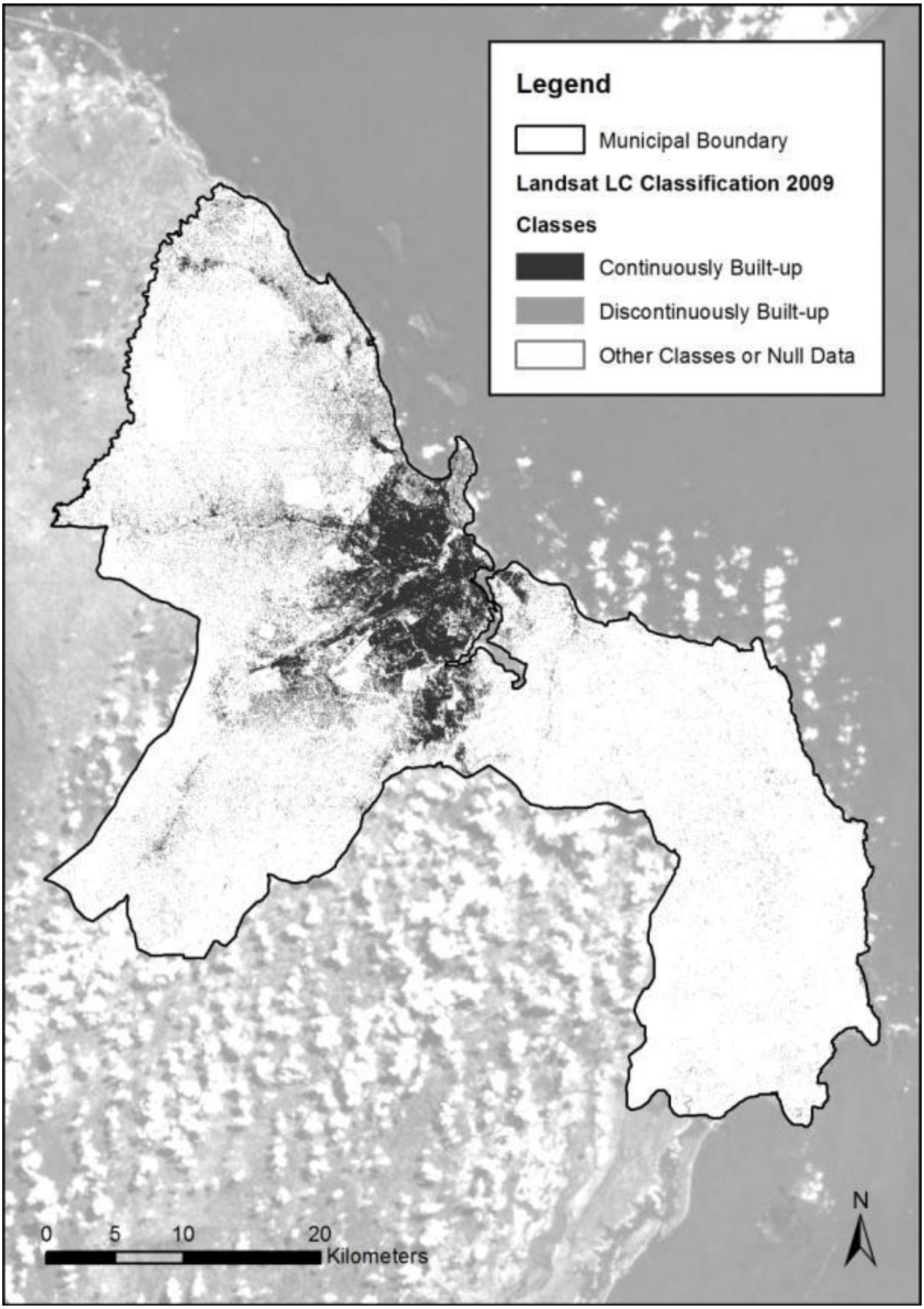

Figure 32: 2009 land cover classification

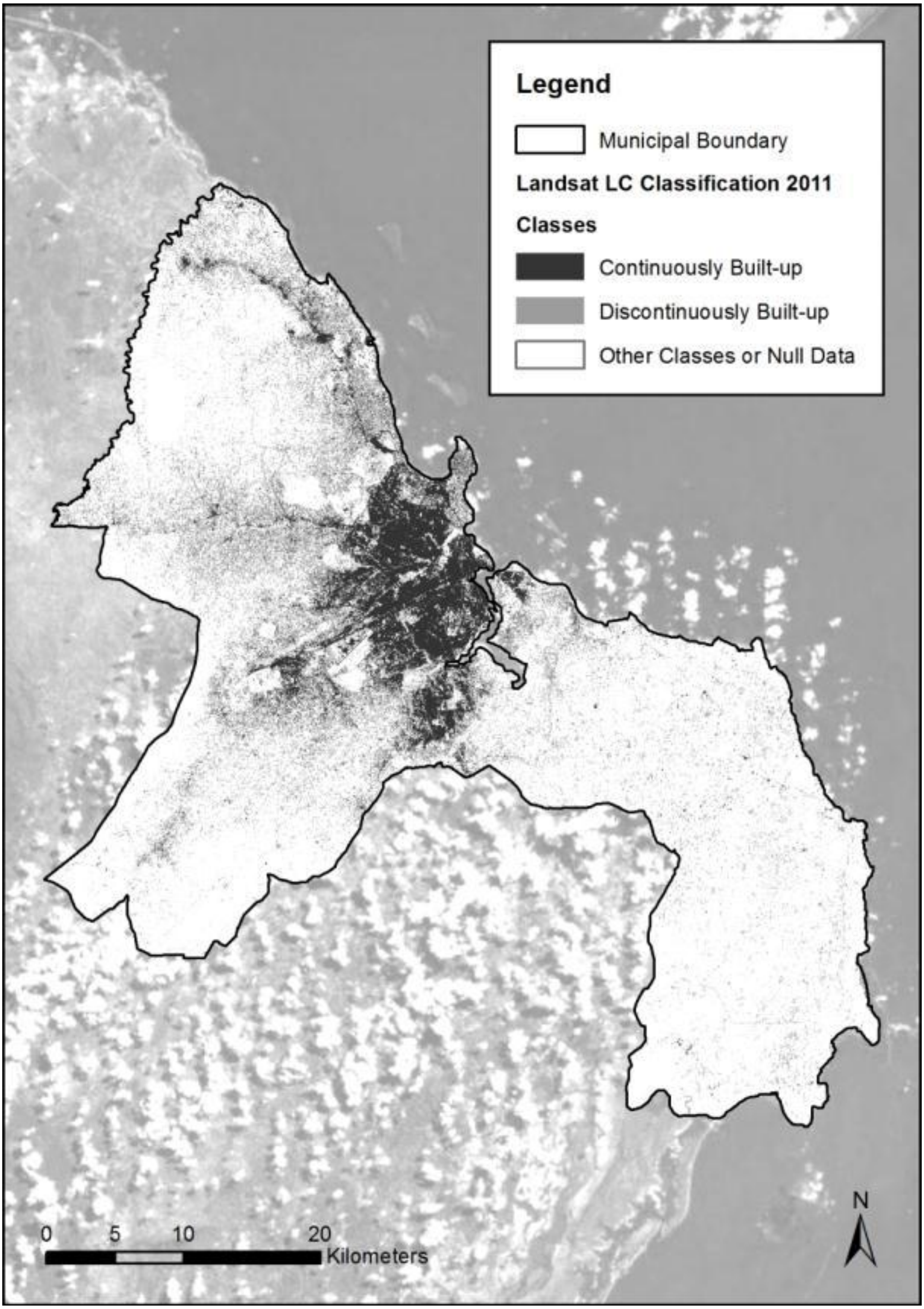

Figure 33: 2011 land cover classification

Appendix 3 – Method for Calculating Average Household Density

Household density ρ, assuming homogeneous distribution of households in the space (Figure 34), can be defined as:

$$\rho \; = \frac{HH^2}{d^2} \qquad [household/m^2] \tag{1}$$

where:

- HH is the number of households between a given IHH and the closest one;
- d is the distance between a given IHH and the closest one.

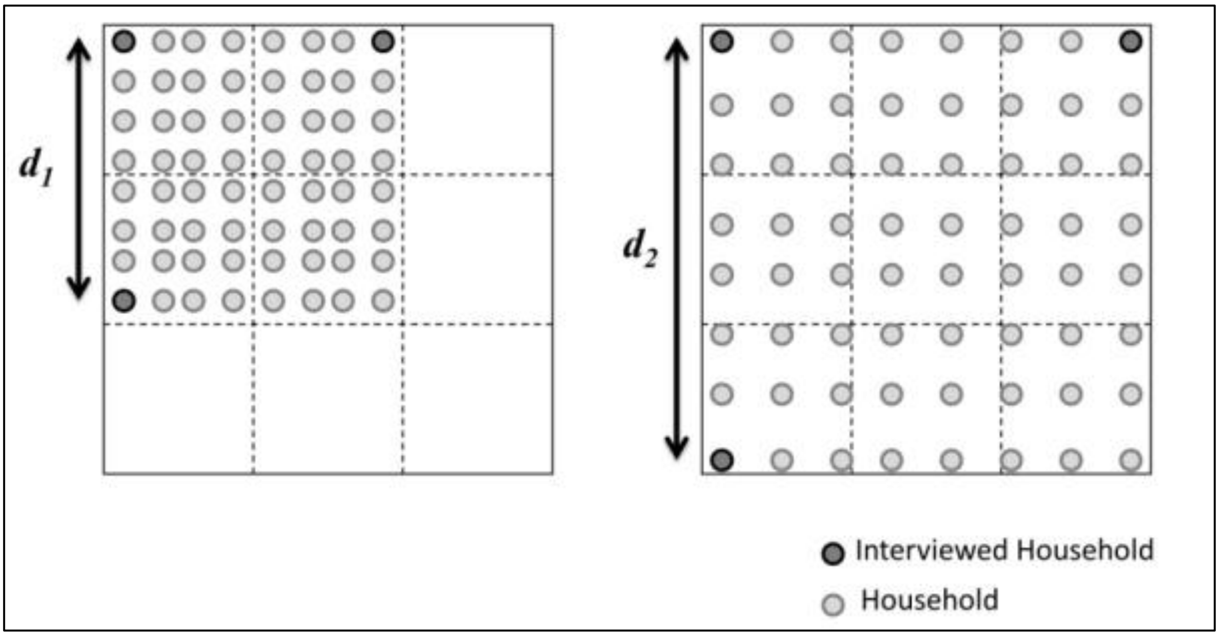

Figure 34: Scheme of household homogeneity in the space; the greater the distance (d), the fewer households there are in the neighbourhood where one has been interviewed

The LC classification dataset consists of a raster file, where the minimum unit (i.e. pixel) is a square of 900m^2. Therefore, the household number in a single pixel (HH_{pixel}) is given by:

$$HH_{pixel} = \rho \, \times Area_{pixel} \; = \frac{HH^2}{d^2} \times \, Area_{pixel} \tag{2}$$

where $Area_{pixel}$ is the area of the LC pixel.

Through photointerpretation and field survey, the maximum number of households per LC pixel ($MaxHH_{pixel}$) is defined as:

$$MaxHH_{pixel} = 8 \tag{3}$$

This maximum number of households per pixel is detectable in the "Continuously Built-up" class (Figure 35), where houses are very close to each other.

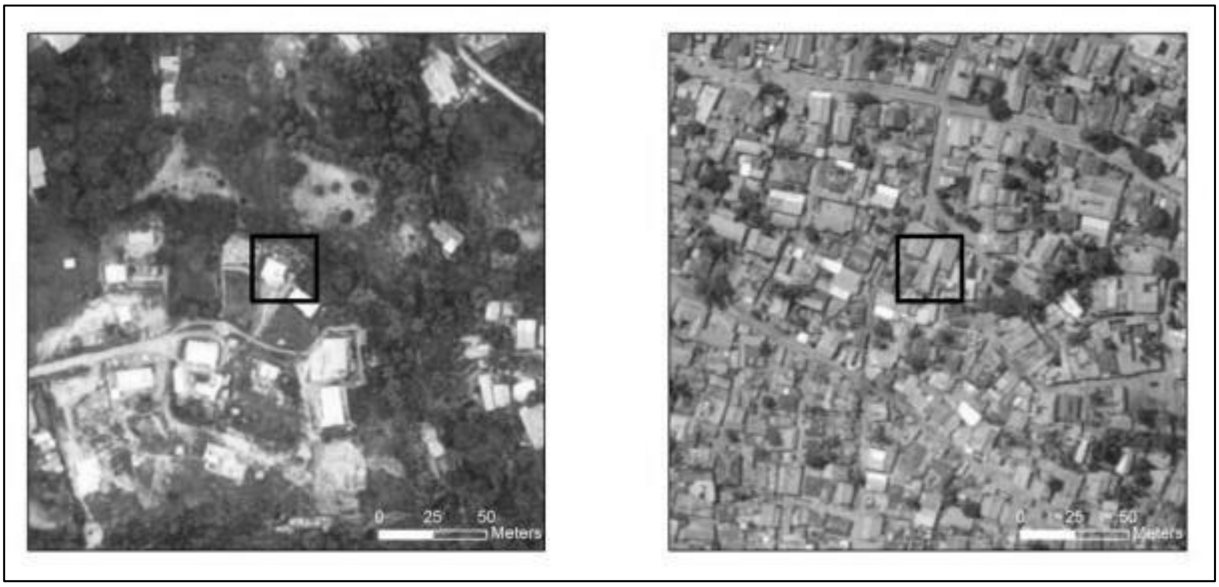

Figure 35: Quickbird images showing different house densities corresponding to the classes “Discontinuously Built-up” (left) and “Continuously Built-up” (right); the dimension of a Landsat pixel (30x30m) is superimposed on the images

The minimum distance between two IHH (d_{min}), which corresponds to the $MaxHH_{pixel}$, is defined as:

$$d_{min} = 20 \quad [4]$$

Thus, HH^2 can be calculated from the inverse of eq.2, for $HH_{pixel} = MaxHH_{pixel}$ and $d = d_{min}$, as:

$$HH^2 = \frac{MaxHH_{pixel}}{\frac{Area_{pixel}}{d_{min}{}^2}} = \frac{MaxHH_{pixel} \times d_{min}{}^2}{Area_{pixel}} \quad [5]$$

Finally, by substituting eq.5 in eq. 2, the household number in a single pixel HH_{pixel} is given by:

$$HH_{pixel} = \frac{MaxHH_{pixel} \times d_{min}{}^2}{Area_{pixel}} \times \frac{Area_{pixel}}{d^2} = \frac{MaxHH_{pixel} \times d_{min}{}^2}{d^2} = \frac{8 \times 400}{d^2} = \frac{3200}{d^2} \quad [6]$$

Eq.6 relates the household density per pixel to the distance between a given IHH and the nexy closest one. The distance d can be calculated using the household shapefile (e.g. with the “Near” tool in ArcGIS that calculates the mutual distance of IHHs). Therefore, HH_{pixel} for each IHH will be calculated by applying eq.6.

With a spatial join (a GIS operation that can link the features of two datasets, according to their spatial location), the LC class to which each IHH belongs (i.e. the LC class of the pixel where an IHH point is) is identified, allowing for calculation of the average of the HH_{pixel} values ($\overline{HH}_i$), for each LC class (i) and the average household density ($\bar{\rho}_i$) for each LC class:

$$\bar{\rho}_i = \frac{\overline{HH}_i}{Area_{pixel}} \quad [household/m^2] \quad [7]$$

Consequently, an estimation of the number of households for each LC (EHH_i) class is provided by:

$$EHH_i = \overline{\rho}_i * Area_i \quad [8]$$

where $Area_i$ is the surface of the LC class i.

Project title:

Adapting to Climate Change in Coastal Dar es Salaam

Project acronym:	**ACC Dar**
Contract number:	**2010/254-773**
Project duration:	**01/02/2011 – 31/01/2014**
Grant Contract Beneficiary:	**DICEA Sapienza University of Rome**
Contact Person:	**Silvia Macchi**
Partner in the Action:	**Ardhi University Dar es Salaam**
Associate in the Action:	**Dar es Salaam City Council**