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The dynamics of urban expansion and land use/land cover changes using remote sensing and spatial metrics: the case of Mekelle City of northern Ethiopia

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ABSTRACT

Information on the rate and pattern of urban expansion is required by urban planners to devise proper urban planning and management policy directions. This study evaluated the dynamics and spatial pattern of Mekelle City's expansion in the past three decades (1984–2014). Multi-temporal Landsat images and Maximum Likelihood Classifier were used to produce decadal land use/land cover (LULC) maps. Changes in LULC and spatial pattern of urban expansion were analysed by post-classification change detection and spatial metrics, respectively. The results showed that in the periods 1984–1994, 1994–2004, and 2004–2014, the built-up area increased annually by 10%, 9%, and 8%, respectively; with an average annual increment of 19% (100 ha year^{-1}), from 531 ha in 1984 to 3524 ha in 2014. Between 1984 and 2014, about 88% of the gain in built-up area was from conversion of agricultural lands, which decreased by 39%. Extension of existing urban areas was the dominant growth type, which accounted for 54%, 75%, and 81% of the total new development during 1984–1994, 1994–2004, and 2004–2014, respectively. The spatial metrics analyses revealed urban sprawl, with increased heterogeneity and gradual dispersion in the outskirts of the city. The per capita land consumption rate (ha per person) increased from 0.009 in 1984 to 0.014 in 2014, indicating low density urban growth. Based on the prediction result, the current (2014) built-up area will double by 2035, and this is likely to have multiple socioeconomic and environmental consequences unless sustainable urban planning and development policies are devised.

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1. Introduction

In today's world, more than half of the global population lives in urban areas and by 2050, this figure is projected to increase to more than 65% (United Nations 2014). Based on this projection, 2.5 billion people will add to the world's urban population, with

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nearly 90% of the urban growth concentrated in less developed countries. Developing countries started the process of urbanization lately, but they are the ones which are rapidly urbanizing (Montgomery 2008). As such, in the past few decades, rapid and often unplanned urban expansion has considerably accelerated more in developing countries than in developed nations (Cohen 2006; Grimm et al. 2008). Several studies (e.g. Long et al. 2007; Bhatta 2009; Thapa and Murayama 2010; Haregeweyn et al. 2012) attributed unprecedented population growth and socioeconomic development as the major drivers of such unplanned urban expansion. In most developing countries, urban expansion is recognized as an important phenomenon as it offers increased opportunities for employment, production, and goods and services (Cohen 2006). Such increased opportunities in urban areas further enhanced rural–urban migration (Chen et al. 2014). As a result, significant urban expansion takes place faster than ever over a short period of time (Angel et al. 2011), and in some countries, the space taken-up by urban areas is increasing faster than the urban population itself (Tewolde and Cabral 2011).

Depending on the definitions of urban land, estimates of the global urban area vary from less than 1–3% of the world's land surface (Liu et al. 2014). Despite the fact that urban areas cover a small fraction of the world's land, the rapid urban expansion in different parts of the world has led to significant changes on other land use/land cover (LULC) types. A number of studies reported that urban expansion resulted in encroachment of surrounding landscape such as agricultural lands (e.g. Pauchard et al. 2006; Soffianian et al. 2010; Forkuor and Cofie 2011; Tewolde and Cabral 2011; Haregeweyn et al. 2012), grass lands (e.g. Banzhaf, Grescho, and Kindler 2009; Mundia and Murayama 2010), forest and bush lands (e.g. Pauchard et al. 2006; Banzhaf, Grescho, and Kindler 2009; Araya and Cabral 2010; Mundia and Murayama 2010), and waterbodies and wetlands (e.g. Pauchard et al. 2006; Fazal and Amin 2011; Haregeweyn et al. 2012). As such, from a LULC change perspective, the change induced by urban expansion has considerable effects impacting the environment, ecosystem, and society (Grimm et al. 2008; Wilson and Chakraborty 2013). These impacts are particularly important in developing countries where there is limited capacity to cope with the environmental and social consequences of rapid urban expansion (Cohen 2006).

Urban expansion and its impacts are relatively better studied for megacities worldwide (e.g. Herold, Goldstein, and Clarke 2003; Xiao et al. 2006; He et al. 2008; Sun, Zhao, and Qu 2015); however, they are not well-documented for small- and medium-sized cites in developing countries, primarily attributed to lack of reliable and up-to-date demographic and spatial data (Cohen 2006). Recent advances in remote-sensing data with improved spatial accuracy and availability of free to less expensive satellite images coupled with geographical information system (GIS) allow quantitative analyses of the rate and pattern of urban expansion with reasonable cost and better accuracy (Epstein, Payne, and Kramer 2002). In recent studies, several of the remote-sensing methods such as unsupervised classification (Schneider and Woodcock 2008), supervised classification (Bhatta 2009; Mundia and Murayama 2010; Tewolde and Cabral 2011; Sharma, Pandey, and Nathawat 2012), normalized difference vegetation index (Banzhaf, Grescho, and Kindler 2009; Soffianian et al. 2010) and image differencing (Lu et al. 2010) have been effectively applied to evaluate urban expansion at different spatiotemporal scales. Furthermore, integrated with remote-sensing data, Herold, Couclelis, and Clarke (2005) suggested the use of spatial metrics as quantitative measures of urban growth pattern to enhance the understanding and representation of spatiotemporal changes of urban expansion. Regular and up-to-date information on urban land use changes is required to visualize growth patterns and improve land use planning and management (Debolini et al. 2015) as well as for appropriate allocation of services and infrastructure (Witten, Exeter, and Field 2003). Moreover, accurate information on urban dynamics is important for predictive urban modelling (He et al. 2008), but also to assess ecological changes and their environmental implications (Grimm et al. 2008).

With a population of more than 90 million and an annual growth rate of 2.3%, Ethiopia has the second largest population in Africa. The urban population growth rate is 4.2%, which is higher compared with the average rate (2.2%) for developing countries (United Nations 2014). In addition, based on World Bank (2015), Ethiopia's economy experienced broad based growth in recent years. The rapid urban population growth coupled with the economic development led to rapid and unplanned urban expansion in various parts of the country. Mekelle City of Tigray region in northern Ethiopia has experienced rapid development especially over the past few decades following the rise to power of the current Ethiopian government in 1991. Mekelle City's expansion has posed serious threats to the small-scale farmers and the natural environment as the surrounding farmlands and nearby rural communities become part of the city's expansion zones. However, the extent and spatial characteristics of the city's expansion and its effect on other LULC types is not well-documented. This research was, therefore, initiated to analyse the spatiotemporal dynamics of Mekelle City's expansion for the past three decades (1984–2014) using multi-temporal Landsat images and spatial metrics. The objectives of this study were threefold: (i) to quantify the rate and type of urban expansion and its associated effects on the traditional LULC pattern; (ii) to examine urban sprawl in the form of change in the spatial pattern of urban expansion; and (iii) to examine the relationship between population and built-up area using regression analysis and to project the future built-up area demand. This study can help better understand the dynamics and spatial pattern of urban growth and provide pertinent information to devise proper urban planning and management policy directions for sustainable future urban development with minimal associated impacts.

2. Materials and methods

2.1. *Description of the study area*

Mekelle City is the seat of Tigray Regional State in northern Ethiopia (Figure 1(a)). Mekelle is one of the fastest growing and the second largest city next to the capital, Addis Ababa. The city is located at about 780 km north of Addis Ababa between 13° 25′ 24″ and 13° 33′ 44″ N and 39° 25′ 26″ and 39° 33′ 14″ E. Its altitude ranges from 1930 to 2353 m above mean sea level. Based on meteorological records from Alula Aba Nega International Airport station for the period 1980–2010, the average annual rainfall of the city is around 615 mm, of which about 75% falls during the wet season (June–September). The mean daily minimum and maximum temperatures for the corresponding period are 11°C and 27°C, respectively. Based on the Population and Housing Census data (CSA 2008), the total population of Mekelle City was 61,583 in 1984, 96,938 in 1994, and 215,914 in 2007. Administratively, Mekelle is considered as a Special Zone, which

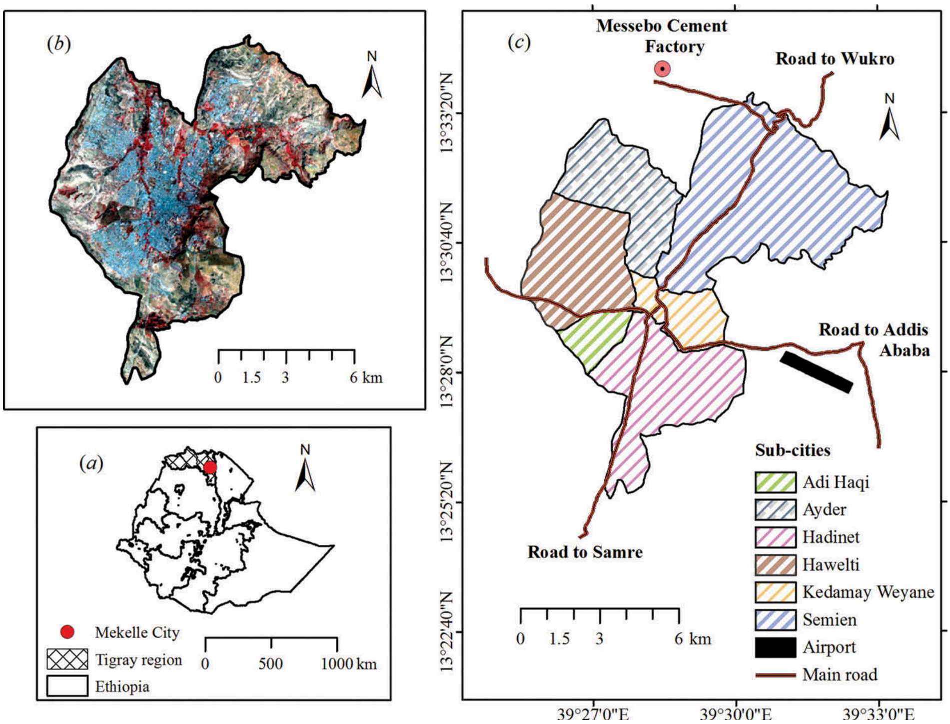

Figure 1. Location map of the study area (a) – country map including Mekelle City and Tigray region, (b) – false colour composite Landsat image of 2014, and (c) – sub-cities of Mekelle City.

comprises seven sub-cities namely: Adi Haqi sub-city, Ayder sub-city, Hadinet sub-city, Hawelti sub-city, Kedamay Weyane sub-city, Quiha sub-city, and Semein sub-city. Quiha sub-city is located at some 8 km distance from the city centre to the east of the airport and is recently added into the city's administration zone. This study, however, did not address the Quiha sub-city, and therefore it is not represented in Figure 1(c).

2.2. *Data sources*

Landsat Thematic Mappers (TMs) for 1984, 1994, and 2004 and Operational Land Imager (OLI) for 2014 were used to produce the decadal LULC maps of the city. The choice of the study periods was dictated by availability of supplementary data for image classification. The Landsat images (path 168, row 51) were downloaded free of charge from the United States Geological Survey (USGS) via http://earthexplorer.usgs.gov/. For change detection studies, appropriate selection of image acquisition dates is an integral component of the analysis. As such, for clear identification of the LULC types from the spectral response, the image acquisition dates were selected based on availability of cloud free images and for the dry season. TMs images acquired on 1 December 1984; on 13 December 1994; and on 14 November 2004; and OLI image acquired on 4 December 2014 were used in this study. The Landsat images have a medium spatial resolution of 30 m, which based on Yeh and Li (2001), is good enough to provide information on urban expansion. A combination of data collected from Mekelle City Administration

Office, interpretation of topographic maps and aerial photographs (scale 1:50,000) collected from Ethiopian Mapping Agency (EMA), historical high resolution Google Earth Pro images, and field observation using handheld Garmin global positioning system (GPS) were used for supervised image classification of the Landsat images. All the GIS data layers were projected to the Universal Transverse Mercator (UTM) map projection (Zone 37 N), Adindan datum and Spheroid – Clarke 1880. Population data was collected from the Ethiopian Central Statistical Authority (CSA 2008).

2.3. *Methodology*

2.3.1. *Image classification*

Band combinations of 4–3–2 (i.e. near-infrared (NIR)–red–green) for the TMs images and 5–4–3 (i.e. NIR–red–green) for the OLI image were used to make false colour composite (FCC) images (e.g. Figure 1(b)) as it was most effective for LULC mapping (Jensen 2004). Based on the spectral responses of features on the Landsat images and field observation, five LULC types were identified. With some modification from Mayaux et al. (2004), the descriptions of the LULC types are given in Table 1. Supervised image classification was done using the Maximum Likelihood (ML) classifier algorithm which is one of the most popular and widely used types of image classification techniques in remote sensing (Chen and Stow 2002). In supervised image classification, training sample points are required to generate spectral signatures for each LULC type. For classifiers like the ML, it is often recommended that a training sample size for each class should not be fewer than 10–30 times the number of bands (Van Niel, McVicar, and Datt 2005). For each LULC type, except for waterbody, a minimum of 90 training sample points were collected. Two-third of the training sample points were randomly selected and used for classification and the remaining data were used for accuracy assessment using confusion matrix (Congalton 2001).

2.3.2. *Land use/land cover change detection*

The change in LULC for the periods 1984–1994, 1994–2004, 2004–2014, and 1984–2014 was analysed by using post-classification change detection technique in a GIS environment. Post-classification change detection was selected as it reduces the possible effects of spectral resolution and sensor differences between the multi-temporal images (Lu et al. 2004). This method enables to assess the temporal changes of the LULC types and to compute the extent of LULC conversion induced by the urban expansion. The change statistics for LULC maps of two time periods was calculated as

Table 1. Description of the land use/land cover (LULC) types.

LULC type	Description
Agricultural land	Land used for growing crops, including areas currently under crop, fallow and land under preparation; it also includes grazing lands
Built-up	All types of artificial surfaces, including residential, commercial, and industrial areas as well as transportation infrastructures
Plantation	Areas covered with planted trees around settlements (e.g. Eucalyptus tree)
Shrub land	Land covered with shrubs, bushes, and small trees with little wood mixed with some grasses
Waterbody	Intermittent ponds and small dammed water fed by rainfall and small streams

$$\text{Change}(\%) = \left(\frac{A_{\text{final year}} - A_{\text{initial year}}}{A_{\text{initial year}}}\right) \times 100, \tag{1}$$

where A is the area coverage of each LULC type (in ha). Positive percentage values suggest an increase whereas negative values imply a decrease in area coverage.

2.3.3. *Rate and type of urban expansion*

In order to analyse the rate of urban expansion for the periods 1984–1994, 1994–2004, 2004–2014, and 1984–2014, the LULC maps were reclassified into built-up and non-built-up areas. Based on Herold, Goldstein, and Clarke (2003), built-up areas refer to residential, commercial, industrial complexes including pavement and other infrastructure that are closely associated with built-up environment. After extracting the built-up areas, the annual rate of urban expansion (RUE) for the specified periods was evaluated by using Equation (2), modified after Xiao et al. (2006):

$$\text{RUE} = \frac{(\text{BUA})_{i+n} - (\text{BUA})_i}{n \times (\text{BUA})_i} \times 100, \tag{2}$$

where BUA_{i+n} and BUA_i are the built-up area (in ha) at time $i + n$ and i, respectively, and n is the interval of the calculating period (in years).

The type of new urban development for decadal time periods (1984–1994, 1994–2004, and 2004–2014) was analysed using the Urban Landscape Analysis Tool (ULAT). The ULAT was developed with the support of the Centre for Land use Education and Research (CLEAR) and the University of Connecticut department of Natural Resources and the Environment (http://clear.uconn.edu/%5C/tools/ugat/index.htm) to analyse the urban spatial patterns in a city over multiple time periods. The LULC maps were reclassified into three classes as 'urban area', 'other areas', and 'no data' for the years 1984, 2004, and 2014; and into four classes including 'waterbody' for the year 1994. The ULAT tool classified the urban development that occurred between two consecutive time periods based on its proximity to previously existing built-up areas as infill, extension, and leapfrog. Infill refers to newly developed built-up areas in the urbanized open spaces of the previous time period. Extension is the new development intersecting and extending outward from the earlier built-up areas; whereas the new development that is not intersecting and no contiguity with the previous built-up areas is referred as leapfrog.

2.3.4. *Shannon's entropy analysis*

Shannon's entropy is commonly used to measure the degree of spatial concentration or dispersion of a geographical variable (built-up area) over time (Yeh and Li 2001). In this study, Shannon's entropy integrated with GIS tools was used to evaluate the spatial pattern of urban expansion and detect the presence of sprawl. Following the work of Ramachandra, Aithal, and Sanna (2012), the study area was divided into nine different zones using concentric circles with a consecutive incrementing radius of 1 km created around the city centre, with centroid at the location of Kedamay Weyane Market Centre (13° 29′ 43″ N and 39° 28′ 18″ E). Zone 1 is the inner most zone and zone 9 is the outer most zone. By clipping out the built-up areas of each zone, the Shannon's entropy in each zone was calculated as

$$H_n = \sum_{i=1}^{n} P_i \ln\left(\frac{1}{P_i}\right), \tag{3}$$

where H_n is the Shannon's entropy, P_i is the percentage of built-up areas in each zone computed as a ratio of built-up areas in ith zone to the total built-up areas in all zones, n is the total number of zones.

The Shannon's entropy values vary between 0 and ln(n), zero entropy value indicates that built-up areas have very concentrated distribution; whereas value of entropy closer to ln(n) indicates very high dispersion of built-up areas. Relative Shannon's entropy (H'_n) gives clearer understanding about the spatial pattern of urban expansion (Yeh and Li 2001), since it scales the entropy value into ranges between 0 and 1. H'_n was computed by

$$H'_n = \left[\sum_{i=1}^{n} P_i \ln\left(\frac{1}{P_i}\right)\right] / \ln(n). \tag{4}$$

The change in the rate of urban dispersion between two time periods helps evaluate the urban expansion as a process and assess whether urban expansion is towards a more dispersed or compact pattern (Yeh and Li 2001). Hence, the magnitude of change rate of urban dispersion was calculated as

$$\Delta H_n = H_n(t_2) - H_n(t_1), \tag{5}$$

where ΔH_n is the difference in entropy values between two time periods, $H_n(t_1)$ is the relative Shannon's entropy at time (t_1) and $H_n(t_2)$ is the relative Shannon's entropy at time (t_2).

2.3.5. *Computation of spatial metrics*

Spatial metrics provide quantitative description of the composition and configuration of urban landscape. A single spatial metric cannot capture all the aspects of landscape characteristics; therefore, a suite of selected metrics may be useful in the interpretation of landscape change. In this study, spatial metrics which cover the different dimensions of sprawl, including pattern, shape, density, and surface indicators were used to measure urban sprawl. The metrics include number of urban patches, mean patch size, largest patch index, and landscape shape index. These metrics were computed zone-wise for each circle using classified LULC data with the help of FRAGSTATS (McGarigal and Marks 1995) extension in ArcGIS. In addition, density of built-up area and landscape diversity were computed using neighbourhood analysis in a GIS environment. Built-up density values were computed by dividing the number of built-up pixels to the total number of pixels in a 3 × 3 moving window. This operation converted the built-up areas of the reclassified satellite images to density values and following the procedure of Sudhira, Ramachandra, and Jagadish (2004), the built-up density maps were reclassified as low, medium, and high using equal interval classification. The built-up density analysis offers information on whether the new urban development was low or high density, as well as enables to identify the presence of urban sprawl and further compare the results with Shannon's entropy. Landscape diversity provides information on the number of different LULC classes within a 3 × 3 moving window. As such, landscape diversity measures the number of heterogeneous LULC pixels over a particular area, and the greater the landscape diversity, the more heterogeneous the landscape is (Murphy 1985). For this study, window size was chosen based on the number of LULC classes available in a particular image. The maximum number of LULC classes in the classified images was 5, which is less than the number of pixels in a 3 × 3 size window. Therefore, window size of 3 × 3 was enough to assess the landscape diversity in this study.

2.3.6. *Population growth and urban expansion*

The increase in built-up area is generally related to population growth since population growth is a major driver for built-up area expansion. Comparison of growth rates of population and built-up area helps analyse the characteristics of urban growth. Bhatta (2009) showed that urban sprawl can be identified by careful assessment of changes in built-up area expansion and population growth. The land consumption rate (LCR), which was used as an index to measure the progressive spatial expansion of the city vis-à-vis its population, was computed by using Equation (6) (Sharma, Pandey, and Nathawat 2012):

$$\text{Land consumption rate} = \frac{\text{Built-up area}}{\text{Population}}. \tag{6}$$

Projecting future built-up area demand is important to assess urban dynamics so that timely action can be taken to minimize the subsequent impacts. However, accurate projection is a challenge because of the complexity of related socioeconomic factors (He et al. 2008). Taking population growth as a major driving force for urban expansion, population size can be used to estimate built-up area or vice versa. Recent studies by He et al. (2008) and Haregeweyn et al. (2012) demonstrated that linear regression of built-up area and population can be used to project future built-up area demand. The relationship between population and built-up area was established by regression analysis using the built-up area for the years 1984, 1994, 2004, and 2014 and the corresponding population number. The population data for the years 1984, 1994, and 2007 were obtained from the Ethiopian Population and Housing Census (CSA 2008). The 2004 and 2014 population data were projected using the 1994 and 2007 population data, respectively and an exponential relationship, recommended by the Ethiopian Central Statistical Agency (CSA 2013):

$$P_t = P_o e^{r \times t}, \tag{7}$$

where P_t is the population projected at a given time, P_o is the population size of a base year, e is the natural logarithm base, r is average annual population growth rate (4.2% for urban areas of Ethiopia based on United Nations 2014), and t is the time interval between the base year and the projected year.

3. Results and discussion

3.1. *Accuracy assessment*

The LULC maps (Figure 2) produced from classification of the Landsat images were validated by creating confusion matrices from which producer accuracy, user accuracy, overall accuracy and kappa coefficient (κ) were computed. Based on the summarized results of the classification accuracy (Table 2), for all LULC types except plantation in 1994, the producer and user accuracy values were greater than 80%. Overall accuracy values of 86%, 85%, 87%, and 89%, and κ values of 0.81, 0.80, 0.82, and 0.86 were achieved for the

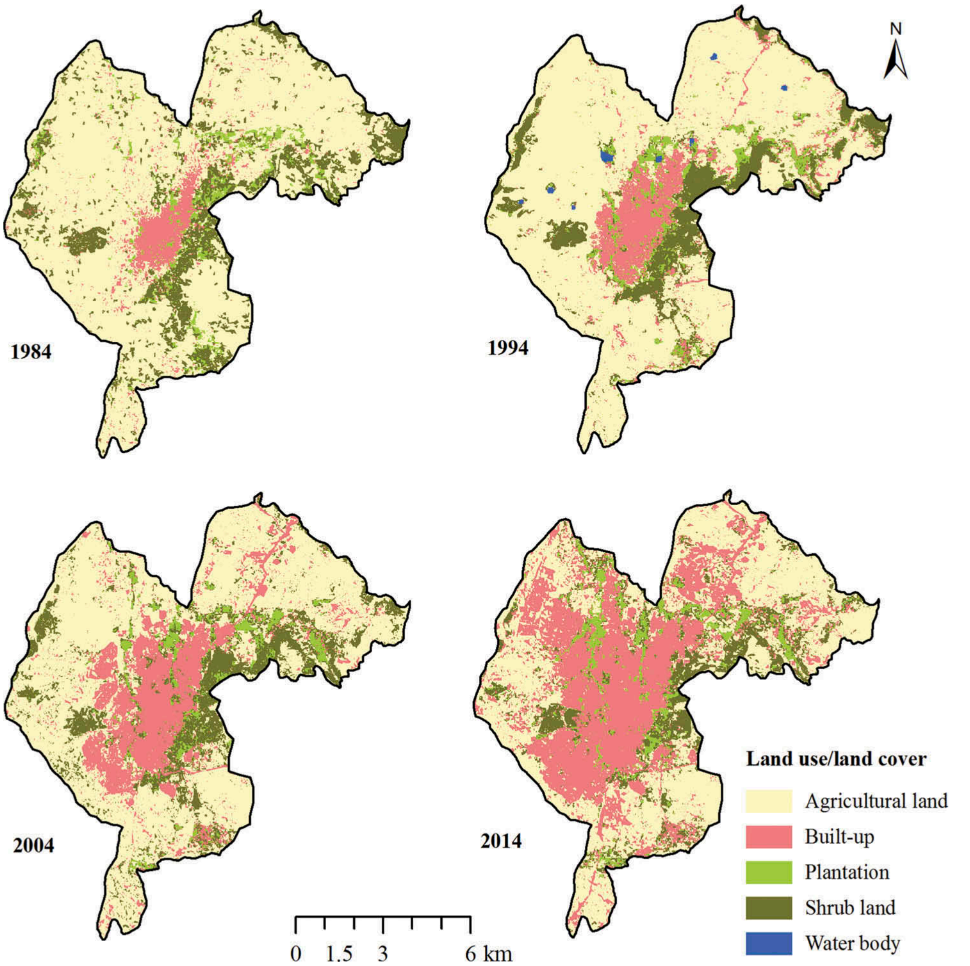

Figure 2. Land use/land cover (LULC) maps of Mekelle City administration zone for the years 1984, 1994, 2004, and 2014.

Table 2. Accuracy assessment of the classified images of 1984, 1994, 2004, and 2014.

	Accuracy (%)							
	1984		1994		2004		2014	
LULC type	Producer	User	Producer	User	Producer	User	Producer	User
Agricultural land	87	87	86	86	89	86	91	94
Built-up	96	93	91	91	91	91	94	92
Plantation	80	83	78	78	81	84	87	84
Shrub land	81	81	82	84	85	85	85	88
Waterbody	–	–	100	100	–	–	–	–
Overall accuracy	86		85		87		89	
Kappa coefficient (κ)	0.81		0.80		0.82		0.86	

classified images of 1984, 1994, 2004, and 2014, respectively. Based on Congalton (1991), the above results indicated strong agreement between the ground truth and the classified classes. Furthermore, the overall accuracy and κ values met the minimum accuracy requirements for LULC change detection studies (Anderson et al. 1976).

3.2. LULC change and urban expansion during 1984–2014

Agricultural land was the major LULC type, which covered 7140 ha (75%) in 1984 and until 2004 it covered more than 60% of the area delineated as the city's administration zone; but the area of agricultural land was significantly reduced to 4379 ha (46%) in 2014 (Table 3). In 1984 and 1994, shrub land was the second largest LULC type followed by built-up area and plantation. However, in the past three decades, shrub land showed a gradual decrease from 1424 ha (15%) in 1984 to 1097 ha (11.5%) in 2014. By contrast, the built-up area registered dramatic increase from 531 ha (5.6%) to 3524 ha (37.1%) between 1984 and 2014, and a gradual increase was observed for plantation from 405 ha (4.3%) to 500 ha (5.3%) during the same period (Table 3). In the periods 1984–1994, 1994–2004, and 2004–2014, built-up area increased by 99%, 87%, and 79%, respectively; whereas during the same change periods, agricultural land decreased by about 7%, 13%, and 24%, respectively (Table 3). The annual rate of change for the three decadal periods (1984–1994, 1994–2004, and 2004–2014) showed that the built-up area increased by 10% (53 ha year^{-1}), 9% (91 ha year^{-1}) and, 8% (155 ha year^{-1}), respectively; with an average annual increment of 19% (100 ha year^{-1}) for the whole study period, from 1984 to 2014 (Table 4). This showed that annually on average about 100 ha of non-urban land had been used for built-up purposes over the past three decades. Between 1984 and 2014, the built-up area increased sixfold (about 3000 ha), and about 88% of the gain in built-up area was from conversion of agricultural lands, which decreased by about 39%. This indicated that in the past three decades, rapid urban expansion took place primarily at the expense of agricultural lands in the urban fringe. Overall, between 1984 and 2014, a significant shift in the distribution of LULC was observed and agricultural lands and built-up area were the most dynamic LULC types. Elsewhere, several other studies (e.g. Forkuor and Cofie 2011; Tewolde and Cabral 2011; Haregeweyn et al. 2012) showed that in developing countries rapid urban expansion largely affected the nearby agricultural lands, which in turn considerably impacted the livelihoods of farmers in the urban fringe.

Identifying the types of urban growth in a quantitative means is essential to help urban planners better analyse the characteristics of urban expansion. As such, the urban growth types of Mekelle City during the 1984–1994, 1994–2004, and 2004–2014 change periods were categorized into infill, extension, and leapfrog (Figure 3). It was observed that new urban development of 525 ha during 1984–1994 comprised 10% as infill, 54% as extension, and 36% as leapfrog developments. During 1994–2004 period, 75% of new urban development (914 ha) was extension type; whereas the leapfrog and infill types covered 16% and 9%, respectively. The extension type of urban development further increased to 81% of the total new development (1554 ha) during 2004–2014 period; however, the infill and leapfrog developments covered only 14% and 5%, respectively. The results showed that extension type mainly at the edge of the areas built-up in previous years was the predominant type of urban growth. Wilson et al. (2003) suggested that infill growth can be a remedy for environmental degradation caused by unplanned urban expansion; however, this type of development is very low in Mekelle City. This indicated that the city has the potential for compact growth through enhancing infill type of urban development. This would require implementation of well-studied urban development plans that promote infill type of urban expansion and

Table 3. Land use/land cover change between 1984 and 2014.

	1984		1994		2004		2014		Percentage changes in LULC			
LULC types	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	1984–1994	1994–2004	2004–2014	1984–2014
Agricultural land	7140	75.2	6618	69.7	5767	60.7	4379	46.1	−7	−13	−24	−39
Built-up	531	5.6	1056	11.1	1970	20.7	3524	37.1	99	87	79	564
Plantation	405	4.3	392	4.1	398	4.2	500	5.3	−3	2	26	23
Shrub land	1424	15.0	1400	14.7	1365	14.4	1097	11.5	−2	−3	−20	−23
Waterbody	0	0	34	0.4	0	0.0	0	0.0	+100	−100	0	0
Total	9500		9500		9500		9500					

Table 4. Built-up area expansion between 1984 and 2014.

Year	Built-up area (ha)	Rate of urban expansion (% year^{-1})			
		1984–1994	1994–2004	2004–2014	1984–2014
1984	531	10			
1994	1056		9		
2004	1970			8	
2014	3524				19
Change (ha year^{-1})		53	91	155	100

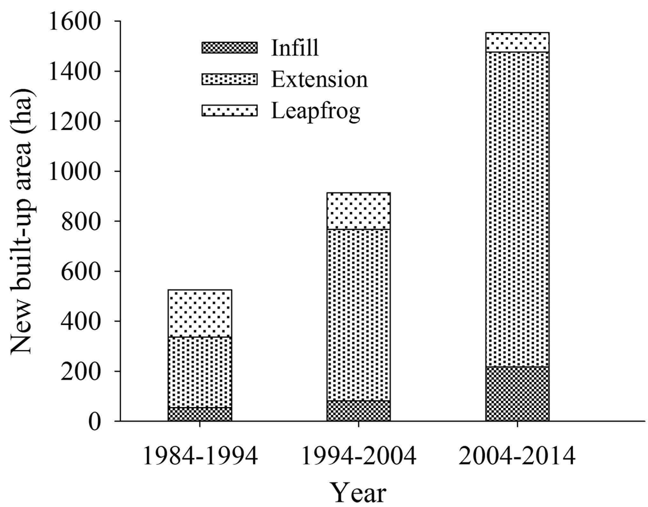

Figure 3. The types of new urban development of Mekelle City and area coverage in hectares.

usage of inner city, which in turn will allow for a more intensive use of existing infrastructure and other public services as well as help preserve the natural landscape in the urban fringe.

To better understand urban growth vis-à-vis direction, the built-up area was extracted for the northeast, northwest, southeast, and southwest directions from the city centre (Figure 4). Mekelle City's expansion took place mainly in three directions, towards the northeast (along the highway to Wukro town) in Semien sub-city, to the northwest (in the direction of Messebo Cement Factory) in Ayder sub-city and to the southwest in Adi Haqi and Hadinet sub-cities. The above three directions experienced the biggest expansion in built-up areas because of the availability of abundant flat land suitable for construction of residential houses and also the presence of industrial and economic development zones, especially in the direction of Messebo Cement Factory. The expansion to the southeastern part of the city, however, was limited by the presence of hills and the rugged topography. A recent investigation on the topographic and geological constraints for Mekelle City's expansion by Berhane and Walraevens (2013) has shown that in all directions most areas with flat to gentle slope (<5% slope) are urbanized and further expansion is expected to be towards moderately steep/hilly landforms (<30% slope). Such topographic features, however, are unsuitable for urban development because of prevalence of damaging natural processes, such as erosion and mass movement.

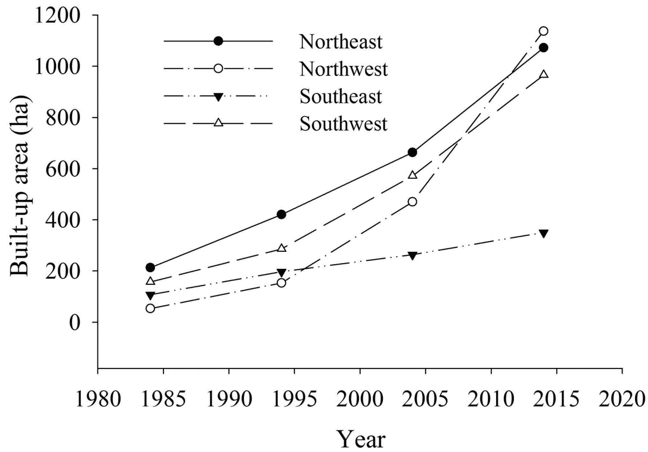

Figure 4. Direction-wise built-up area (ha) between 1984 and 2014.

3.3. *Spatial metrics of urban sprawl*

3.3.1. *Shannon's entropy*

For the inner core circles (Figure 5), the relative Shannon's entropy decreased from 0.17 in 1984 to 0.09 and 0.14 in 2014 for first two zones. This showed the presence of infill or intensification, which indicated the increasing density of built-up areas within the first 2 km radius. However, a general increasing trend in entropy values was observed for the outer seven zones indicating more dispersion of built-up areas. The relative Shannon's entropy values in 1984, 1994, 2004, and 2014 were, 0.69, 0.84, 0.86, and 0.89, respectively (Table 5). Relatively lower value of Shannon's entropy in 1984 indicated the compact and homogeneous distribution of the built-up areas; whereas the increasing trend of entropy values between 1984 and 2014 demonstrated a high rate of urban sprawl as a result of dispersed urban growth spreading over the urban fringe. Furthermore, the positive values of the changes in entropy (Table 5) indicated that urban expansion is towards a more dispersed pattern (Yeh and Li 2001). The increase in dispersion was due to new peripheral areas being added to the municipal boundaries for the new housing schemes and industrial zones, especially in the past two decades. Several previous studies reported the phenomenon of urban sprawl as a consequent of rapid and unplanned urbanization in different parts of the world. For example, a recent study by Ramachandra, Aithal, and Sanna (2012) in Bangalore City of India reported increased Shannon's entropy values at the outskirts of the city between 1973 and 2010 that confirmed sparse urban growth and inefficient development around cities. Also, increase in entropy of urban areas were reported by Araya and Cabral (2010) for Setúbal and Sesimbra Cities of Portugal and by Tewolde and Cabral (2011) for Asmara City of Eritrea, and the increase in entropy was mainly attributed to unplanned and dispersed development. From these studies it is evident that increasing trend in Shannon's entropy and dispersed urban growth is the case for many cities around the world.

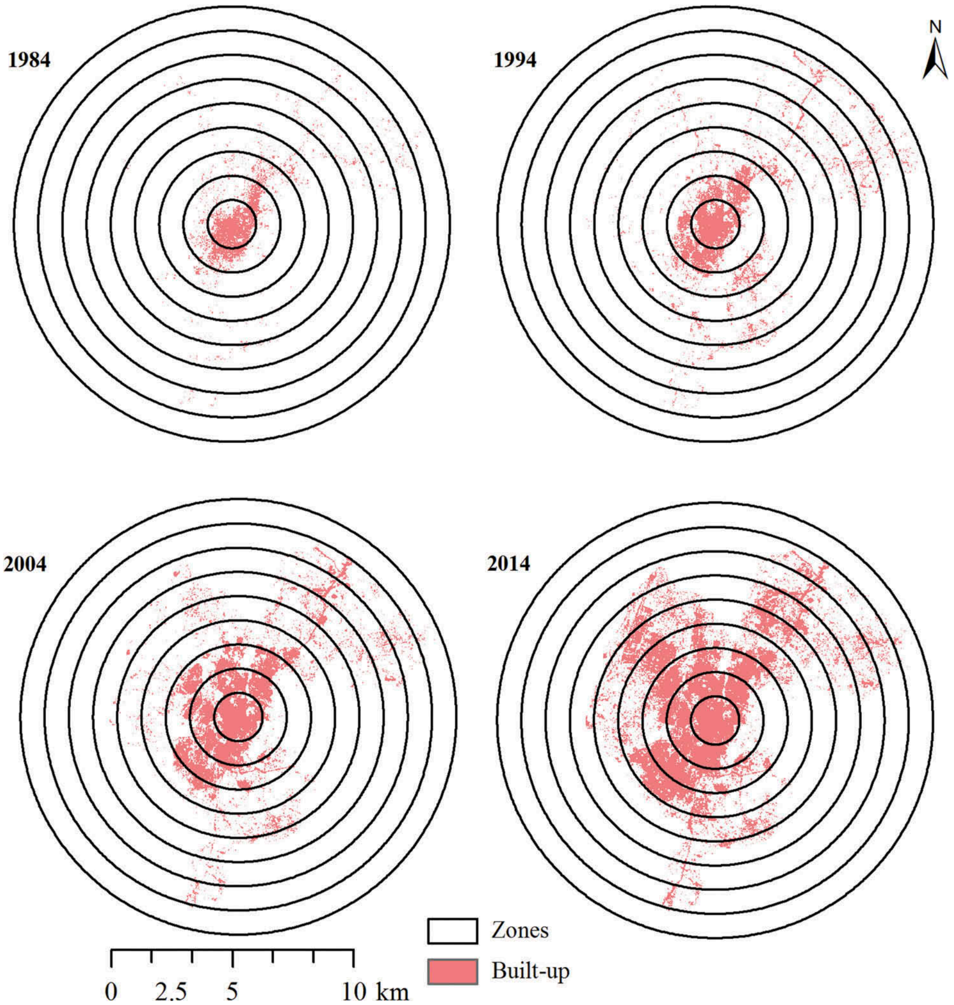

Figure 5. Division of built-up area into concentric circles with radius of 1 km interval.

Table 5. Shannon's entropy and changes in entropy between 1984 and 2014.

Year	Shannon's entropy	Changes in entropy			
		1984–1994	1994–2004	2004–2014	1984–2014
1984	0.69	0.15			
1994	0.84		0.02		
2004	0.86			0.03	
2014	0.89				0.20

3.3.2. *Patch size and shape metrics*

The number of patches of built-up area is a simple measure of the extent of subdivision or fragmentation in built-up landscape. Between 1984 and 2014, the number of built-up patches has steadily decreased in the inner core circles from 21, 162, and 175 in 1984 to 3, 38, and 97 in 2014 for the first three zones, respectively (Figure 6(a)), which indicated aggregation. However, the increase in the built-up patches in the periphery (outer rings) especially in areas beyond zone 3 indicated the presence of numerous small urban patches in recent years pointing to urban sprawl. The mean patch size, the average area of all patches in the landscape (in ha), is inversely related to the degree of fragmentation. Figure 6(b) shows that as we move away from the city centre, the mean patch size considerably decreases and in the outskirts of the city mean patch size was less than 1 ha which signified fragmented urban growth. The largest patch index is an indicator of the largest urban patch as percentage of the total urban area in a zone. Figure 6(c) shows increasing trend in the largest patch index between 1984 and 2014; however, the largest patch index decreases as we move from the inner core to the outer core circles indicating fragmented urban growth due to heterogeneous landscapes in the outskirts of the city. Landscape shape index (Figure 6(d)) is a perimeter or edge ratio which indicates the complexity of shape with values close to one indicating that the landscape consists of maximally compact built-up patch, and the landscape shape index increases without limit as urban growth becomes more disaggregated. Between 1984 and 2014, the landscape shape index decreases for the inner core circles (Figure 6(d)) which showed more compact urban growth at city centre; whereas disaggregated growth was observed in the outer circles with relatively high values of landscape shape index.

3.3.3. *Density of built-up area*

The density of built-up area can be used to show distribution of built-up areas and examine dispersion. Built-up density values computed using a 3 × 3 moving window

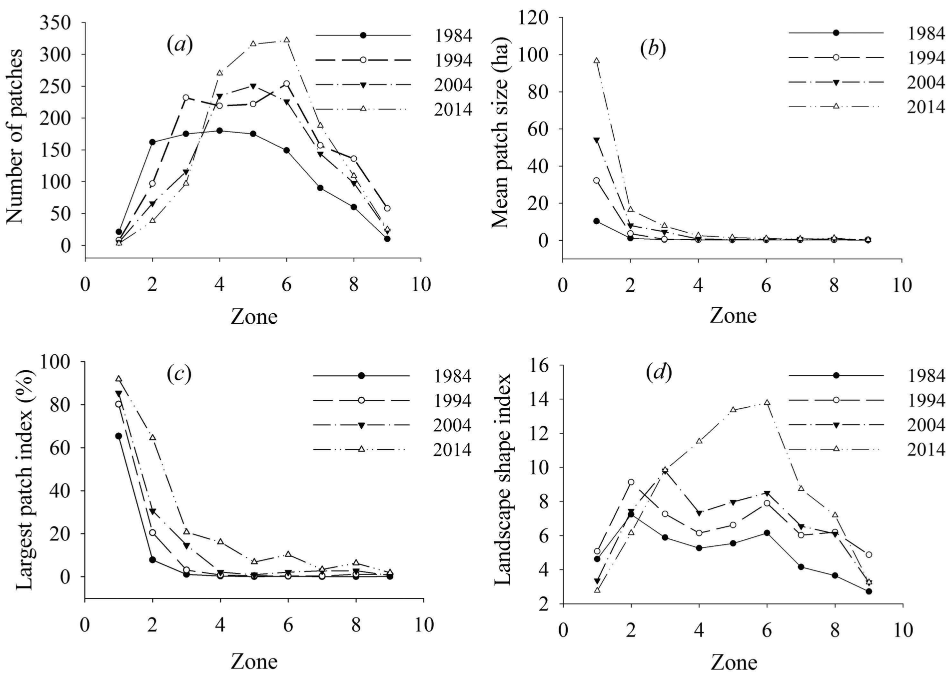

Figure 6. Zone-wise patch size and shape metrics: (a) number of patches, (b) mean patch size, (c) largest patch index, and (d) landscape shape index.

ranges from 0 to 1 (Figure 7). Between 1984 and 2014, the built-up density increased across all zones. High density values were observed in the inner core circles which indicate compact urban growth; whereas in the outer rings a progressive decrease in density confirms low density urban growth. In addition, the built-up density maps were reclassified as low, medium, and high; with high density of built-up indicating more compact nature of the built-up theme, while medium density referred to lesser compact built-up and low density referred to sparsely spread built-up areas. The percentage of low density built-up area increased from 16% in 1984 to 21% in 2014; however, for the same period, high density built-up area decreased from 62% to 58% (Table 6). This showed that percentage of compact or highly dense built-up area declined gradually, while sparsely spread built-up area increased indicating dispersion or presence of sprawl. It is worth noting that the reduction in percentage of high density built-up area does not mean that built-up areas have decreased since 1984. In 1984, the area under high density category was 329 ha, which has increased to 2044 ha in 2014 (Table 6); however, its percentage with respect to the total area under all categories has been reduced. The result of the built-up density analysis is in agreement with the Shannon's entropy values, which substantiate gradual dispersion of urban growth.

3.3.4. *Landscape diversity*

The landscape diversity for the years 1984, 1994, 2004, and 2014 ranged from 1 to 4 LULC categories (Table 7). The 1 LULC category represented that only one LULC type was available within the 3 × 3 moving window, the 2 LULC category represented that any two LULC types were available within the moving window, etc. For all the years, the 1 and 2 LULC categories were dominant together accounting for more than 80% of the area, whereas the 3 and 4 heterogeneous categories covered less than 20% (Table 7). The area of homogeneous class (1 LULC category) decreased from 5700 ha (60%) in 1984 to 4750 ha (50%) in 2014. By contrast, for the 3 LULC category, the area increased from 665 ha (7%) in 1984 to 1330 ha (14%) in 2014; while the 4 LULC category increased from 95 ha (1%) to 285 ha (3%) during the same period, indicating an increase in spatial heterogeneity and landscape fragmentation, resulting in diverse, mixed LULC. These

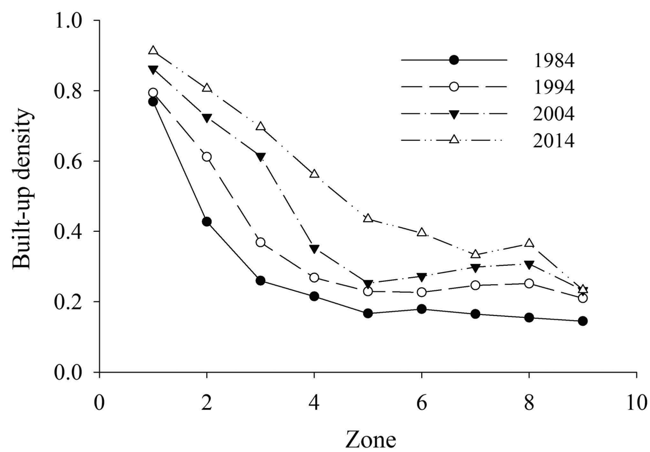

Figure 7. Zone-wise built-up density computed using a 3 × 3 moving window.

Table 6. Density categories of built-up areas and area coverage in hectares and percentage.

	1984		1994		2004		2014	
Density category	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Low	85	16	190	18	394	20	740	21
Medium	117	22	264	25	414	21	740	21
High	329	62	602	57	1162	59	2044	58

results confirmed that with the growing human disturbances, considerable changes in the natural landscape pattern and composition was observed, with landscape patterns becoming more fragmented and dispersed. Based on Sudhira, Ramachandra, and Jagadish (2004) and Jat, Garg, and Khare (2008), the reduction in the number of non-mixed pixels as a consequent of increased landscape heterogeneity could be attributed to the continuous process of urbanization in new areas and confirmed the presence of urban sprawl.

3.4. *Drivers of urban expansion*

Urban expansion and associated LULC changes can result from a combination of geographical and socioeconomic factors, such as population growth, government policy, and economic development. The total population of Mekelle City was 61,583 in 1984, 96,938 in 1994, and 215,914 in 2007. The natural population increase of the city accounted for 78%, whereas migration of people from rural/other areas was about 22% of the population growth between 1994 and 2007. In the periods 1984–1994, 1994–2004, and 2004–2014, the city's population grew by 57%, 52%, and 68%, whereas during the same periods, the built-up area increased by 99%, 87%, and 79%, respectively (Figure 8). In the past three decades, population growth has increased the demand for land, infrastructure and public services. In addition, as shown in Figure 9, the total population and the total built-up area have a strong exponential relationship with time. The exponential relationship revealed that the built-up area is growing at a higher rate, 6.3% year^{-1}, than the population with an average growth rate of 4.6% year^{-1}. The higher growth rate of built-up areas compared with the growth rate of population supports the findings of Bhatta (2009) that cities in developing countries do not always become more compact. However, this contradicts with the results of Richardson, Bae, and Baxamusa (2000) who suggested that urban development in developing countries are less sprawling and are becoming more compact.

The per capita LCR (ha per person) was 0.009, 0.011, 0.013, and 0.014 in 1984, 1994, 2004, and 2014, respectively. The progressive increase in the per capita LCR indicated an overall low-density urban growth, which according to Hasse and Lathrop (2003), is itself

Table 7. Landscape diversity categories and area coverage in hectares and percentage.

	1984		1994		2004		2014	
Number of classes	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
1	5700	60	5985	63	5130	54	4750	50
2	3040	32	2375	25	3230	34	3135	33
3	665	7	950	10	950	10	1330	14
4	95	1	190	2	190	2	285	3

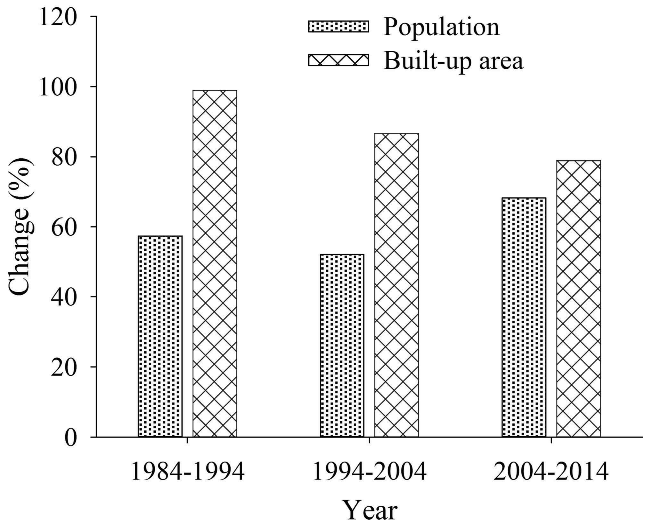

Figure 8. Changes in growth of population and built-up area of Mekelle City.

an indicator of sprawl. This confirmed the rapid urban expansion and an alarm to urban planners and regional authorities to look for proper remedies. The per capita LCR includes a portion of all the built-up areas for urban uses such as, residence houses, commercial shops, infrastructure, factories/industries, religious services, and public facilities such as schools and universities. The increasing trend of the per capita LCR can be attributed to the ever increasing demand of more urban land for various purposes. For instance, between 1991 and 2005, about 8250 new plots of land with size 140–175 m^2 were allocated for residential houses in the city; however, this was only about 30% of the total housing demand. In addition, factors such as presence of conducive environment

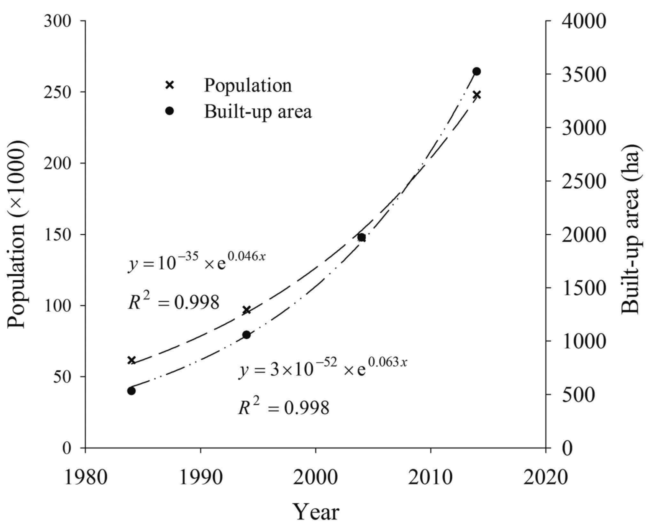

Figure 9. The relationship between Mekelle City's total population and built-up area with time.

for investment which attracts local and foreign investors, as well as better job opportunity which enhance rural–urban migration can lead to increasing demand for urban land. Overall the city is undergoing rapid development in every aspect of the economy which boosted the demand for new land for developing different projects and recently the city has increased number of (i) factories/industries – textile and leather (6), metal, mines and minerals (6), food and beverages (2), machineries and electrical (2), chemicals (1), and other factories (7); and (ii) education facilities – preschool/kindergarten (53), elementary school (49), elementary and high school (13), secondary school (7), special education (2); public and private higher institutions (15). It is worth noting that increasing trends in the per capita LCR and subsequent low density urban growth is a common phenomenon in cities elsewhere (e.g. Bhatta 2009; Soffianian et al. 2010).

To project the future built-up area, a regression analysis between total population and total built-up area was made and found the following linear relationship. The parameters obtained were coefficient of determination, R^2 = 0.998 and significance level, $\alpha < 0.05$:

$$\text{BUA} = 0.016P - 468, \quad (8)$$

where BUA is the total built-up area (in ha), and P is the total population number.

Using this linear relationship, the current (2014) built-up area will double by the year 2035. This implies that in the next 20 years, about 3500 ha of non-urban land will be occupied for new urban development. Such information regarding the amount of land that is likely to be needed to accommodate the growing population is necessary to make informed decision at the present time. Based on the projected area demand, it is more likely that large-scale encroachment on the nearby agricultural lands will occur in the foreseeable future impacting the ecosystem, socioeconomic and environmental settings. Increased built-up area due to urban expansion can also have negative impacts on the environment such as runoff/flood generation, soil erosion and heat island effect (Sun, Zhao, and Qu 2015). Moreover, the rapid urban growth will be a challenge for the regional and local authorities to provide the necessary basic public services and facilities for the residents. In a similar study, Cohen (2006) noted that rapid urban growth in developing countries surpassed the capacity of most cities to provide adequate services and facilities, degrading the quality of life and the environment.

4. Conclusions

Understanding the dynamics and spatial patterns of urban expansion is a basis to devise proper urban planning policies geared towards sustainable urban development. In the present study, multi-temporal Landsat images for the years 1984, 1994, 2004, and 2014 were used to produce the LULC maps and assess the urban expansion of Mekelle City in northern Ethiopia. In the past three decades (1984–2014), the built-up area increased sixfold (about 3000 ha) and about 88% of the gain in built-up area was from conversion of agricultural lands. A general increasing trend in Shannon's entropy was observed in the past three decades (0.69 in 1984 to 0.89 in 2014), which showed the presence of urban sprawl. The spatial metrics results also revealed increase in heterogeneity and gradual dispersion of urban growth, suggesting the prevalence of urban sprawl. Furthermore, increasing trend in the per capita land consumption rate was observed over the past three decades indicating an overall low-density urban growth. It is worth noting that the city experienced more dispersed horizontal urban growth primarily at the expense of agricultural lands where vertical expansion was rarely practiced during previous years. It is, therefore, important that planners and decision makers consider vertical urban development for optimal use of land. In addition, policies that aim to make the city more compact through implementation of higher residential densities and intensification of existing urban areas can help reduce the land absorption as well as allow provision of public services at optimum costs. Driven by the rapid population growth and recent economic developments, the city's expansion is expected to gain even more momentum in the foreseeable future. The built-up area in 2014 is estimated to double by the year 2035, and this is likely to have multiple environmental and social consequences, but also put pressure on the capacity of the regional and local authorities to provide better infrastructure and basic public amenities. It is, therefore, important to enforce timely and appropriate land use planning which considers the requirements of social, economical, and environmental sustainable development. In addition, for effective implementation of policies and strategies, the extent and rate of urban land use dynamics and its multitude impacts should be well understood by all stakeholder including planners, policy makers, environmentalists and people in general. The results of this study provide baseline information to better understand the current status of urban growth as well as to devise comprehensive and up-to-date urban planning and development policies to assure sustainable urban development. Further this study demonstrates that integrating satellite remote-sensing data and spatial metrics provides a powerful and effective means to visualize changes in LULC and spatial pattern of urban expansion.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Anderson, B. J. R., E. E. Hardy, J. T. Roach, and R. E. Witmer. 1976. *A land use and land cover classification system for use with remote sensor data*. USGS Professional Paper 964.

Angel, S., J. Parent, D. L. Civco, A. Blei, and D. Potere. 2011. "The dimensions of global urban expansion: estimates and projections for all countries, 2000-2050." *Progress in Planning* 75 (2): 53–107. doi:10.1016/j.progress.2011.04.001.

Araya, Y. H., and P. Cabral. 2010. “Analysis and modelling of urban land cover change in Setubal and Sesimbra, Portugal.” *Remote Sensing* 2 (6): 1549–1563. doi:10.3390/rs2061549.

Banzhaf, E., V. Grescho, and A. Kindler. 2009. “Monitoring urban to peri-urban development with integrated remote sensing and GIS information: a Leipzig, Germany case study.” *International Journal of Remote Sensing* 30 (7): 1675–1696. doi:10.1080/01431160802642297.

Berhane, G., and K. Walraevens. 2013. “Geological and geotechnical constraints for urban planning and natural environment protection: a case study from Mekelle City, Northern Ethiopia.” *Environmental Earth Science* 69 (3): 783–798. doi:10.1007/s12665-012-1963-x.

Bhatta, B. 2009. “Analysis of urban growth pattern using remote sensing and GIS: a case study of Kolkata, India.” *International Journal of Remote Sensing* 30 (18): 4733–4746. doi:10.1080/01431160802651967.

Chen, D., and D. Stow. 2002. “The effect of training strategies on supervised classification at different spatial resolutions.” *Photogrammetric Engineering and Remote Sensing* 68 (11): 1155–1162.

Chen, R., C. Ye, Y. Cai, X. Xing, and Q. Chen. 2014. “The impact of rural out-migration on land use transition in China: Past, present and trend.” *Land Use Policy* 40: 101–110. doi:10.1016/j.landusepol.2013.10.003.

Cohen, B. 2006. “Urbanization in developing countries: current trends, future projections, and key challenges for sustainability.” *Technology in Society* 28: 63–80. doi:10.1016/j.techsoc.2005.10.005.

Congalton, R. G. 1991. “A review of assessing the accuracy of classifications of remotely sensed data.” *Remote Sensing of Environment* 37 (1): 35–46. doi:10.1016/0034-4257(91)90048-B.

Congalton, R. G. 2001. “Accuracy assessment and validation of remotely sensed and other spatial information.” *International Journal of Wildland Fire* 10 (4): 321–328. doi:10.1071/WF01031.

CSA. 2008. *Population statistical abstract*. Addis Ababa, Ethiopia: Federal Democratic Republic of Ethiopia, Population Census Commission.

CSA. 2013. *Population Projections for Ethiopia 2007-2037*. Addis Ababa, Ethiopia: Federal Democratic Republic of Ethiopia, Population Census Commission.

Debolini, M., E. Valette, M. Francois, and J. P. Chéry. 2015. “Mapping land use competition in the rural–urban fringe and future perspectives on land policies: A case study of Meknès (Morocco).” *Land Use Policy* 47: 373–381. doi:10.1016/j.landusepol.2015.01.035.

Epstein, J., K. Payne, and E. Kramer. 2002. “Techniques for mapping suburban sprawl.” *Photogrammetric Engineering and Remote Sensing* 63 (9): 913–918.

Fazal, S., and A. Amin. 2011. “Impact of urban land transformation on water bodies in Srinagar city, India.” *Journal of Environmental Protection* 2: 142–153. doi:10.4236/jep.2011.22016.

Forkuor, G., and O. Cofie. 2011. “Dynamics of land-use/land-cover change in Freetown Sierra Leone and its effects on urban and peri-urban agriculture–A remote sensing approach.” *International Journal of Remote Sensing* 32 (4): 1017–1037. doi:10.1080/01431160903505302.

Grimm, N. B., S. H. Faeth, N. E. Golubiewski, C. L. Redman, J. Wu, X. Bai, and J. M. Briggs. 2008. “Global change and the ecology of cities.” *Science* 319: 756–760. doi:10.1126/science.1150195.

Haregeweyn, N., G. Fikadu, A. Tsunekawa, M. Tsubo, and D. T. Meshesha. 2012. “The dynamics of urban expansion and its impacts on land use/land cover change and small-scale farmers living near the urban fringe: a case study of Bahir Dar, Ethiopia.” *Landscape and Urban Planning* 106 (2): 149–157. doi:10.1016/j.landurbplan.2012.02.016.

Hasse, J. E., and R. G. Lathrop. 2003. “Land resource impact indicators of urban sprawl.” *Applied Geography* 23 (2): 159–175. doi:10.1016/j.apgeog.2003.08.002.

He, C., N. Okada, Q. Zhang, P. Shi, and J. Li. 2008. “Modelling dynamic urban expansion processes incorporating a potential model with cellular automata.” *Landscape and Urban Planning* 86 (1): 79–91. doi:10.1016/j.landurbplan.2007.12.010.

Herold, M., H. Couclelis, and K. C. Clarke. 2005. “The role of spatial metrics in the analysis and modelling of urban land use change.” *Computer Environment and Urban Systems* 29 (4): 369–399. doi:10.1016/j.compenvurbsys.2003.12.001.

Herold, M., N. C. Goldstein, and K. C. Clarke. 2003. “The spatiotemporal form of urban growth: measurement, analysis and modelling.” *Remote Sensing of Environment* 86 (3): 286–302. doi:10.1016/S0034-4257(03)00075-0.

Jat, M. K., P. K. Garg, and D. Khare. 2008. “Monitoring and modelling of urban sprawl using remote sensing and GIS techniques.” *International Journal of Applied earth Observation and Geoinformation* 10 (1): 26–43. doi:10.1016/j.jag.2007.04.002.

Jensen, J. R. 2004. *Introductory digital image processing: a remote sensing perspective*. Upper Saddle River: Prentice Hall.

Liu, Z., C. He, Y. Zhou, and J. Wu. 2014. ““How much of the world’s land has been urbanized, really? A hierarchical framework for avoiding confusion.” *Landscape Ecology* 29 (5): 763–771. doi:10.1007/s10980-014-0034-y.

Long, H., G. Tang, X. Li, and G. K. Heilig. 2007. “Socio-economic driving forces of land-use change in Kunshan, the Yangtze River Delta economic area of China.” *Journal of Environmental Management* 83 (3): 351–364. doi:10.1016/j.jenvman.2006.04.003.

Lu, D., S. Hetrick, E. Moran, and G. Li. 2010. “Detection of urban expansion in an urban-rural landscape with multitemporal QuickBird images.” *Journal of Applied Remote Sensing* 4 (1): 041880–041880. doi:10.1117/1.3501124.

Lu, D., P. Mausel, E. Brondi´Zio, and E. Moran. 2004. “Change detection techniques.” *International Journal of Remote Sensing* 25 (12): 2365–2407. doi:10.1080/0143116031000139863.

Mayaux, P., E. Bartholomé, S. Fritz, and A. Belward. 2004. “A new land/cover map of Africa for the year 2000.” *Journal of Biogeography* 31 (6): 861–877. doi:10.1111/j.1365-2699.2004.01073.x.

McGarigal, K., and B. J. Marks. 1995. *FRAGSTATS: spatial pattern analysis program for quantifying landscape structure*. USDA Forest Service General Technical Report PNW-351.

Montgomery, M. R. 2008. “The urban transformation of the developing world.” *Science* 319: 761–764. doi:10.1126/science.1153012.

Mundia, C. N., and Y. Murayama. 2010. “Modelling spatial processes of urban growth in African cities: a case study of Nairobi City.” *Urban Geography* 31 (2): 259–272. doi:10.2747/0272-3638.31.2.259.

Murphy, D. L. 1985. “Estimating neighborhood variability with a binary comparison matrix.” *Photogrammetric Engineering and Remote Sensing* 51 (6): 667–674.

Pauchard, A., M. Aguayo, E. Peña, and R. Urrutia. 2006. “Multiple effects of urbanization on the biodiversity of developing countries: the case of a fast-growing metropolitan area (Concepción, Chile).” *Biological Conservation* 127 (3): 272–281. doi:10.1016/j.biocon.2005.05.015.

Ramachandra, T. V., B. H. Aithal, and D. D. Sanna. 2012. “Insights to urban dynamics through landscape spatial pattern analysis.” *International Journal of Applied Earth Observation and Geoinformation* 18: 329–343. doi:10.1016/j.jag.2012.03.005.

Richardson, H. W., C. C. Bae, and M. H. Baxamusa. 2000. “Compact cities in developing countries: assessment and implications.” In *Compact Cities: Sustainable Urban Forms for Developing Countries*, edited by J. Mike and R. Burgess, 1–25. New York: Spon Press.

Schneider, A., and C. E. Woodcock. 2008. “Compact, dispersed, fragmented, extensive? A comparison of urban growth in twenty-five global cities using remotely sensed data, pattern metrics and census information.” *Urban Studies* 45 (3): 659–692. doi:10.1177/0042098007087340.

Sharma, L., P. C. Pandey, and M. S. Nathawat. 2012. “Assessment of land consumption rate with urban dynamics change using geospatial techniques.” *Journal of Land Use Science* 7 (2): 135–148. doi:10.1080/1747423X.2010.537790.

Soffianian, A., M. A. Nadoushan, L. Yaghmaei, and S. Falahatkar. 2010. “Mapping and analyzing urban expansion using remotely sensed imagery in Isfahan, Iran.” *World Applied Sciences Journal* 9 (12): 1370–1378.

Sudhira, H. S., T. V. Ramachandra, and K. S. Jagadish. 2004. “Urban sprawl: metrics, dynamics and modelling using GIS.” *International Journal of Applied Earth Observation and Geoinformation* 5 (1): 29–39. doi:10.1016/j.jag.2003.08.002.

Sun, Y., S. Zhao, and W. Qu. 2015. “Quantifying spatiotemporal patterns of urban expansion in three capital cities in Northeast China over the past three decades using satellite data sets.” *Environmental Earth Science* 73: 7221–7235. doi:10.1007/s12665-014-3901-6.

Tewolde, M. G., and P. Cabral. 2011. "Urban sprawl analysis and modelling in Asmara, Eritrea." *Remote Sensing* 3 (10): 2148–2165. doi:10.3390/rs3102148.

Thapa, R. B., and Y. Murayama. 2010. "Drivers of urban growth in the Kathmandu Valley, Nepal: examining the efficacy of the analytic hierarchy process." *Applied Geography* 30 (1): 70–83. doi:10.1016/j.apgeog.2009.10.002.

United Nations. 2014. *World Urbanization Prospects, The 2014 Revision*. http://esa.un.org/unpd/wup/index.htm. Accessed May 2015.

Van Niel, T. G., T. R. McVicar, and B. Datt. 2005. "On the relationship between training sample size and data dimensionality: Monte Carlo analysis of broadband multi-temporal classification." *Remote Sensing of Environment* 98 (4): 468–480. doi:10.1016/j.rse.2005.08.011.

Wilson, B., and A. Chakraborty. 2013. "The environmental impacts of sprawl: emergent themes from the past decade of planning research." *Sustainability* 5 (8): 3302–3327. doi:10.3390/su5083302.

Wilson, E. H., J. D. Hurd, D. L. Civco, M. P. Prisloe, and C. Arnold. 2003. "Development of a geospatial model to quantify, describe and map urban growth." *Remote Sensing of Environment* 86 (3): 275–285. doi:10.1016/S0034-4257(03)00074-9.

Witten, K., D. Exeter, and A. Field. 2003. "The quality of urban environments: mapping variation in access to community resources." *Urban Studies* 40 (1): 161–177. doi:10.1080/00420980220080221.

World Bank. 2015. *Economic Overview, Ethiopia*. The World Bank, IBRD-IDA, working for a world free of poverty. http://www.worldbank.org/en/country/ethiopia/overview. Accessed April 2015.

Xiao, J., Y. Shen, J. Ge, R. Tateishi, C. Tang, Y. Liang, and Z. Huang. 2006. "Evaluating urban expansion and land use change in Shijiazhuang, China, by using GIS and remote sensing." *Landscape and Urban Planning* 75 (1): 69–80. doi:10.1016/j.landurbplan.2004.12.005.

Yeh, A. G., and X. Li. 2001. "Measurement and monitoring of urban sprawl in a rapidly growing region using entropy." *Photogrammetric Engineering and Remote Sensing* 67 (1): 83–90.