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Inter-regional pattern of urbanization in southern Ghana in the first decade of the new millennium

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ABSTRACT

We analyze amounts and spatial patterns of land cover and land use change (LCLUC) and particularly change to Built for four contiguous regions of southern Ghana between 2000 and 2010. Our objective is to understand the degree of urban expansion relative to urban densification during this time frame, to understand the relationship between population growth and LCLUC at the census district level, and to explain the patterns of New Built LCLUC throughout this study area. During the study period 1.5% of the study area transitioned to Built, an increase of 56% Built area since 2000, while population increased by 33%. Most (84% of total study area) of this change to Built involved conversion from Agriculture al land use and occurred predominantly in suburban and periurban areas zones of the Accra and Kumasi metropolitan areas. While total population and amount of Built LCLU variables co-vary strongly at the census district level at the beginning and end of the study period, change in population and Built are less strongly correlated. In fact, we observe that new Built development increased at a greater rate than population growth within peri-urban areas of Accra and Kumasi, frequently occurring as spaced residential land use composed of large houses with minimal urban infrastructure.

1. Introduction

Rural to urban migration is a ubiquitous trend within countries of the Global South (Aide and Grau, 2004). On top of this, countries within Sub-Saharan Africa have birth rates that greatly exceed the replacement level (ICF International, 2015). The result of these two demographic trends for Sub-Saharan Africa has been the rapid expansion and densification of cities over the past decade or two (United Nations Population Division, 2012). Within Ghana, the Sub-Saharan African country of focus in this study, the total population increased from almost 19 million in 2000 to nearly 25 million in 2010—an annual rate of growth of 2.7%—based on data from the censuses in the respective years (Ghana Statistical Service, 2012b). During the same period, the Accra Metropolitan Area (AMA) and Kumasi Metropolitan Area (KMA) census districts (analogous to counties in the U.S.), containing Ghana's two largest urban populations, grew 24.5% and 73.6%, respectively. Concomitant with such rapid urban population growth has been extensive land cover and land use change (LCLUC), particularly from urbanization–the increase in the percentage of the population living in urban places (Weeks, 2015), and urban sprawl–the expansion of urban areas into the adjoining countryside (Bruegmann, 2005). Urban expansion has occurred as Built LCLU on formerly agricultural lands in peri-urban and urban hinterlands of Accra and Kumasi, reducing convenient food sources for the growing population (Cobbinah, Gaisie & Owusu-Amponsah, 2015; Møller-Jensen, Kofie, & Yankson, 2005).

Here we build on previous studies of LCLUC in Ghana, with greater emphasis on urbanization and on the 2000 to 2010 time period. Yorke and Margai (2007) mapped LCLUC in the Densu river basin, located east of Accra using Landsat imagery and post-classification comparison and found that the primary changes in the basin were urban growth, expansion of agricultural land, and decreasing forest cover. Pabi (2007) mapped LCLUC for eight sites in the district of Kitampo in northern Ghana using Landsat imagery and a post-classification comparison approach, finding that a decrease in dense woodlands and an increase in non-intensive cultivation were the primary changes. Also for northern Ghana,

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Braimoh (2004) used a similar approach to correlate land use change and migration, and determined that decreasing woodlands and increasing agricultural land were useful correlates of higher migration rates. For a similar study area, Braimoh and Vlek (2005) found that the effect of accessibility to roads on agricultural land cover was greater than the effect of population growth. For western Ghana, Kusimi (2008) used image differencing of Landsat data to analyze LCLUC in the Wassa West district and determined that substantial changes in LCLU had occurred due to expansion of mining, farming, urbanization, lumbering and fuel wood extraction. Studies by Møller-Jensen and Yankson (1994) and Møller-Jensen et al. (2005) are among the few that have examined LCLUC in the more urbanized southern Ghana by analyzing patterns of peri-urban development in the outskirts of Accra.

While the specific focus is on Ghana, our research builds on and contributes to an ever-wider literature on urbanization and urban sprawl throughout the developing world (see especially Seto, 2003, Seto, 2005 and Seto, Sánchez-Rodríguez, & Fragkias, 2010). Every country in the world not already highly urbanized is moving in that direction, with Sub-Saharan Africa lagging behind other regions but in the process of catching up. These trends seem obvious to people on the ground in each locale, but the vast number of growing cities throughout the world renders it impossible to track broader patterns of LCLUC without the assistance of remotely sensed imagery (Sutton, 2003; Montgomery, 2008; Schneider & Woodcock, 2008; Sutton, Taylor & Elvidge, 2010).

In this paper we analyze the spatial pattern of LCLUC within four contiguous regions (equivalent to states or provinces) of southern Ghana in relation to population change from 2000 to 2010. The emphasis is on New Built LCLU, as determined from post-classification comparison of LCLU maps derived from classification of Landsat 7 Enhanced Thematic Mapper Plus (ETM+) for circa 2000 and circa 2010. We use "circa" as a date qualifier because of some uncertainty and variability in the LCLU map representations that stem from imagery limitations due to prevalent cloud cover. For brevity, we refer to the years 2000 and 2010 in the remainder of the paper. We use "Built" to represent a class of LCLU that can include various stages of urban development from land clearing with the intent to build settlements, to completely dense urban core, or forms ranging from a village of huts to industrial land uses. This Built class is similar to the Urban and Built Up Level 1 class of the US Geological Survey Land Use and Land Cover classification system (Anderson, Hardy, Roach, & Witmer, 1976); this is the level of urban LCLU classification and mapping that is appropriate for Landsat ETM + data, especially in areas of predominant cloud cover. The result of LCLUC involving transition from non-Built to Built from 2000 to 2010 is referred to as New Built.

Within the geographic and temporal context defined above, our objectives in this paper are three-fold: (1) to understand the degree of urban expansion relative to urban densification during this time frame; (2) to understand the relationship between population growth and LCLUC at the census district level; and (3) to explain the patterns of New Built LCLUC.

2. Study area

The study area consists of the Ashanti, Central, Eastern and Greater Accra regions (four of the ten regions within Ghana), which contain the two most populous metropolitan areas (Accra–including Ashiaman and Tema–and Kumasi) as well as an additional three of the country's seven most populous cities in 2010 (Cape Coast, Obuasi, and Koforidua). Overall, the study area includes 55% of the total population of Ghana as of 2010, as depicted in Fig. 1. Because of its political and economic stability compared to neighbors in the region, Ghana is the focus of extensive research and economic development interest, and one of the few West African countries having good population census and health survey data dating back to at least the 1990s. In 1950 the population of Ghana was 5 million, but the 2010 census counted 25 million Ghanaians and the United Nations (UN) projects the population to be 50 million by 2050 (United Nations Population Division 2015). In 1950 only 15% of the population lived in urban places, but by 2010 52% of the population was urban and by 2050 three-fourths of its people are projected to be urban. In 2010, Ghana Statistical Service (2012a) reported that 2,076,546 people lived in the AMA district (based on consistent boundaries between the two censuses; with an additional 330,756 people in Ashiaman and Tema, which are both part of the Greater Accra Metropolitan Area), 2,035,064 in the KMA district, 169,894 in Cape Coast, 143,644 in Obuasi, and 120,971 in Koforidua (Ghana Statistical Service, 2013).

The biophysical setting for the study area is mostly influenced by the equatorial wet-dry climate that varies along an aridity gradient from the Gulf of Guinea (which creates the southern boundary of Ghana) to drier lands in the north and particularly the northeast. Variability in natural vegetation conforms to the aridity gradient. Equatorial forests once covered most of the southern and western portions of the study area, but with deforestation, agricultural development and abandonment, forests have been replaced by secondary forest and shrub thicket. Much of the Eastern region and eastern portions of the Greater Accra region are covered by savanna vegetation, which has a high burn frequency from fires set to produce charcoal for cooking. Few non-vegetated lands occur in the study area and are mostly limited to tidal flats near the coast and some rock outcrops in more mountainous areas. Topography is generally flat to hilly, with the exception of low mountains west of Lake Volta and near Obuasi.

Agricultural land use is dispersed throughout the non-urban portions of the study area, with small subsistence agricultural plots intermixed with natural vegetation in a complex manner. The predominant crop types are cassava, yam, maize, banana, and plantain. Larger agricultural plots associated with commercial agriculture vary from palm oil plantations in the Central and Ashanti regions to larger mixed crop commercial farms in the savanna lands of the Afram Plain of the Eastern region.

3. Data and methods

Our general methodological approach was to generate 2000 and 2010 LCLU and LCLUC maps through classification of a dense time series of Landsat multispectral image data, extract population data from decadal census at the district level for the same years, and then to analyze distributions, changes and co-variability of Built LCLU and population variables. We derived and analyzed relative and absolute change, and normalized LCLU and population variables. Descriptive and inferential statistics and district-level map comparisons supported these analyses.

Data on LCLUC and particularly urbanization were derived from Landsat 7 ETM + data. Four adjacent Landsat image scenes, each covering approximately 165 km × 165 km, are required to cover the study area. A very small part of the western portion of the Ashanti region (5% of region and 2% of four-region study area) is not covered by these four Landsat scenes and was excluded from the study due to the high cost of data production relative to the limited added coverage. This area is mostly rural and experienced almost no urbanization within the study period (as interpreted from GoogleEarth imagery). Cloud-free images of the study area are rare and most scenes near the coast typically contain 20%–80% cloud cover, with the mean cloud cover per-scene around 50%. In addition, with the scan line corrector failure in May 2003 (resulting in SLC-off conditions), substantial data gaps are present near the edges of

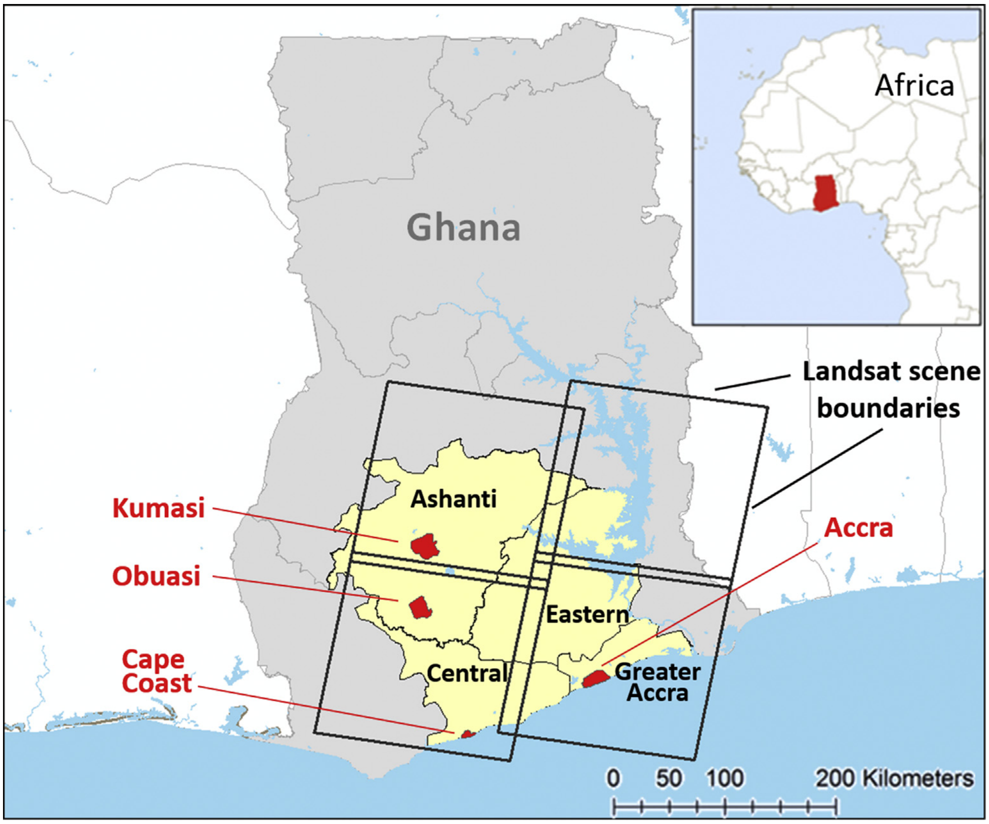

Fig. 1. Map of southern Ghana study area depicting four study regions, four major cities and Landsat Thematic Mapper satellite scene boundaries.

all Landsat 7 ETM + scenes collected after 31 May 2003 (Markham, Storey, Williams, & Irons, 2004). Thus, a multi-temporal compositing approach was used to attain coherent, cloud-free image products from a series of images collected over five-year periods at the beginning (1999–2003) and end (2009–2013) of the study period.

A threshold-based, discrete decision rule image classification approach was applied, where each LCLU class was classified in a sequential manner using ERDAS Imagine software. Spectral and texture indices were generated from Landsat 7 ETM + surface reflectance images and maximum value composite images for each index image for each time period (i.e., 1999–2003 and 2009–2013) were used as input to the image classifier. These indices included: (1) normalized difference vegetation index (NDVI) [(NIR−Red)/(NIR + Red)], (2) normalized difference water index [(Green−NIR)/(Green + NIR)] spectral variability vegetation index (SVVI) [$\sigma_{infrared} - \sigma_{all}$] and texture SVVI, where Green, Red and NIR are ETM + bands 2, 3 and 4, respectively, $\sigma_{infrared}$ is the pixel-wise standard deviation of bands 4,5 and 7, $\sigma_{infrared}$ is the pixel-wise standard deviation of bands 1 through 7 (not included the band 6 thermal infrared band), and texture SVVI is the spatial standard deviation of a 3 × 3 kernel of SVVI values. Threshold values used to classify the LCLU classes were calibrated using visual and quantitative methods, and the calibration work was performed with 1999–2003 Landsat imagery not affected by SLC-off data gaps. Threshold values were determined through visual interpretation and trial and error adjustments based on accuracy statistics for test areas. Following classification of individual LCLU classes, resulting layers were merged into single multi-class products using discrete decision rules and a specific priority, as described at the end of this section.

Synthetic aperture radar imagery from ERS-2 and ENVISAT satellites was also incorporated to aid in the detection of small settlements in rural areas. A layered (class-by-class) image classification approach based on threshold values of composited spectral indices and derived spatial texture products was implemented. Visual interpretation of the Landsat 7 ETM+ and Landsat 8 OLI data enabled the automated classification products to be refined and edited. Further details of the image classification procedures used to generate LCLU maps for 2000 and 2010 and subsequently data on LCLUC between 2000 and 2010 are provided in Coulter et al. (submitted for publication).

The output classification products portray eight LCLU classes: Water, Forest, Built, Agriculture, Secondary Forest, Savanna, Commercial Agriculture, and Mining. Water, Forest, Built, Secondary Forest, Savanna, and Agriculture were classified using semi-automated processing, while Commercial Agriculture and Mining were delineated using visual interpretation.

The accuracy of c.2000 and c.2010 LCLU maps and associated LCLUC product was assessed based on stratified random sampling. For the LCU maps 30 samples were selected for each of the six classes (strata), except for the Built class. Given the importance of the Built class for urbanization and population analyses, 60 samples were selected for the accuracy assessment. Mapped areas within the four-region study area that were selected for accuracy assessment were limited to: (1) patches of c.2000 LCLU where 5 × 5 blocks of pixels (150 × 150 m) contain the same class and represent consistent LCLU and (2) areas containing cloud-free c.2000 SPOT 10 m (10 scenes) and 5 m (one scene) panchromatic imagery to be used for visual reference for the accuracy assessment. The overall accuracy of the 2000 and 2010 LCLU maps is 95% and 89%, respectively. In addition, the Built class was found to have a user's accuracy of 100% and 100% and a producer's accuracy of 98% and 100%, for 2000 and 2010, respectively.

Maps and tabular data on LCLUC were derived by post-classification comparison of the LCLU maps representing the beginning and end of the study period. An emphasis is placed on Change to Built (an indicator of urbanization), meaning that LCLU transition was "from" non-Built (e.g., Forest, Agriculture, Secondary Forest, or Savanna) in 2000 and "to" Built in 2010, for the LCLUC transition sequence. The accuracy of the LCLUC product was based on the three primary classes of interest: Built, Agriculture, and Natural Vegetation. Thirty stratified random points were generated for each of six transition types that did not represent Built in c. 2000 (since these should not change). The accuracy of Agriculture to Built and Natural Vegetation (i.e., Forest, Secondary/Degraded Forest, and Savanna) to Built is 83% and 72%, respectively, and the commission error of Agriculture to Built and Natural Vegetation to Built is 17% and 19%, respectively.

Areal amounts and percentages of LCLU classes were tabulated at the census district level. Census data and accompanying district (and other) boundary geographic information system (GIS) files for 2000 and 2010 were obtained from Ghana Statistical Service. Substantial reconciliation of district boundaries between the 2000 and 2010 census by manual editing was required because of shifting boundaries and inconsistent base maps. In 2000, the country had been divided into 110 districts (the second-level geographic boundaries) distributed within the 10 regions (first-level geographic boundaries, comparable to states in the U.S.) and by 2010 the number of districts had increased to 170 because of population growth (Ghana Statistical Service, 2012c). In order to measure change over time, it was necessary for us to create a crosswalk between the 2000 and 2010 district boundaries so that data for 2010 could be aggregated back to the 2000 boundaries. We began with the geographically more detailed and more accurate 2010 district boundary files and adjusted all 2000 district boundaries accordingly. Then we dissolved the 2010 boundaries into the 2000 district polygons to form a consistent set of geographic units for temporal change analysis.

Buffers based upon distance from major roads were generated to analyze the association of urbanization with major roads. Road GIS layers were obtained from OpenStreetMap. We used the two highest (primary and secondary) categories of major roads. These vector maps were overlaid on orthorectified high spatial resolution satellite imagery to verify major road status and edit road positions. Buffers of 0–250 m, 250–500 km, 500–1000 m, 1000–2000 m, 2000–5000 m and >5000 m were generated, based on the expectation that the percentage of New Built would follow a distance decay pattern. Thus, percentages of New Built LCLUC pixels were derived for each distance from road buffer.

Quantitative and qualitative examinations of spatial-temporal patterns of change to Built LCLU in relation to total population and its change during the study period were conducted through descriptive and inferential statistical analysis and visual map interpretation. Various derivative measures, such as relative change (absolute change per 2000 baseline) and density (quantity per district for 2000 Built or Non-Built areas), were calculated and analyzed for both LCLU and population variables. We conducted bivariate regression analysis for different combinations of Built and New Built versus population and population change variables. Linear, log-linear, and semi-log regressions were run. We also ran stepwise multiple regressions to determine how well 2010 Built variables could be estimated from 2000 population and Built variables, and insured that models met regression criteria of normality, non-collinearity and spatial independence.

4. Results

4.1. Amount and distribution of new built LCLU

A total of 872.4 km^2 in land area or 1.5% of the four-region study area transitioned to Built LCLU, based on post-classification comparison of the 2000 and 2010 LCLU maps derived from Landsat image data sets, as shown in Table 1. This represents a 55.5% increase relative to the area of Built in 2000. The largest areal extent (294.7 km^2) of New Built LCLU occurred in the Ashanti region, followed closely by the Greater Accra region with 278.9 km^2. Much less Built development occurred in the Central and Eastern regions and where it did occur was mostly in peri-urban areas of Accra that lie within the Central region.

A map of change to Built LCLU from 2000 to 2010, which also depicts the 2000 ("from") class for the entire four region study area is shown in Fig. 2. The general pattern of urbanization during the study periods portrayed in Fig. 2 is dominated by urban sprawl (Bhatta, Saraswati, & Bandyopadhyay, 2010) in suburbs and peri-urban developments, particularly north and west (along the coast) of Accra, surrounding Kumasi in most directions, and as strip development along major highways and roads. Infill also occurred within Accra and to a lesser degree in Kumasi. Urban development is more scattered around the mid-size cities of Obuasi, Cape Coast and Koforidua. Most small towns and larger villages exhibit some degree of expansion from 2000 to 2010. Very few instances of scattered or isolated Built development (i.e., New Built located away from 2000 Built) are evident.

The vast majority (85%) of the transition to Built LCLUC map occurred from Agriculture land cover, while 15% of the New Built transitioned from Natural Vegetation. Most of the peri-urban expansion of Built occurred as a replacement of Agriculture, while some (but still a minority) of the expansion of Built in more rural areas and around small settlements involved replacement of Natural Vegetation.

The association of New Built with distance from major roads for the four regions and the entire study area (not including the already urbanized AMA and KMA districts) is portrayed in Fig. 3. Eighty-nine percent of New Built occurred within 5 km of major roads; the lowest percentage (11%) occurred for areas greater than 5 km from major roads. Within the 5 km buffer, the percentages of New Built are fairly evenly distributed for the six interval classes shown in Fig. 3, with 0–250 m and 2–5 km having the highest percentages at about 21%. Since the intervals for these distance buffers were selected to increase as a function of distance from major roads, the relatively equal distributions per interval class confirms our expectations and visual observations that percentage New Built decreases non-linearly as a function of distance from major roads. Development in the more rural districts almost exclusively occurred along major roads, which explains why almost a third of New Built occurred within 250 m in the Eastern region that is mostly rural. Greater amounts of New Built occurred at farther distances from major roads in suburban and peri-urban districts of the mostly urbanized Greater Accra region, because of the presence of minor roads that enable more convenient transport of building materials and access to infrastructure, food sources and employment opportunities.

4.2. District level analysis of built and population distributions and changes

Distributions of percentage Built and population density for 2000 and 2010 and their changes between those dates are portrayed as census district-level maps in Fig. 4. The highest densities of Built LCLU and population for both years are located in the AMA

Table 1
Amounts, percentages and densities of Built LCLU and total population for 2000, 2010 and change from 2000 to 2010 for the four study regions.

Region	Area (km^2)	Built 2000 (%)	Built 2010 (%)	Absolute built change (km^2)	Relative built change (%)	New built (%)	Built change per nonBuilt 2000 (%)	Natural vegetation to built (%)	Agriculture to built (%)	Pop. 2000 (10^3 people)	Pop. 2010 (10^3 people)	Pop. change (10^3 people)	Relative pop. change (%)	Pop. density 2000 (km^{-2})	Pop. density 2010 (km^{-2})	Pop. density change (km^{-2})	Pop/Built area 2000 (km^{-2})	Pop/Built area 2010 (km^{-2})	Pop/Built area change (km^{-2})
Ashanti	24904.0	2.0	3.2	294.7	59.3	1.2	1.2	15.8	84.2	3621	4766	1146	31.6	148.5	195.5	47.0	7285.9	6021.4	−1264.5
Central	9653.9	2.6	4.2	156.3	62.0	1.6	1.7	24.3	75.7	1589	2207	619	38.9	164.4	228.4	64.0	6321.8	5422.1	−899.7
Eastern	18523.3	1.6	2.4	142.5	45.9	0.7	0.8	20.7	79.3	2118	2632	514	24.3	111.5	138.6	27.1	6892.1	5868.7	−1023.4
Greater Accra	3696.3	13.8	21.3	278.9	54.5	7.5	8.7	8.8	91.2	2916	4012	1097	37.6	786.7	1082.5	295.8	5698.6	5075.5	−623.2
Total Area	56777.5	2.8	4.3	872.4	55.5	1.5	1.6	15.9	84.1	10,243	13,618	3374	32.9	180.5	240.0	59.5	6535.8	5586.4	−949.4

and KMA districts as well as in several suburban/peri-urban districts surrounding them, consistent with other research (Doan & Oduro, 2012). The degree of correspondence between population change and land cover change to Built is visually apparent between 2000 (Fig. 4a and d) and 2010 (Fig. 4b and e) (i.e., static) maps and less apparent for maps depicting changes in Built cover and population density (Fig. 4c and f).

The amounts, percentages and densities of Built LCLU and total population for 2000, 2010 and change from 2000 to 2010 for the four-region study area and for the top 15 districts in terms of % New Built are listed in Tables 1 and 2, respectively. In 2000 the AMA district had the highest percentage of Built and population density, and both variables increased substantially in the intercensal period. As can be seen in Table 2, Built percentage in the AMA increased over time as the AMA was becoming built out (89% Built in 2010), so we can infer that population pressure was pushing LCLUC. At the same time, LCLU and population change were much more dramatic in the four districts surrounding the AMA–Tema, Ga, Dangbe West, and Awutu. However, Built percentage in those mostly peri-urban districts was declining over time due to the fact that the Built area was increasing at a faster rate than the population, as Built development preceded population growth.

As was true for the AMA, the KMA district exhibited a high (indeed, the highest) increase in both Built percentage and population density. However, its surrounding districts (Bosomtwi, Afigya/Kwabre/Skeyere, and Ejisu/Juaben) exhibited an increase in percent Built that was faster than population growth, as was true for the peri-urban areas of Accra.

By far the greatest amount of land area of New Built occurred in suburban and peri-urban areas of Accra and particularly in the Ga district (143.1 km^2), followed by Awutu and Tema districts at just over 83 km^2. Unlike the AMA–which was already largely built out in 2000–much of the urban expansion of the Kumasi metropolitan area occurred within the KMA (49.0 km^2), although the adjacent district of Bosomtwi had an even greater increase of 51.7 km^2 Built land area.

The highest rates of urbanization, represented by New Built as a percentage of 2000 Built (i.e., relative change in Built) can be observed in Table 2 and are shown in Fig. 5a. The districts surrounding or nearby the AMA (particularly Awutu, Ga and Tema) and KMA (e.g., Afigya, Bosomtwi and Ejisu) had the highest rates of New Built, showing that most of the New Built occurred as either part of or a prelude to suburbanization and peri-urban development. The Tema district, just to the east of AMA, which was already established as an urban satellite center to Accra in the 2000 period, still had the second highest percentage of New Built within the district.

The spatial distribution of Built change per developable (i.e., Non-Built) land ([2010−2000 Built]/2000 Non-Built) is displayed in Fig. 5b and shown in Table 2. As would be expected, the districts that were already heavily urbanized in 2000 exhibit the highest rates of urban development per land available for development, with AMA (40.4%) and KMA (58%) having much higher percentages. By 2010 the AMA and KMA were 89% and 85% respectively "built out", with Tema district at 50% and the other districts <40%.

With respect to population, the greatest numerical (860,160 people), relative (+73.6%) and density (3560 km^{-2}) increases occurred within the KMA district, almost twice the same measures as for the AMA. The Ga district that surrounds the AMA to the north and west exhibited numerical (458,650), relative (+83.0%) and density (541 km^{-2}) population increases that were second highest to KMA (higher in relative change) and higher than AMA. These population change measures for the urban core districts of the study area are substantially higher than the other districts, even though areal amounts and rates of Built change were higher in the

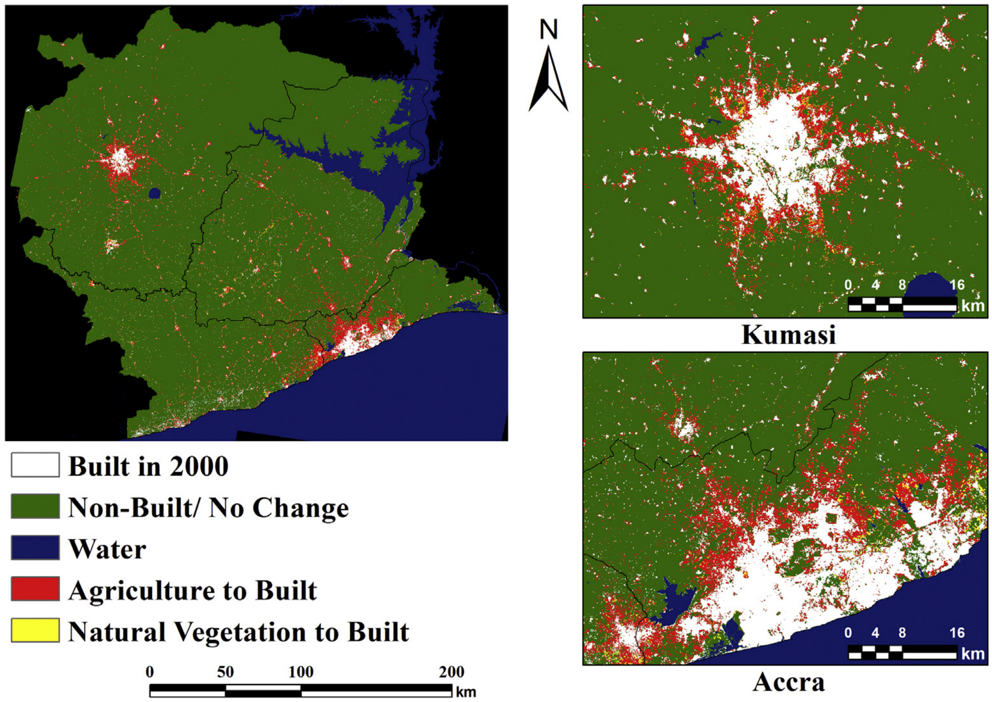

Fig. 2. Maps of New Built LCLU occurring between 2000 and 2010 for the entire four region study area, and enlarged display of region surrounding Kumasi (top right) and Accra (bottom right). The map of New Built is based on spatial cross-tabulation (pixel-level) of 2000 and 2010 LCLU maps derived from a layered, rule-based classification of a dense time stack of Landsat ETM + images for each period.

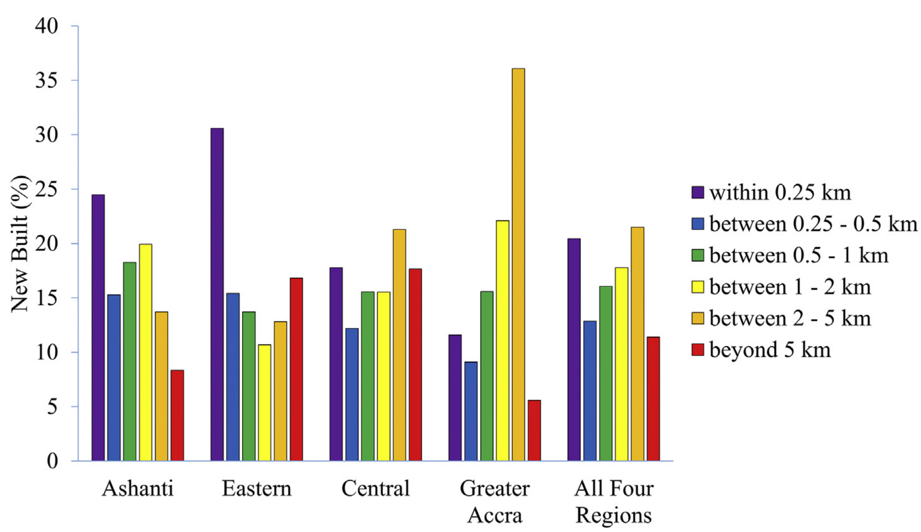

Fig. 3. Bar graphs showing percentages of New Built land area for five distances from road interval classes, for each of the four regions and all four regions combined. Data for heavily urbanized Accra Metropolitan Area and Kumasi Metropolitan Area districts were excluded.

suburban and peri-urban districts. This reflects both the already high population size and density at the beginning of the study period in the urban core districts, and the desire of people to live close to the urban core. Since residential housing tends to be low-rise throughout sub-Saharan Africa, the demand for housing is best met in the suburban and peri-urban areas, which explains the development occurring in those areas in anticipation of demand.

Note that we are introducing a new measure of density that relates population size in a district to that district's Built area (population per Built area). This measure is shown at the region level in Table 1 and for the top 15 districts in Table 2, and is portrayed in Fig. 6. An important use of this population per Built area measure is in its change over time. If it declines, it may indicate change to Built is proceeding at a faster pace than population growth, and thus the change in LCLU is foreshadowing an increase in the population. If, on the other hand, the population per Built area is increasing, we infer that population is increasing more quickly than the conversion of land to Built, although that reaches its limit as the percent Built approaches 100% in any given district (e.g, AMA and KMA). An interesting spatial-temporal pattern is observed, where the AMA and KMA urban core areas exhibit some of the highest levels of population per Built area, as expected, but

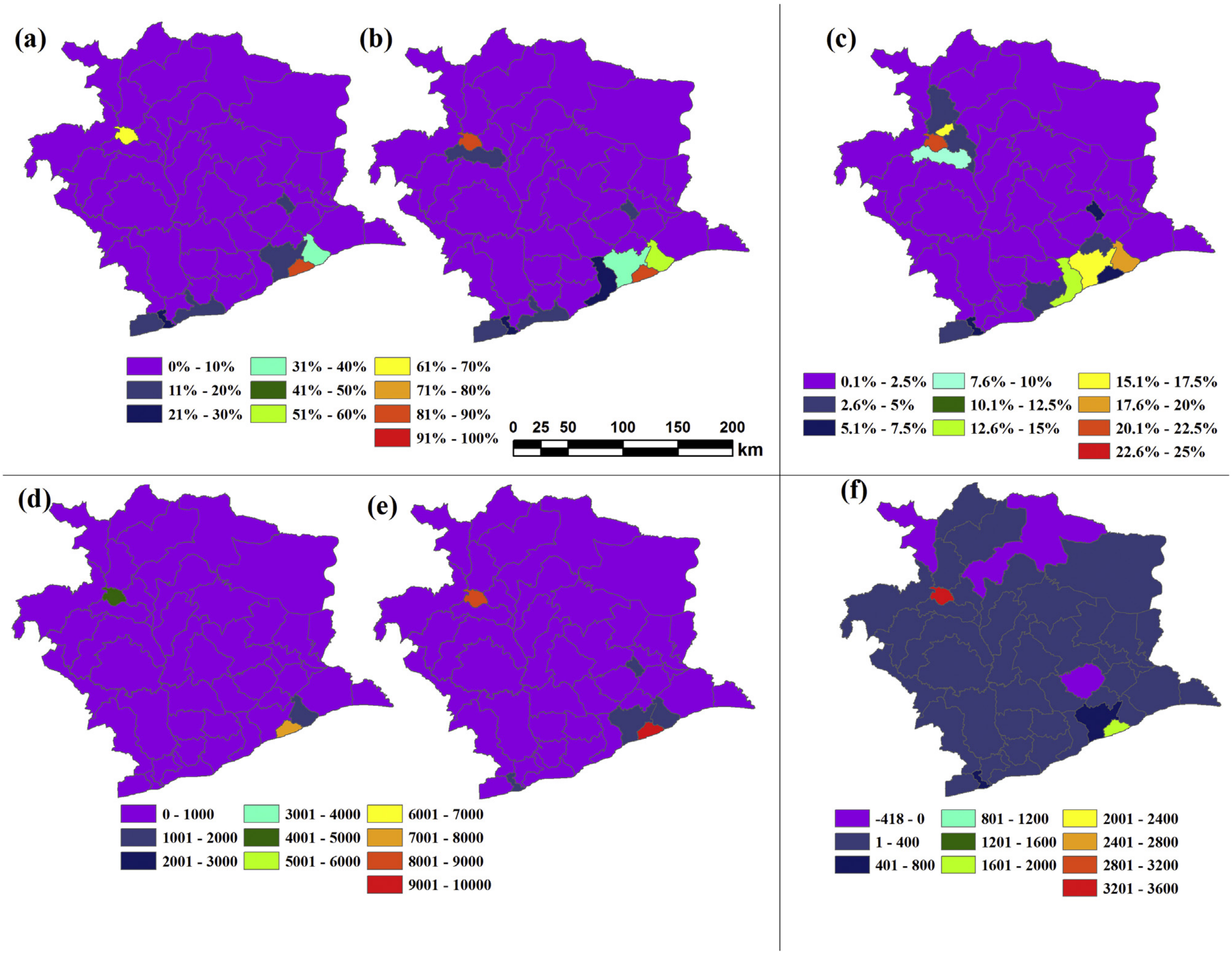

Fig. 4. District-level maps of percentage Built and population density for 2000 and 2010 and 2000 to 2010 changes between those dates. (a) 2000 Built percentage, (b) 2010 Built percentage, (c) change in Built percentage, (d) 2000 population density, (e) 2010 population density, and (f) absolute change in population density.

the highest levels actually correspond to the most rural, savanna districts in the northeast portion of the study area. Some of the latter could be due to rural populations living in areas not identified as Built, e.g., residential structures that are small or may exist under vegetated canopy and thus not directly observable by the satellite imagery. A general trend can be seen in Fig. 6c where the northern part of the study area (particularly Ashanti region) exhibits strong declines in population per Built area density while the southwestern portion shows slight increases. Again, declines in population per built Built area likely signify that the New Built area is expanding faster than (e.g., ahead of) population growth.

4.3. Explaining the observed patterns

Bivariate linear regression results for static (single year) population vs. Built variables (district level) are shown in Table 3, with scatterplots and least square lines and regression model parameters for the relationships with the highest R^2 values for 2000 and 2010 shown in Fig. 7a and b. All population vs. Built variable combinations yielded significant relationships for linear and non-linear models, with R^2 values ranging from 0.36 to 0.95. Linear models and particularly those based on population density (population per unit area) vs. % Built area per district area yielded the highest regression coefficients (exceeding 0.90). Non-linear models yielded higher R^2 values for a few of the population vs. Built combinations, but none were as high as the population density vs. % Built linear model. Extreme population and Built magnitudes for AMA and KMA districts enhance an apparent linear trend and ensure high R^2 values for many variable combinations as can be seen in Fig. 7.

Bivariate regression results for linear and log-linear models and dynamic (change) population vs. Built variables (district level) are shown in Table 4, with scatterplots and least square lines and regression model parameters for the relationships with the highest R^2 values for 2000 and 2010 shown in Fig. 7c and d. The highest R^2 values were for the log-linear model of population density change vs. %New Built (0.57) and the linear model of population density change vs. New Built area/2000 Non-Built area (0.86). None of the models for population change vs. relative Built change (New Built/2000 Built) were significant.

Stepwise multiple regression models yielded two informative models for estimating %Built in 2010 based on 2000 population and Built variables that met all normality, non-collinearity and spatial independence criteria. A two-component model with log 2000 population density and 2000 Built area as independent variables resulted in an adjusted R^2 of 0.91. A three-component model that also included 2000 population per 2000 Built area was not significantly different than the two-component model.

Table 2
Amounts, percentages and densities of Built LCLU and total population for 2000, 2010 and change from 2000 to 2010 for the top 15 districts in New Built (listed in rank order) for the variable percentage New Built land per district area.

District	Region (%)	Area (km^2)	Built 2000 (%)	Built 2010 (%)	Absolute built change (km^2)	Relative built change (%)	New built (%)	Built change/nonBuilt 2000 (%)	Pop. 2000 (10^3 people)	Pop. 2010 (10^3 people)	Pop. change (10^3 people)	Relative pop. change (%)	Pop. density 2000 (km^{-2})	Pop. density 2010 (km^{-2})	Pop. density change	Pop/Built area 2000 (km^{-2})	Pop/Built area 2010 (km^{-2})	Pop/Built area change (km^{-2})
Kumasi (KMA)	Ashanti	241.6	65.0	85.3	49.0	31.2	20.3	58.0	1169	2030	860	73.6	4839.8	8399.6	3559.8	7442.6	9845.3	2402.6
Tema	Greater Accra	424.1	30.4	50.1	83.5	64.7	19.7	28.3	506	675	169	33.4	1192.9	1591.0	398.1	3921.4	3176.1	−745.3
Ga	Greater Accra	847.7	18.2	35.1	143.1	92.7	16.9	20.6	553	1011	459	83.0	652.1	1193.2	541.0	3578.3	3401.2	−177.1
Awutu	Central	600.6	8.9	22.6	83.3	156.5	13.9	15.2	172	266	95	55.0	285.9	443.2	157.3	3226.1	1957.4	−1268.7
Bosomtwi	Ashanti	674.1	3.2	10.9	51.7	240.4	7.7	7.9	147	184	37	24.8	218.5	272.9	54.3	6855.2	2514.2	−4341.0
Accra (AMA)	Greater Accra	225.1	81.6	89.0	16.7	9.1	7.4	40.4	1668	2078	410	24.5	7411.0	9230.3	1819.2	9082.4	10,371.3	1288.9
Cape Coast	Central	122.4	22.7	29.8	8.6	31.1	7.1	9.1	119	172	53	44.1	975.1	1404.9	429.8	4295.5	4720.7	425.2
New Juaben	Eastern	159.9	12.9	18.2	8.4	40.6	5.2	6.0	136	185	49	35.8	849.7	1153.8	304.2	6577.7	6351.4	−226.2
Afigya/Kwabre/Skeyere	Ashanti	946.9	4.5	9.1	43.8	103.5	4.6	4.8	285	342	57	19.9	300.9	360.7	59.8	6730.5	3963.8	−2766.7
Ejisu/Juaben	Ashanti	581.6	3.3	7.4	24.3	128.1	4.2	4.3	126	143	17	13.1	217.3	245.8	28.5	6662.3	3303.2	−3359.0
Akwapim South	Eastern	389.0	3.7	7.7	15.5	108.8	4.0	4.1	118	124	6	5.2	303.3	319.1	15.8	8271.5	4169.9	−4101.6
Gomoa	Central	837.1	4.6	7.3	23.1	60.5	2.8	2.9	195	343	148	75.7	233.5	410.2	176.7	5118.3	5609.0	490.6
Komenda	Central	452.6	10.5	13.2	11.9	25.0	2.6	2.9	113	146	33	29.5	248.8	322.1	73.4	2363.9	2449.0	85.1
Dangbe West	Greater Accra	1594.2	2.0	4.3	36.3	113.1	2.3	2.3	95	118	24	24.9	59.4	74.2	14.8	2953.2	1736.2	−1217.0
Mfantsiman	Central	577.8	10.3	12.4	12.2	20.4	2.1	2.3	150	192	41	27.3	260.3	331.4	71.2	2521.3	2667.1	145.8

5. Discussion and conclusions

5.1. Distribution of new built as an indicator of urbanization

A substantial amount of Built LCLUC occurred between 2000 and 2010 in the four-region study area of southern-central Ghana, mostly as urban expansion associated with a relatively rapid increase in population. Almost 52% of this New Built LCLU occurred in six suburban and peri-urban districts near the AMA and KMA, suggesting that most of the development occurred as urban sprawl, as described by Cobbinah and Amoako (2012) for the KMA. Residential structures in the study area are rarely more than two stories, and most of the AMA and much of the KMA were already covered by Built LCLU in 2000. Thus, most New Built development in the major urban centers occurred primarily as "expansion" growth, according to the five classes of urban growth defined by Wilson, Hurd, Civco, Prisloe, and Arnold (2003). Limited densification associated with multi-story development or "infill" growth occurred in the AMA, which already had 80% Built cover in 2000 and was 89% built out by 2010. The form of urbanization in both the Greater Accra and Kumasi metropolitan areas (the larger and less officially defined metropolitan extents that include Accra and Kumasi cities) can also be classified as "expansive-growth cities with extensive dispersion at low population densities" following the urban growth classification system of Schneider and Woodcock (2008). The only "outlying" type of urban development occurred in the southeastern portion of the Central region (e.g., the town of Kasoa), along the coastal strip just west of and beyond the sprawling expansion of the Greater Accra metropolitan area. These new and expanding settlements are close enough to the economic activities in Accra and Tema for residents to commute to work.

The Built area of most small cities and villages in rural areas also expanded between 2000 and 2010, as urbanization occurred in patterns that included expansion and infill. Substantial strip development or "linear branch" growth (Wilson et al. 2003) occurred along primary and secondary roads in rural areas, particularly in the Ashanti and Eastern regions. The only isolated New Built occurred among small villages away from major roads, where residents travel mostly by foot to subsistent agricultural plots. "Isolated" growth—the formation of new villages away from other development–was not observed.

5.2. Field observations

In winter 2014 two of the authors conducted a field reconnaissance trip throughout much of the four-region study area. Geo-tagged ground images were captured to document evidence of recent Built development. All four of the major cities were visited, with most observations occurring along the expanding urban edge and along major roads extending from and connecting the cities. Though the observations were made four years after the study period and were limited in spatial extent with spatial bias (e.g., expansion over infill), they were very useful in helping to explain satellite-derived patterns of LCLUC for the study period.

Two important types of information related to urbanization in the study area emerged from our field observations that could not be discerned or inferred from interpretation or classification of Landsat ETM + data, or even high spatial resolution commercial satellite data that we are using for more detailed intra-urban analyses. The first is that residential development in the study area can be a long, protracted process, such that ground breaking to building completion and owner occupancy may take five to ten years or more. Residential structures in incomplete or

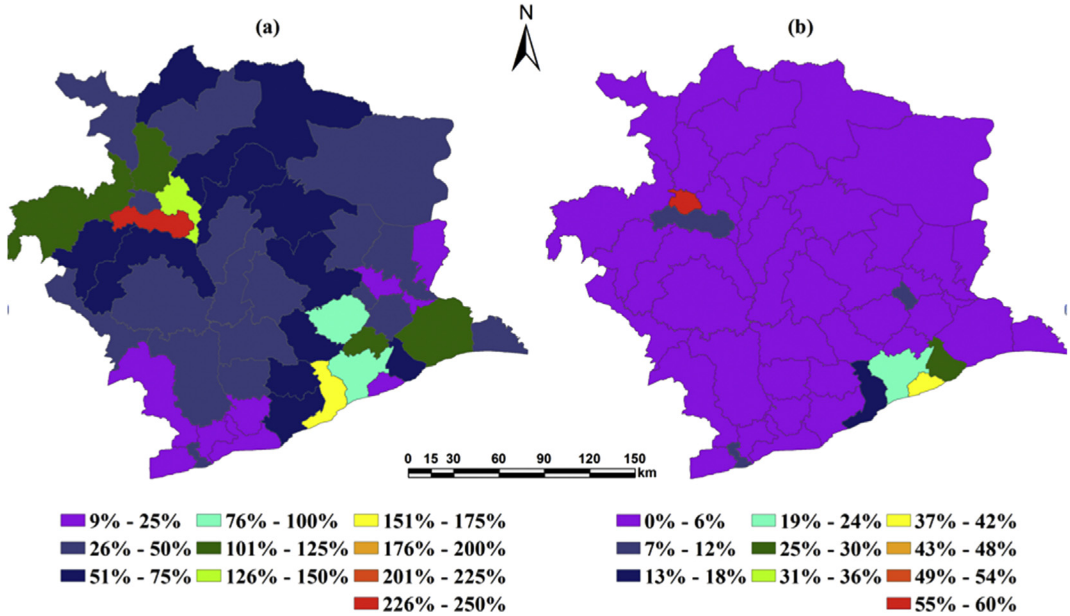

Fig. 5. District-level maps of Built change. a. Relative Built change ([2010–2000 Built]/2000 Built), b. Built change per developable land ([2010–2000 Built]/2000 Non-Built).

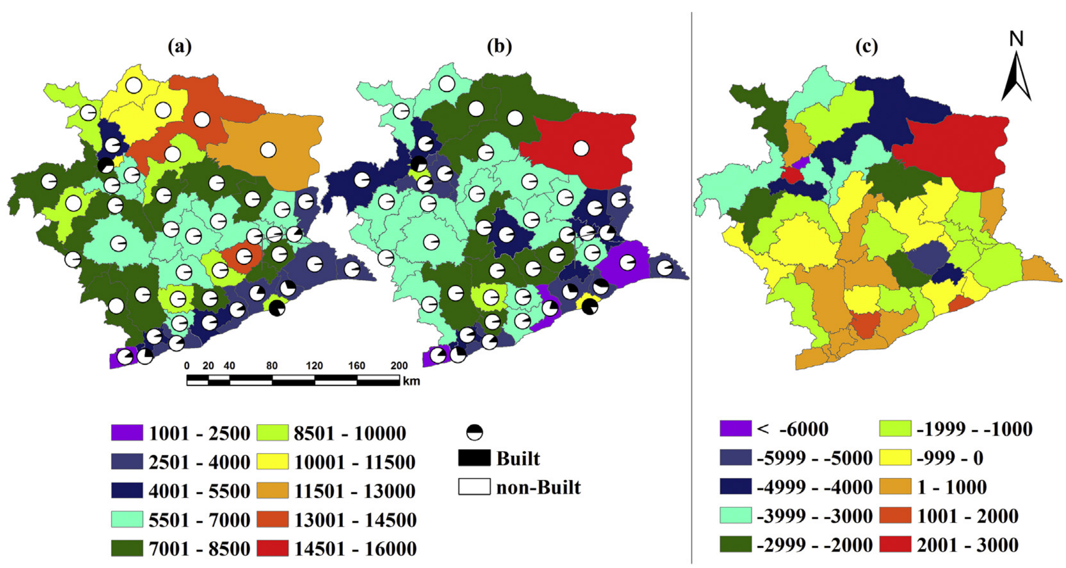

Fig. 6. District-level maps of population per Built land area with pie charts showing percentage of Built (black) and non-Built (white) areas for each district. (a) 2000; (b) 2010; (c) 2000–2010 change.

Table 3
Linear regression model coefficients (R^2 values) for various combinations of static Built LCLU on population variables.

	Bu2000	%Bu2000	Bu2010	%Bu2010
Pop2000	0.79	0.88	0.54	0.82
Pop2010	0.83	0.87	0.62	0.86
PopDens00	0.63	0.94	0.36	0.84
PopDens10	0.65	0.95	0.39	0.88

Note: $n = 43$; all coefficients are statistically significant at $p < 0.05$.
Pop = population, Dens = density, Bu = Built.

abandoned states of construction are common elements of the urban and suburban landscape, and are often the sites of residential occupancy by squatters or renters. The other primary observation is that suburban and peri-urban expansion that has been the predominant form of urbanization in the study area is not necessarily occurring as "the seemingly uncontrollable slums sprawling around the capital cities in developing countries" described by Besussi, Chin, Batty, Longley (2010:16), but more commonly as lower density settlements of moderate to high quality residential housing, albeit with limited urban infrastructure. Based on qualitative interviews and informal observations, we hypothesize that many of the numerous large and apparently high quality structures are built by wealthier family members with the intention to provide housing for members of an extended family. These may be financed in particular by remittances from family members working abroad. Typical examples of both incomplete and high quality residential structures are shown in Fig. 8.

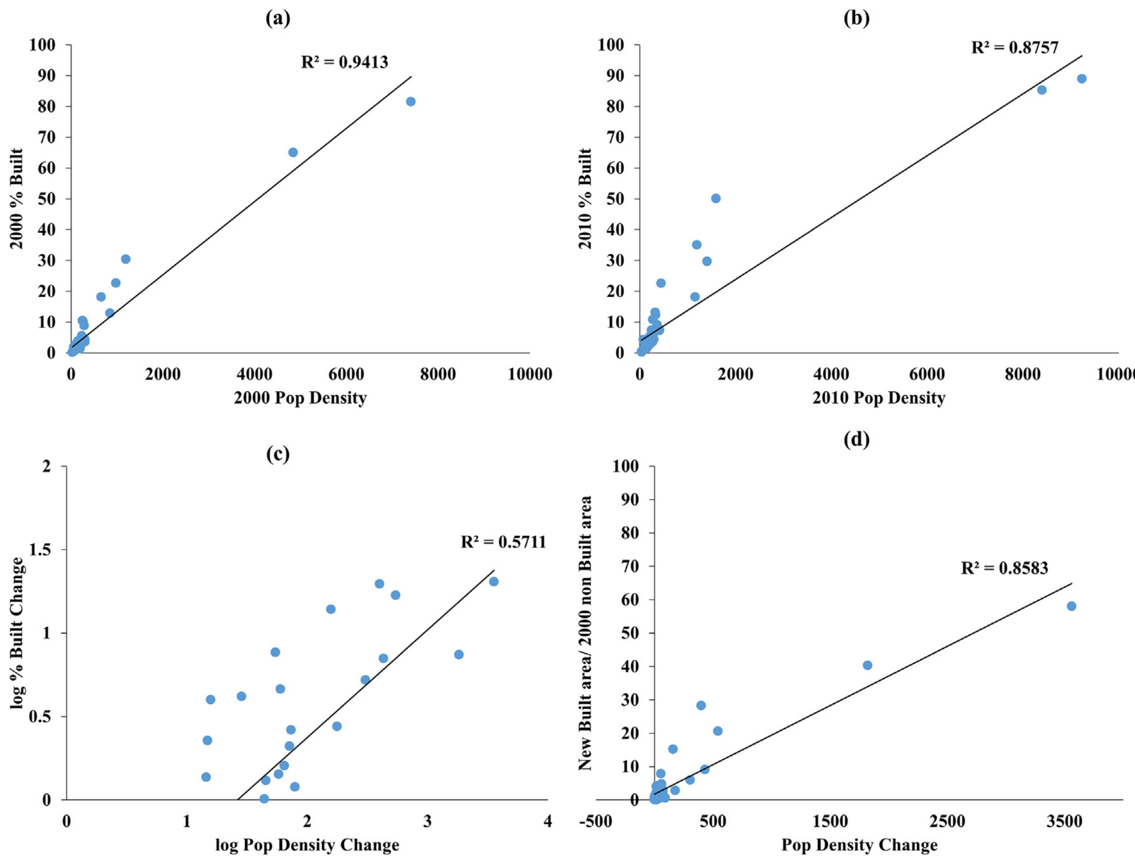

Fig. 7. Scatterplots and least square lines for significant regression models of several population vs. Built variable combinations: (a) 2000 population density vs. 2000%Built, (b) 2010 population density vs. 2010%Built, (c) log population density change vs. log %NewBuilt, and (d) population density change vs. NewBuiltArea/2000NonBuiltArea. $n = 45$ and $p < 0.05$.

Table 4
Regression model coefficients (R^2 values) for various combinations of New Built on population change variables. a. Linear models, b. Log-linear models.

	NewBu	%NewBu	RelNewBu	NBu/NnBu00
a.				
PopChng	0.27*	0.56*	0.00	0.84*
RelPopChng	0.23*	0.27*	0.00	0.19*
PopDnsChng	0.08	0.43*	0.02	0.86*
n=46				
b.				
PopChng	0.31*	0.30*	0.00	0.36*
RelPopChng	0.08	0.11*	0.00	0.11*
PopDnsChng	0.25*	0.57*	0.01	0.65*
n=43				

*models significant at $p < 0.05$.
Pop = population, Dens = density, Bu = Built, Chng = change, Rel = relative, N = new, Nn = non-.

5.3. Relationship between LCLUC and population change

Determining the relative timing and degree of association between urbanization and population change is challenging, particularly when based on decadal data sets for a single ten-year period. Clearly, population increased substantially within our Ghanaian study area, which has driven the need for greater housing stock and urban infrastructure to support these added residents. Furthermore, the population in these areas was already growing at the beginning of the study period, so the increase in Built area is partly a response to an increase in demand for housing and other buildings associated with urban living. Both static and dynamic measures of Built and population are significantly and linearly correlated at the district level, with the reminder that such correlations are enhanced by the extreme values of AMA and KMA. For example, there is a moderate R^2 (0.25) between the intercensal rate of population growth in a district and the percentage of its total area that was converted to Built in the intercensal period. However, if we restrict our attention to only those districts that already had at least 200,000 people in 2000, the R^2 jumps to 0.73. Urbanization is taking place most decisively in those districts that were already most populous at the start of the study period.

It is not possible to draw cause and effect relationships between Built and population change from our limited data, and it is likely that relationships are operating in both directions. In some places it is likely that past or expected future population is driving change in land use, whereas in other locations it may be the opposite. For example, AMA, KMA, Tema and also several rural districts exhibit higher relative population than Built change, while the suburban/peri-urban districts around both Accra and Kumasi experienced much higher relative changes in Built than in population growth. This agrees with our field observations of what appeared to be speculative (unoccupied) housing development around Kumasi and other parts of the Ashanti region, and suggests that in some urbanizing areas Built LCLUC is driving localized population changes. Through surveys of inhabitants and logistic regression models, Appiah, Bugri, Forkuo, and Boateng (2014) concluded that three important drivers of peri-urbanization in the Bosomtwi district south of Kumasi (a district that went from 3% Built in 2000 to 10% Built in 2010 – one of the greatest increases in percent Built among all districts), were: (1) availability of social amenities, (2) increasing physical infrastructure, and (3) easy access to land,

a.

b.

Fig. 8. Ground images from Ghana study area taken February 2014. a. Example of unfinished residential structure, where building can take five to ten years to complete and squatters may reside during various stages of construction. b. Example of large, moderate to high quality residential structures commonly built in the peri-urban areas of Accra and Kumasi.

although population change was deemed to have an interaction effect.

5.4. Data challenges

Both primary sources of data used in this study, Landsat TM and GSS census data, presented significant challenges in terms of timeliness and quality. However, in contrast to much of sub-Saharan Africa, at least they are available for studies such as ours.

Landsat imagery availability and quality has been limited because of the lack of a Landsat 5 TM ground station in Western Africa and because the area is prone to cloud cover and associated shadows, smoke, haze and dust transported by the Harmattan (dry desert winds). These factors, along with the Landsat 7 ETM + scan line corrector off (SLC-off) effect since April 2003 (Storey 2005) result in a noisy and patchy image time sequence. For the Landsat scene that covers Greater Accra and much of the Eastern region during period 1999 to 2014, two cloud free Landsat 7 ETM + images were captured and one of these was influenced by SLC-off effects. By exploiting the dense time series of surface reflectance products from Landsat 7 ETM + we were able to develop reliable LCLU classification products, though for a fairly general level of class specificity (e.g., Built, Agriculture and Natural Vegetation). Thus, our analyses of urbanization are limited to the general Built category, without a differentiation for areas used for residential and non-residential activities.

Accessing and analyzing district-level census data from Ghana Statistical Services also presented a challenge. The 2010 census tables became available in 2013, district boundary files in 2014 and finer level enumeration area boundary files are still not completed for much of Ghana. As mentioned in the Data and Methods section, considerable effort was required to reconcile discrepancies between the 2000 and 2010 district boundaries. Using 2010 district boundaries as the basis facilitated this reconciliation. We are reasonably confident that population numbers have been apportioned to the proper spatial units in a manner that is consistent between the two years.

5.5. Policy implications

At first glance, impacts of urbanization on food security may be considered an issue given that a majority of the urbanization in the study area occurred at the expense of agricultural land use and population increased by approximately 25% and 75% respectively in the greater metropolitan areas of Accra and Kumasi. However, while replacement of Agriculture by Built LCLU was prevalent, Agriculture lands expanded (i.e., Natural Vegetation to Agriculture LCLUC) by 8860 km^2 (15.6% of study area). Research by Appiah et al. (2014) in the Ashanti region suggests that farmers may sell land in peri-urban areas as land prices rise. This may then lead them to start up farming in areas beyond the reach of higher land prices.

Information on the rates and distribution of land being converted to Built, and other LCLUC, such as that associated with agriculture, may help national and regional level decision makers to understand land development trends and potentially develop and/or implement comprehensive national policies. In 1999, the Ghana Ministry of Lands and Forestry (1999) instigated a National Land Policy to regulate land development. However, even with regulations in place, illegal development has occurred extensively around the country, because law enforcement may be compromised both by lack of resources and by local tribal chiefs who have strong control over land development. The rapid growth of the Greater Accra Metropolitan area has been characterized by a high degree of informality and a low level of formal infrastructure, with implications for land use planning. Our LCLUC maps may provide insight into locations where past development has occurred in the context of disagreements between government land policy and tribal chief decisions. More regular monitoring of illegal development can support regulation and mitigation of rapid or unwise urbanization, such that the National Land Policy can be better enforced (Cobbinah and Amoako 2012).

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