QUANTIFYING URBAN SPRAWL AND ITS IMPACT ON CARBON SEQUESTRATION FOR PROMOTING REGULATED URBANIZATION AND A HEALTHY ENVIRONMENT IN CITIES

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Abstract. Urban sprawl involves both challenges and opportunities, such as impacting hinterland resources and fostering urbanizations. However, the undetected expansion of urban areas into productive land uses has often been emphasized in terms of urbanization, while its negative consequences are mostly overlooked. This research aims to quantify urban sprawl and its impact on carbon sequestration in the selected cities of Shashemene, Hawassa, and Dilla using satellite image analysis and field measurements. Thirty years (1992-2022) of time series data were generated from Landsat (1992-TM, 2002-ETM+, and 2012-OLI) and Sentinel-2A (2022) images. Urban sprawl was tested using Shannon's entropy. An allometric equation was used to estimate above-ground tree biomasses and below-ground carbon stocks as a measure of carbon sequestration. The total carbon stock was then multiplied by a factor of 3.67 to convert it into CO_2 equivalent (CO_2e). The results showed that: (1) All three selected cities have experienced non-linear urban expansion over the past thirty years at the expense of forestland, cultivated land, and agroforestry land use types. Built-up area increased by 186%, by 359.5%, and by 287.2% in Dilla, Hawassa, and Shashemene cities, respectively. (2) Shannon's entropy suggested the presence of urban sprawl in the three cities, leaning towards a more dispersed form of urban development. The relative Shannon entropy values of all cities were found less than 1 with average values of 0.73, 0.85, and 0.78 for Dilla, Hawassa, and Shashemene cities, respectively. The minimum values were 0.6 for Dilla, 0.7 for Hawassa, and 0.5 for Shashemene city. (3) An inverse relationship between built-up area expansion and vegetation cover was observed, indicating a significant loss of carbon sequestration potential of the areas due to deforestation in the hinterlands of the

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cities, contributing to higher CO_2 emissions. Ineffective implementation of urban land use planning has resulted in unregulated and unordered urban expansion, encouraging land speculators to hoard land and illegal settlements to occupy productive areas. Establishing and effectively implementing a strong urban growth boundary could help control urban sprawl, regulate urbanization, and improve the health of the local environment in these cities.
Keywords: *carbon footprint, Ethiopia, informal settlement, land use types, urban lease*

Introduction

The numbers of people living in urban area are increasing worldwide (Terfa et al., 2019; World Bank Group, 2023; Abebe, 2024), giving rise to unprecedented urbanization (Dadi et al., 2016, 2024; Zhang, 2016; Deribew, 2020; Eshetu et al., 2021; Abebe, 2024). More than 4.4 billion people, which is 54% of the world's inhabitants, live in urban areas (Terfa et al., 2019; Abebe, 2024) and by 2050, this percentage is expected to reach 68%, out of which 90% are expected to be from Africa and Asia (Tan et al., 2005). Urbanization not only involves a change in the percentage of population but also an increase in the size of the area occupied by the inhabitants (Koroso et al., 2021). Between 2000 and 2014, the rate at which urban boundaries expanded was 1.3 times faster than the rate of population growth (UN ECOSOC, 2019). Unregulated and unplanned urban expansion leads to urban sprawl (Zhang and Xie, 2019; Koroso et al., 2021; Chen et al., 2021; Getu and Bhat, 2021; Dasgupta et al., 2022), which has significant repercussions on ecosystem services, energy consumption, and carbon sequestration capacity of the area.

Urban sprawl contributes to increased carbon footprint of an area through direct and indirect greenhouse gas (GHG) emissions (Ala-Mantila et al., 2013; Arko et al., 2024). Access to land/house in the cities is limited, so people move to hinterlands in search of space for constructing their own house (Girma et al., 2019; Koroso, 2020, 2023). Such movement encroaches rural lands (Liu et al., 2011; Miller, 2012; Wang et al., 2019; Daguio et al., 2021) and become a cause for the loss of croplands, wetlands, and other green spaces (Terfa et al., 2019; Getu and Bhat, 2021; Beshir, 2021; Perry et al., 2022; Abebe, 2024). By 2030, urban sprawl could cause a 1.8–2.4% global loss of cropland (d'Amour et al., 2017), causing urban land use to expand by 1.8-5.9 time, with per capita use increasing 1.1-4.9 times, often reducing green spaces (Ahmadi, 2012; Gao and O'Neill, 2020). In Sub-Saharan Africa (SSA), urbanization rate increased from 28% in 1990 (de la Masselière et al., 2017) to 42.91% in 2023, making it the fastest urbanizing region globally (Gao and O'Neill, 2020; Statista, 2024). Urbanization in the region has led to widespread slums and informal settlements, with infrastructure development lagging behind population growth (Abebe, 2024; Kolowa et al., 2024) internally disconnected (Venables et al., 2017). The high poverty levels in the region exacerbate deforestation as people rely on wood for house construction and energy, further reducing carbon sequestration capacities. The UN predicts that by 2050, urban populations in SSA will exceed rural populations, intensifying urban sprawl and associated challenges (Farrell, 2017; Saghir and Santoro, 2018; Coulibaly and Li, 2020; Deribew, 2020; Perry et al., 2022; Abebe, 2024). Effective urban planning and regulation are crucial to address the adverse impacts of urban sprawl, particularly in SSA where policy attention has been minimal. Policymakers must prioritize sustainable urban growth strategies to mitigate environmental degradation and support efficient infrastructure development.

Urban areas are responsible for 40-85% of total anthropogenic GHG emission (Satterthwaite, 2008). Controlling urban sprawl can help to mitigate climate change impacts in cities (Sallustio et al., 2015; Churkina, 2016). Raising awareness among

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residents in sprawled areas also helps preserve ecosystems services coming from forests and soils. Trees absorb CO_2, and soils store decaying organic matter as carbon (Kuittinen et al., 2016). However, urban sprawl reduces carbon sequestration by removing trees and paving over soils (Gao and O'Neill, 2020). This study quantifies urban sprawl and its impacts on carbon sequestration in three Ethiopian cities: Dilla, Hawassa, and Shashemene. Like many Sub-Saharan Africa (SSA) cities, they experience unplanned and unregulated urban expansion, encroaching on forest, cropland, and wetlands. These cities are among the rapidly growing cities in East Africa, located along the highway connecting Addis Ababa to Nairobi, Kenya. Formerly, these cities were located in two regional states namely, Oromia regional state and southern nations, nationality people regional state (SNNPR). However, due to the country's (Ethiopia) current reform and tribal conflict demanding their own regional states, SNNPR has been split into four regional states namely, South Ethiopia, Central Ethiopia, Sidama region, and South West Ethiopia. The three cities (Hawassa, Shashemene, and Dilla) are characterized by high population, slum areas, and illegal buildings. They are among the cities that are showing rapid urbanization in Ethiopia. The growth the selected cities is influenced by a complex interplay of sociopolitical and environmental factors (Talema and Nigusie, 2023; Negesse et al., 2024; Ogunbode et al., 2025). From environmental factors point of view, these cities (Hawassa, Dilla, and Shashemene) undergo rapid land use changes due to population growth, economic development, and urbanization (Ogunbode et al., 2025).

Despite focus on urban development, little attention is given to unplanned and unregulated settlements, leading to unsustainable and unhealthy urban growth. Currently, large areas of land are occupied by informal settlements. The connection between urban sprawl and its impact on carbon sequestration remains poorly understood, posing challenges for urban inhabitants, planners and decision-makers. Lack of data on urban sprawl based carbon sequestration is a problem in the cities, highlighting the need for primary data collection in selected cities. To the level of our knowledge, no research has yet been conducted on this issue in these areas. Therefore, this study was initiated to fill the above-mentioned gaps and aimed to address the following three research objectives:

- To measure urban sprawl (1992-2022) and its impact on landscape pattern in the selected town between 1992 and 2022,
- To estimate urban sprawl based carbon sequestration capacity of the selected cities, and
- To recommend how cities regulate their growth and maintain healthy environment.

Addressing these objectives helps policymakers and urban planners design evidence-based solutions to promote regulated urbanization and healthier environments in the selected cities. It also uncovers links between urban sprawl and carbon footprints, raising awareness and understanding of its consequences. The methods and results of this study can be applied to other regions with similar socioeconomic and environmental conditions.

Materials and methods

The study area

The study was conducted in three cities (Dilla, Hawassa, and Shashemene) located in three regional states namely, South Ethiopia, Sidama, and Oromiya, respectively. The cities are located along the same route on the international road that connects Addis Ababa with Nairobi, Kenya. They are situated between the following coordinates:

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Latitude 6°24′30″ N to 7°3′0″ N and 7°11′60″ N, and Longitude 38°18′30″ E to 38°28′0″ E and 38°35′59.99″ E, respectively, for the cities of Dilla, Hawassa, and Shashemene (*Figure 1*). The selected cities are located in the southeastern escarpment of the Ethiopian Rift Valley and contribute hydrological flows to nearby lakes, including Abijata-Shalla, Hawassa, and Abaya-Chamo. These cities have a scattered urban settlement morphology, encompassing a large number of kebeles.

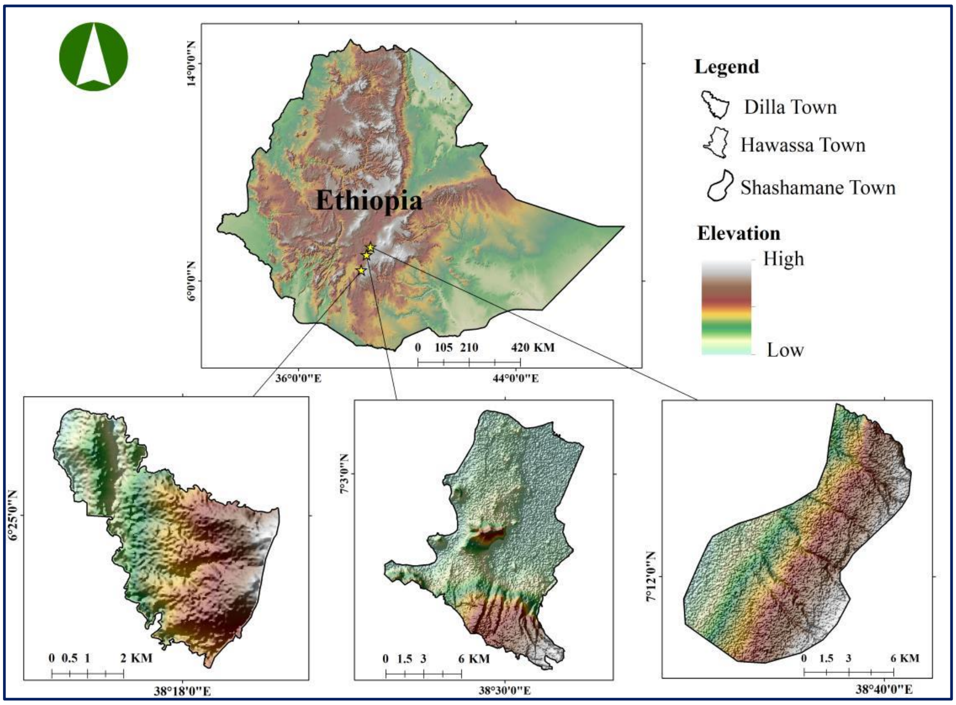

Figure 1. *Map of the study area*

Urban sprawl is a common phenomenon in these cities, characterized by horizontal expansion into surrounding areas, often including informal settlements (unregulated and unordered expansion). With rapid urbanization and demographic shifts, these cities are expected to become focal points for future urban growth in Ethiopia. The government's formal land supply has failed to meet the growing demand, resulting in the rise of fragmented peri-urban settlements driven by informal land transactions, known as urban sprawl.

Data sources and methods

Data acquisitions for time series data analysis

The study used two types of data: remote sensing and reference data, along with primary and secondary data, for analyzing urban sprawl and its impact on carbon sequestration of the cities. Time-series data was generated from Landsat (1992-2012) and Sentinel-2A (2022) images and used as remote sensing data. All the data sources (Landsat and Sentinel-2A) were obtained from U.S. Geological Survey (USGS) earth explorer. The images were obtained based on a criterion of images having <10% cloud cover, regime change and subsequent urban policy shifts after 1991, and availability of satellite images covering the area of interest (*Table 1*).

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Table 1. *Description of imagery datasets used in the LULCC analysis*

Sensor	Resolution	Year	Path and Row	Sources/ website
Land-sat TM	30m	1992	168/055 & 168/056	USGS data portal
Land-sat ETM+	30m	2002	168/055 & 168/056	USGS data portal
Land-sat OLI	30m	2012	168/055 & 168/056	USGS data portal
Sentinel-2A	10m	2022		Copernicus hub/USGS

The data were used for estimating urban expansion in each selected cities. Urban sprawl based carbon sequestration was estimated using data from field measurement and models.

For geo-referencing, 220 random ground control points (GCPs) were collected from the area as a classification-training site and image signatures. Moreover, 250 GCPs were also collected using a GPS device from all land use classes for the 2022 (recent image) classification year. The images were classified into five and three LULC types for Hawassa, Shashemene, and Dilla cities respectively using maximum likelihood classification algorithm. Using ERDAS IMAGIN software, the study area (towns) for all the satellite images was extracted for processing and analysis since they were the regions of interest. Ancillary data such as digital elevation model (DEM) and administration maps were used to obtain appropriate LULCC classification results. For delineation and navigation purposes of the urban sprawl, topographic map sheet at a scale of 1:50,000 and 1:250,000 were used, respectively.

Change detection

For urban sprawl based LULC change analysis, post-classification change detection was used. This method provides detailed information about place of change, extent, and magnitude of LULC changes in the study area. All post-classification processes were conducted using ERDAS IMAGIN 2014 and ArcMap 10.3.1 to analyze changes across three intervals: 1992–2002, 2002–2012, and 2012–2022. The final LULC change maps were generated for each year and compared over three decades (1992–2022) as per the classification scheme (*Table 2*).

Table 2. *Description of LULC classes used to in the study (1992-2022)*

LULC classes	Description
Cultivated land (CL)	Lands covered with temporary crops followed by harvest and a bare soil period
Wetland/Water body (WeL)	This includes Lakes, marshy areas with shallow water and permanent reed vegetation.
Agroforestry (AF)	Traditionally managed multi-strata agroforests where annual/perennial crops and/or animals deliberately used together on the same land.
Built-up area (BU)	This includes built-up areas or areas covered by man-made structures. Within this category, residential areas, industrial areas, and commercial areas are available.
Forestland/Plantation (FL)	Land dominated by naturally grown trees or area mainly under eucalyptus trees planted on visible plots of varying size.

Using the datasets, the percentage of urban sprawl-related cover change for each period (relative to the initial year) and the annual rate of change were calculated. The

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percentage of change within the same LULC class between two time points was determined using *Eq. (1)*, as described by Temesgen et al. (2018):

$$\Delta CL = \left(\frac{A_{f-A_i}}{A_i}\right) \times 100 \quad \text{(Eq.1)}$$

where: ΔCL is the percent change of LULC in relation to the initial year coverage. A_i is the initial year area; A_f is the final year area. Annual rate of urban sprawl based LULC change was calculated using *Eq. (2)* as described by Puyravaud (2003).

$$r = \left(\frac{1}{t_{2-}\ t_1}\right) \ln \left(\frac{A_f}{A_i}\right) \quad \text{(Eq.2)}$$

where: r represents the annual rate of cover change; t_2 and t_2 are the final and initial years.

Urban sprawl measurement

To measure urban sprawl, Shannon entropy was used together with GIS tools. Built-up areas were extracted from classified images to obtain urban built-up images for the analysis. Raster Calculator in ArcGIS was used to extract built-up images from 1992 to 2022, which were then reclassified into built-up and non-built-up areas. Based on this reclassification, buffer zones were generated based on a chosen reference point at the center of each city. Fifteen (15) concentric buffer zones were generated for each city, focusing on the central area. Market centers (for Dilla and Shashemene) and the old bus station (for Hawassa) were chosen as city centers. The buffer zones were created at a distance interval of 1km around the center point using ArcGIS. There are different ways to define buffer zones based on spatial criteria, including the distance-based approach, multi-ring buffers, adaptive buffers, and GIS implementations. For validating entropy calculations, various techniques have been used, including comparative analysis, sensitivity analysis, statistical tests, and GIS mapping, which are commonly applied in this field.

Within each buffer, the total number of pixels and built-up areas were calculated using ArcGIS's Zonal Statistics tool as part of Shannon's entropy analysis. The results for each year were saved and exported to Microsoft Excel for further entropy calculations. The Shannon Entropy measures the degree of dispersion or compactness of a spatial variable. The Shannon entropy calculations was done using the following formula as described by Biney and Boakye (2021) under *Eq. (3)*:

$$H_n = -\sum_i^n p_i\, Log\left(1/p_i\right) \quad \text{(Eq.3)}$$

where; P_i is the value of the geospatial variable in each zone divided by the total land area in that particular zone. Therefore, the ratio of the spatial element in the i^{th} concentric zone (buffer zone) is expressed in the following *Eq. (4)* as stated by Biney and Boakye (2021), n is the total number of buffer zones.

$$P_i = \frac{x_i}{\sum_i x_i} \quad \text{(Eq.4)}$$

where; x_i is the spatial elements in the i^{th} buffer zone. The Shannon entropy (H_n) values are available or vary between 0 and the values of Log (n). The Shannon entropy values

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closer to zero means compacted growth of urban or higher density. The values closer to Log (n) indicate the dispersed distribution of the town's built environment. For more understanding, it is advisable to rescale the entropy value into the range between 0 and 1. Rescaling entropy allows for meaningful comparisons between different probability distributions (Studholme et al., 1998). The normalized entropy value of 0 indicates no uncertainty (perfectly predictable outcomes), while 1 represents maximum uncertainty (equal probability for all outcomes). Moreover, normalization entropy simplifies interpretation, making it easier to understand how much uncertainty exists in a system without needing to consider the specific number of categories (Studholme et al., 1998). Rescaling was done by computing the relative entropy (H_n) as expressed under *Eq. (5)* by Biney and Boakye (2021).

$$H_n = -\sum_i^n p_i \, \mathrm{Log}\left(\frac{1}{p_i}\right) / \mathrm{Log}\,(n) \qquad \text{(Eq.5)}$$

Estimation of change in carbon sequestration

Land-use change and CO_2 emissions are strongly related, with the former being a primary cause of the latter in relation to deforestation. Carbon sequestration was estimated focusing on change in forestland and agroforestry LULC classes in response to urban sprawl. Carbon sequestration changes were analyzed for four periods: 1992, 2002, 2012, and 2022. The initial dataset was generated from the direct measurements of the aboveground biomass (AGB) from forestland and agroforestry land uses for the year 2022. The biomass datasets were converted into carbon stock using allometric equation (eq-6, eq-7, and eq-8). Carbon stock of 2022 was converted into CO_2 equivalents (CO_2e) by multiplying the carbon stock by a conversion factor. The amount of CO_2e was then changed into CO_2e per hectares for the year 2022. Using this value, the CO_2e for 1992, 2002, and 2012 was estimated based on the forest or agroforestry LULC size per hectare in 2022. For AGB measurements, inventory-based estimation of carbon stock was considered using on-plot tree measurements following the procedures used by Negash and Starr (2015). The data were collected from trees available in the study cities including fruit and coffee trees, as sources of aboveground carbon stock. The data collection was done at land use level. For each land-use type, all trees with a diameter $\geq$2 cm and a height $\geq$1.5 m were measured for diameter at breast height (DBH) and height using a caliper and/or a diameter tape and hypsometer. DBH was measured in two perpendicular directions and averaged. Tree density was calculated by dividing the number of tree stems by the plot area.

The above-ground tree biomass and carbon stocks were estimated using allometric equation. However, such equations are limited for locally available tree species in Ethiopia (Negash and Starr, 2015). Therefore, the researchers in this study opted to use the general allometric equation developed by Kuyah et al. (2012) as presented in *Eq. (6)*.

$$\mathrm{AGB} = 0.225 * \mathrm{dbh}^{2.341} * \rho^{0.73} \qquad \text{(Eq.6)}$$

where:
AGB is the estimation of the aboveground biomass (Kg dry matter/plant),
DBH is the diameter (cm) at breast height (1.3 m) and
ρ is species wood density (g cm^{-3}).

Wood densities (ρ) were retrieved from the online databases (Haile et al., 2017). If species-level data is not available, mean genus-level values was used. Carbon was

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estimated from the biomass of trees by multiplying the carbon stock with the values of 0.47 (IPCC, 2006). The AGB of carbon stock is determined from each tree and summed together to obtain the total AGB carbon stock of the study cities. The final result of the carbon stock was determined by hectare. The CO_2e of the area was calculated by multiplying the total C stock by a factor of 3.67 (IPCC, 2006) and this could be used as carbon footprint of the cities.

In addition to tree species available in the area, coffee crops grown under the shade trees was considered. This is especially relevant for the Dilla and Hawassa areas because coffee is the dominant crop available in these areas. For estimating the AGB of coffee or the carbon sequestration role of coffee was calculated using the allometric equations developed by Negash and Starr (2015) as presented in the following way under *Eq. (7)*.

$$AGB_{coffee} = 0.147\mathrm{d}_{40}^{2}; R2 = 0.80; n = 31 \quad \text{(Eq.7)}$$

where:
AGB is the aboveground biomass of coffee plants,
d_{40} is stem diameter (cm) of the coffee plant at 40 cm height.

The carbon stock of belowground biomass (BGB) was estimated using equation developed by Kuyah et al. (2012) under *Eq. (8)*:

$$BGB = 0.490AGB^{0.923};\ R^2 = 0.95, n = 72 \quad \text{(Eq.8)}$$

where:
BGB is the belowground biomass (kg dry matter/plant),
AGB is the aboveground biomass (kg dry matter/plant).

The total carbon stock results of trees and coffee derived from above and belowground biomasses was summed together and changed into CO2e per hectares for the year 2022 and estimated for 1992, 2002, and 2012.

In addition to physical measurements, a focus group discussion (FGD) and key informant interview (KII) was conducted with selected elders who are familiar with the local area. For this, 9 FGD and 4 KII (municipal heads) was carried out in the study cities.

During the data collection period, the authors implemented different techniques for validating both primary and secondary data. For primary data, pilot testing, triangulation, consistency checks, cross-verification, and data cleaning were the main techniques used for validation. For secondary data validation, the authors focused on the credibility of the sources and the publication data of the articles.

Results

LULC dynamics in response to urban sprawl

Land use land cover (LULC) change is caused by various factors, with urban sprawl being the dominant cause in the selected cities (Hawassa, Dilla, and Shashemene) between 1992 and 2022. The satellite images of the study cities were classified into four LULC classes for Shashemene (*Figure 2*), six for Hawassa (*Figure 3*), and three for Dilla (*Figure 4*) between 1992 and 2022. Over this period, built-up areas consistently expanded, while other LULC categories declined. For example, in the first period (1992 to 2002), built-up areas increased by 59.6% in Shashemene, 34.85% in Hawassa, and 68.7% in Dilla. Detailed information on the LULC changes, including area coverage, is provided in *Appendix 1*.

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During the second period (2002-2012), built-up areas increased by 37.1%, 93.9%, and 26.2% in Shashemene, Hawassa, and Dilla, respectively. Similarly, in the third period (2012-2022), the increase was 79.95%, 28.42%, and 34.2% in the same cities. In 1992, Dilla's built-up area was 407.94 ha, covering 19.07% of the study area, while AF and CL accounted for 1,145.57 ha (53.54%) and 586.01 ha (27.39%), respectively. Between 1992 and 2022, Dilla's built-up area grew by 185.5%, while AF and CL decreased by 37.3% and 56.2%, respectively (*Figure 2*).

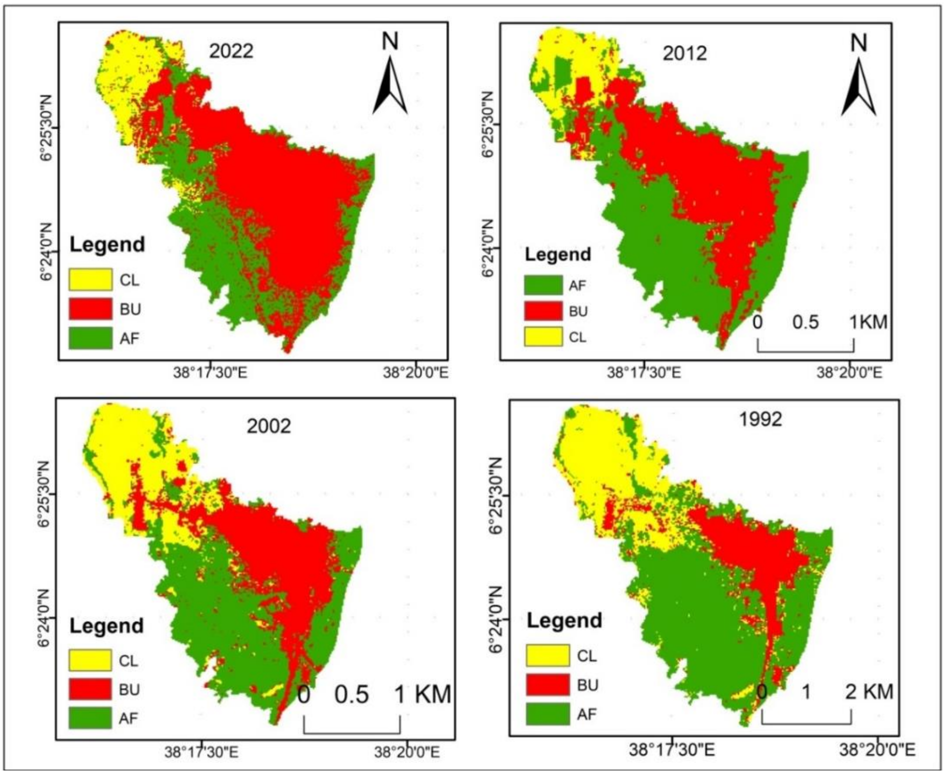

Figure 2. *LULC change in response to urban sprawl in Dilla City (1992-2022), CL = Cultivated land, BU = Built-up area, and AF = Agroforestry*

In Shashemene, the built-up area covered approximately 1,023 hectares (7.92%) in 1992, increasing to 1,633.65 hectares (12.64%) in 2002, 2,239.32 hectares (17.32%) in 2012, and 3,962.58 hectares (30.65%) in 2022. This marks a significant 287.2% increase in built-up area from 1992 to 2022. Meanwhile, other LULC classes, such as CL, FL, and GL, declined during this period. CL increased slightly by 12.3% and 8.2% in 2002 and 2012, respectively, compared to the reference year (1992). However, after 2012, CL decreased by 1,953.74 ha (20.5%) between 2012 and 2022. Over the past 30 years, CL declined by 13.9%, showing a trend opposite to the growth of built-up areas in Shashemene city. FL consistently declined between 1992 and 2022, with a 31.9% reduction from 1992 to 2002, a slight 1.6% increase from 2002 to 2012, and a further 15.6% decrease between 2012 and 2022. Overall, FL decreased by 41.6% during this period. GL also declined significantly, dropping by 63% between 1992 and 2022 in Shashemene city (*Figure 3*).

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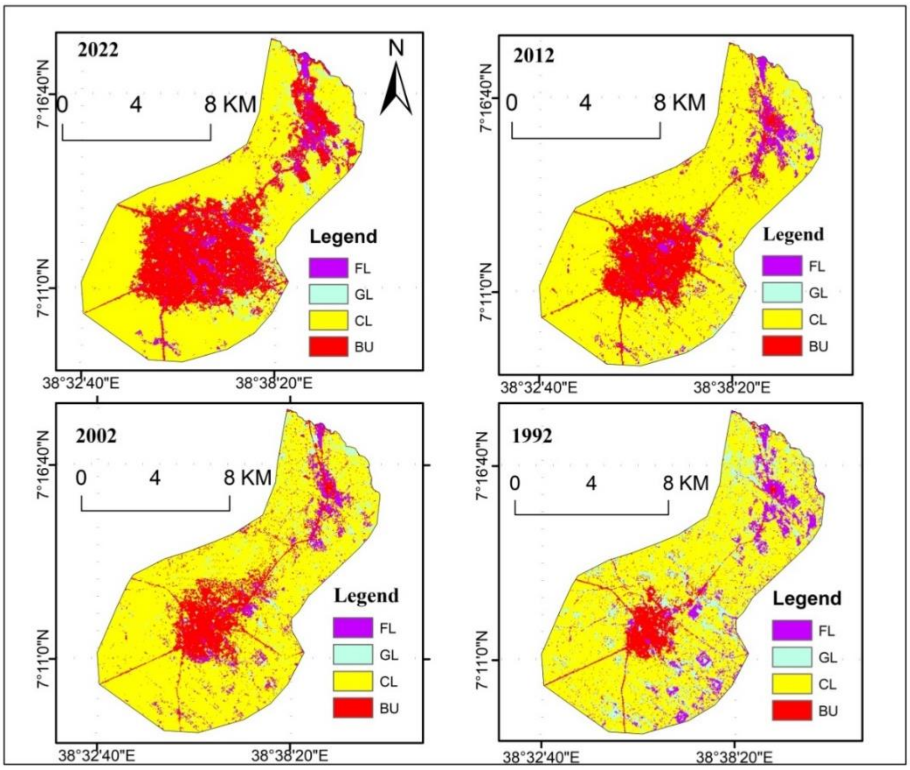

Figure 3. *LULC change in response to urban sprawl in Shashemene city (1992-2022), FL = Forest land, GL = grazing land, CL = Cultivated land, and BU = Built-up area*

In Hawassa, as shown in *Figure 4*, the land use was classified into six (WB, FL, GL, CL, BU, and AF) classes between 1992 and 2022. In 1992, WB, FL, GL, CL, and BU respectively covered an area of 2,877.21 ha, 464.22 ha, 1,052.91 ha, 3,750.03 ha, and 1,211.85 ha, representing 18.03%, 2.91%, 6.6%, 23.49%, and 7.59% of the total area, respectively. In 2002, AF covered the largest land area, while FL covered the smallest. WB, CL, and AF represents 17.55%, 14.67%, and 39.67% of the total area, respectively. In contrast, FL, GL, and BU increased to 1,186.58 ha, 1,666.91 ha, and 1,634.16 ha, representing 7.43%, 10.44%, and 10.24% of the total area, respectively. Despite AF covering the largest land area, it showed a decreasing trends similar with WB and CL between 1992 and 2022 in Hawassa city. In 2012, WB, CL, AF, and GL had declined, while BU increased significantly. Although FL expanded compared to 1992, its area had dropped by 10.87% in 2012. In 2022, there was a significant increase in BU due to a decrease in other LULC classes in Hawassa city (*Figure 4*).

Accuracy assessment

To evaluate the quality of LULC analysis, we calculated the user's accuracy (%) and kappa coefficient (%) for each city. The average user's accuracy for Hawassa, Shashemene, and Dilla was 93%, 88%, and 89%, respectively, with kappa coefficients of 90%, 85%, and 84%. Detailed results are provided in *Appendix 2*.

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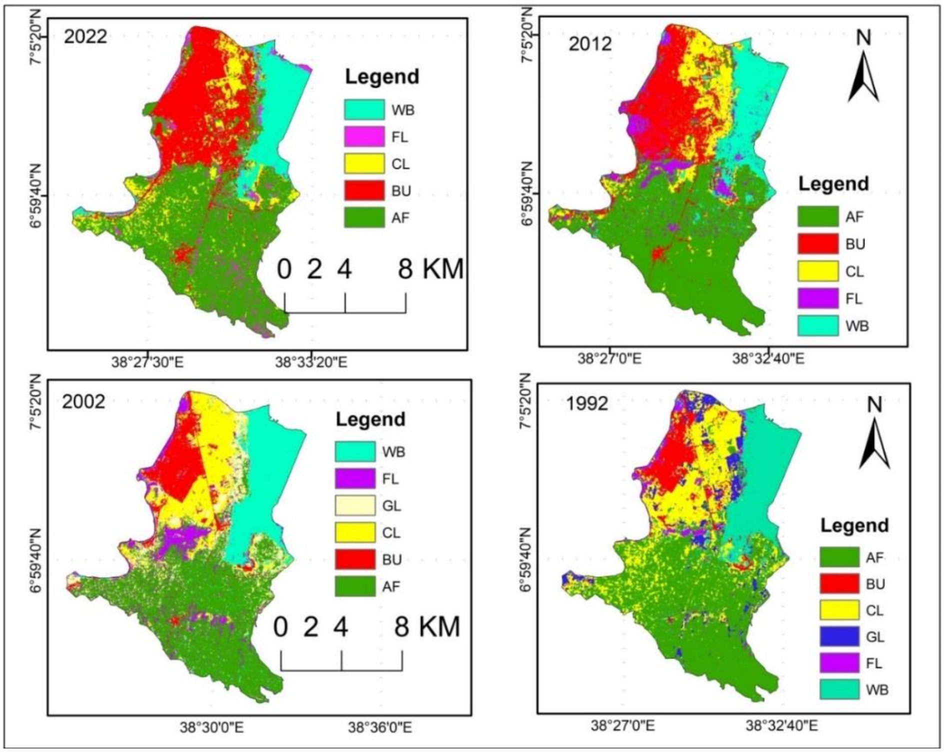

Figure 4. *LULC change in response to urban sprawl in Hawassa city (1992-2022), FL = Forest land, GL = grazing land, CL = Cultivated land, AF = Agroforestry, WB = Water Body, and BU = Built-up area*

Trends of LULC change from 1992 to 2022

Trend analysis of LULC change reveals a non-linear transition of LULC types in the selected cities. In Dilla City, AF and CL decreased by 37.31% and 56.21%, respectively, while BU significantly increased by 185.54% between 1992 and 2022. In Hawassa city, WB, CL, AF, and GL were reduced by 23.3%, 56.36%, 14.06%, and 100% respectively between the year 1992 and 2022. Conversely, BU and FL rose sharply, by 235.71% and 88.08%. In Shashemene city, CL, FL, and GL were reduced by 13.91%, 41.59%, and 62.96%, respectively, while BU increased by 287.16% between 1992 and 2022 (*Appendix 1*).

Urban sprawl analysis

Built-up area expansion

To analyze the nature and pattern of urban sprawl in the study area, the LULC maps from 1992, 2002, 2012, and 2022 were reclassified into built-up and non-built-up areas. The built-up area was significantly increased between 1992 and 2022. Detailed information on the expansion of built-up areas for each city is provided in *Appendix 3*.

The built-up area in Dilla city increased from 407.94 hectares (19.07%) to 1,164.82 hectares (54.44%) between 1992 and 2022 (*Figure 5*). In 1992, the city's total land area was approximately 2,139.52 hectares, with 407.94 hectares built-up and 1,731.58 hectares non-built-up. The then population was 30,087. By 2002, the built-up area expanded to 688.18 hectares, reducing the non-built-up area to 1,451.34 hectares,

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while the population grew to 42,403. In 2012, the built-up area further increased to 868.23 ha, leaving 1,271.29 ha as non-built-up land, with the population rising to 82,035. By 2022, the built-up area reached 1,164.82 ha, marking a 34.2% increase since 2012, while the non-built-up area declined to 974.7 ha. The population also grew significantly, nearly doubling (94% increase) compared to 2012 in Dilla city. The city was expanded to the south and northwest directions (*Figure 5*).

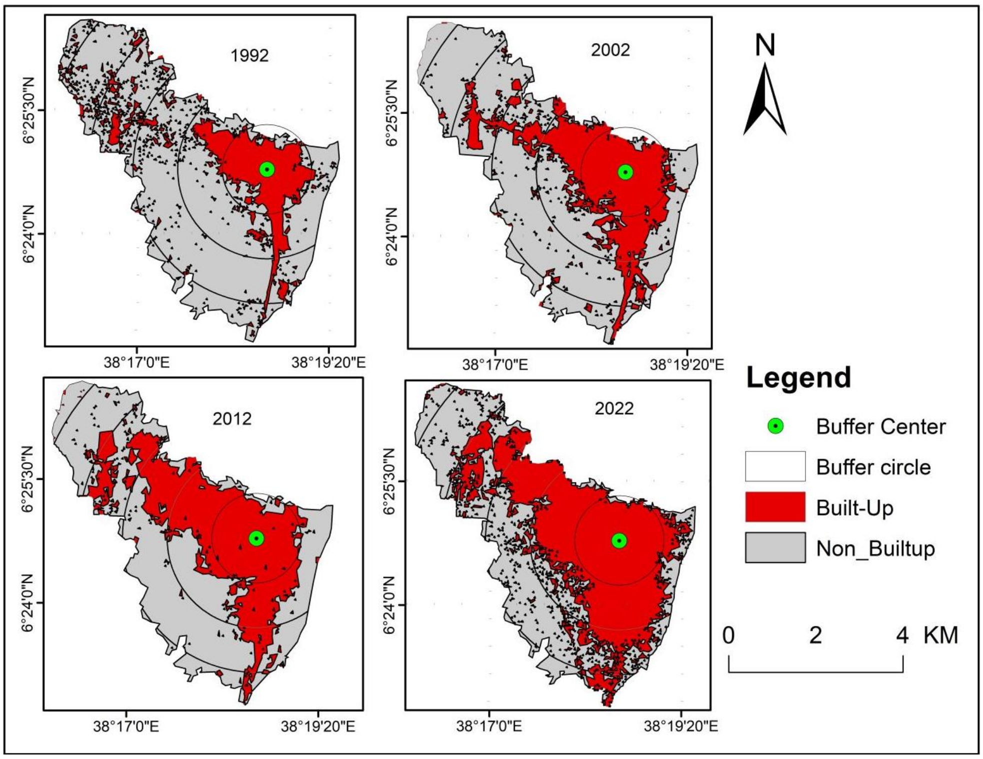

Figure 5. *Reclassified map of built-up and non-built-up area of Dilla city (1992-2022)*

In Hawassa city, the built-up area expanded significantly by 235.7% between 1992 and 2022 (*Figure 6*). In 1992, the built-up area was 1,211.85 ha, while the non-built-up area became 14,749.45 ha, with a total population of 45,464. By 2012, the built-up area grew by 19.85%, while the population increased by 58.62% to 95,975, reducing the non-built-up area to 12,793.3 ha. In 2022, the built-up area increased by another 28.42%, while the population reached to 422,200, further reducing non-built-up areas. The city was expanded (outward expansion) to the south, southeast, east, northeast, and north directions (*Figure 6*).

In Shashemene, the total area within the city boundary is 12,927.6 ha (*Figure 7*). Built-up land accounted for 7.92% (1,023.51 ha) in 1992, 12.64% (1,633.65 ha) in 2002, 17.32% (2,239.32 ha) in 2012, and 30.65% (3,962.58 ha) in 2022. In 2022, the built-up area of Shashemene city increased significantly by 287.2%, covering 30.65% of the total area. The non-built-up area decreased to 8,965 ha, with urban population of 208,400 people (*Figure 7*). The city was expanded towards all direction from the center, with gradual dispersion towards northeast direction.

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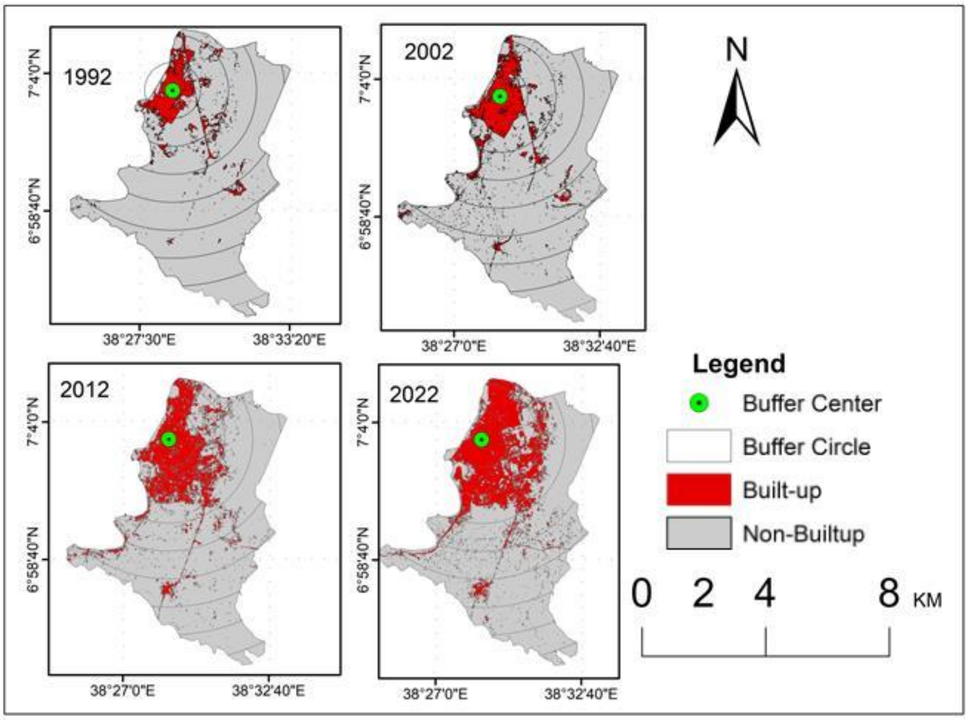

Figure 6. *Reclassified map of built-up and non-built-up area of Hawassa city (1992-2022)*

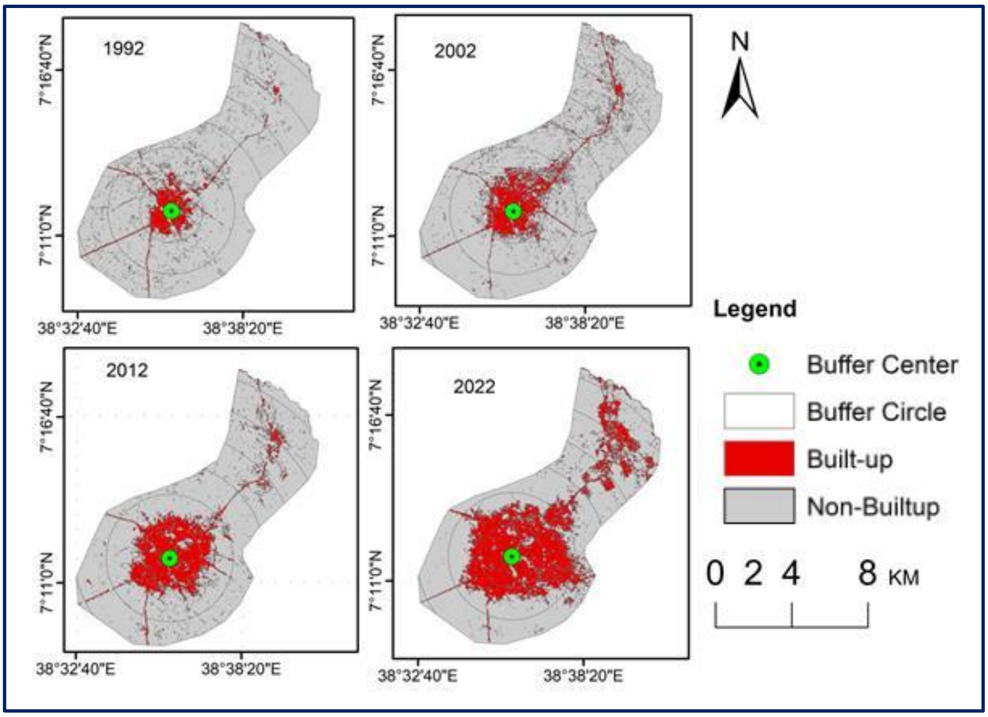

Figure 7. *Reclassified map of built-up and non-built-up area of Shashemene city (1992-2022)*

Urban sprawl and urban population pressure are closely interconnected, with one often driving the other (Talema and Nigusie, 2023). Increased population pressure is a key driver of urban sprawl, and urban sprawl, in turn influences future population distribution

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and city planning challenges. Effective sustainable urban development strategy and urban planning are necessary to manage both issues (urban sprawl and population pressure) and create livable and well-planned cities. As shown in *Figure 8*, the number of people living in urban areas in Ethiopia increased in all cities between 2007 and 2022. Consequently, population density has risen, suburban areas have expanded (*Figure 2, Figure 3,* and *Figure 4*), and the demand for more land has gradually grown, making urban sprawl an inevitable phenomenon in the region. There is a feedback loop between population pressure and urban sprawl. Sprawl can attract more people since it provides cheaper housing. Once the sprawled areas become crowded, a new wave of urban sprawl emerges, pushing city boundaries further outward.

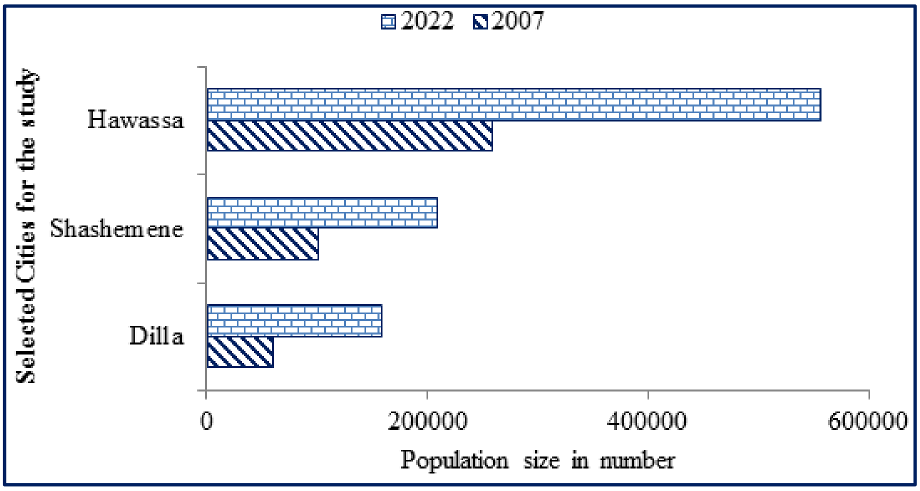

Figure 8. *Population size of the three cities between 2007 and 2022*

Assessing urban sprawl using Shannon entropy

As shown in *Table 3*, the values of Shannon's entropy display a non-linear pattern. The entropy values are relatively high, with differences of less than 1% over the years. The Log(n) values for the cities were 1.79, 2.08, and 1.95, representing the highest Shannon entropy values for Dilla, Hawassa, and Shashemene, respectively. The relative Shannon entropy was high for all cities. The average Shannon entropy values for the cities of Dilla, Hawassa, and Shashemene were 1.3, 1.87, and 1.51, respectively, between 1992 and 2022. The relative Shannon entropy values of all cities were found less than 1 with average values of 0.73, 0.85, and 0.78 for Dilla, Hawassa, and Shashemene cities, respectively. The minimum values were 0.6 for Dilla, 0.7 for Hawassa, and 0.5 for Shashemene cities (*Table 3*).

Carbon sequestration analysis

The carbon sequestration analysis was focused on forestland and agroforestry land use types. These land use types are selected because they are the major land uses that play a role in climate regulation in cities. The detection of aboveground and belowground carbon stock from biomass using allometric equations showed higher CO_2 equivalent (CO_2e) values in Dilla (15.8 t/ha), followed by Shashemene (average: 7.65 t/ha) and Hawassa (3.74 t/ha) in 2022. The higher CO_2e values in Dilla are attributed to the extensive coverage of agroforestry land use in the area. Consequently, high carbon

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sequestration (t/ha) was observed in Dilla, followed by Shashemene and Hawassa. However, when compared to 1992, a decreasing trend in CO_2e values has been observed across all three cities. As shown in *Table 4*, non-linear trends in carbon sequestration levels were observed in each selected city between 1992 and 2022.

Table 3. *Shannon entropy and relative values for Dilla, Hawassa, and Shashemene cities*

Year	Dilla		
	Built-Up area (ha)	**Shannon's entropy value**	**Relative Shannon's entropy value**
1992	407.94	1.08	0.6
2002	688.18	1.05	0.59
2012	868.23	1.66	0.93
2022	1164.82	1.41	0.79
	Log (6)	1.79	-
Year	**Hawassa**		
	Built-Up area (ha)	**Shannon's entropy value**	**Relative Shannon's entropy value**
1992	1211.85	1.47	0.66
2002	1634.16	1.80	0.81
2012	3168.00	2.19	1.00
2022	4068.36	2.00	0.91
	Log (8)	2.08	-
Year	**Shashemene**		
	Built-Up area (ha)	**Shannon's entropy value**	**Relative Shannon's entropy value**
1992	1023.51	0.98	0.5
2002	1633.65	1.41	0.73
2012	2239.32	1.81	0.93
2022	3962.58	1.83	0.94
	Log (7)	1.95	-

Table 4. *CO_2 equivalent level of the selected cities as affected by urban sprawl*

LULC types	Dilla				
	CO_2 equivalent t/ha	**Total CO_2e (in one million tons)****			
		1992	**2002**	**2012**	**2022**
AF	15.8	18,102.115	15,049.52	16,287.59	11,347.46
LULC types	**Hawassa**				
	CO_2 equivalent t/ha	**Total CO_2e (in one million tons)****			
		1992	**2002**	**2012**	**2022**
FL	5.66	2,625.97	6,712.17	5,982.5	4,938.84
AF	1.822	12,038.6	11,540.69	11,156.62	10,345.8
Total		14,664.56	18,252.85	17,139.13	15,284.63
LULC types	**Shashemene**				
	CO_2 equivalent t/ha	**Total CO_2e (in one million tons)****			
		1992	**2002**	**2012**	**2022**
FL	7.65	8,249.52	5,619.6	5,708.9	4,818.21

** it was calculated by LULC change size and multiplied by CO_2 Sequestration (t/ha)

In 1992, more than 18 billion tons of CO_2 were sequestered by the agroforestry land-use system in Dilla City. However, this value decreased to 15 billion tons in 2002, 16 billion tons in 2012, and 11 billion tons in 2022 (*Table 4*). In Hawassa city, forestland and agroforestry land use types are commonly found, and their CO_2 sequestration levels showed an increasing trend between 1992 and 2022. The minimum value was recorded

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in 1992, while the maximum value was observed in 2012. In 1992, more than 14 billion tons of CO_2 were sequestered by both agroforestry and forestland use types. However, this value increased to 18 billion, 17 billion, and 15 billion tons in 2002, 2012, and 2022, respectively. In Shashemene, forest land was identified as a major carbon-sequestering land-use type, and the values of CO_2 sequestration capacity showed a decreasing trend between 1992 and 2022. The maximum value was recorded in 1992 (8,249.52 billion tons), while the minimum value was observed in 2022 (4,818.21 billion tons).

Discussion and conclusion

Expansion of Built-up area: Is it healthy?

Ethiopia has experienced rapid economic growth and urbanization (Koroso and Zevenbergen, 2024) in the past two decades, attracting people from rural areas seeking better opportunities (Dadi et al., 2016; Benti et al., 2022). This influx has led to increased urban populations, causing urban expansion into peri-urban areas, which are mostly covered by crops, forests and scattered rural houses. This phenomenon, known as urban sprawl, has resulted in significant land-use changes, particularly the conversion of agricultural and forested land into urban settlements (Koroso and Zevenbergen, 2024). According to existing literature, urban encroachment is an unavoidable phenomenon that initiate urban sprawl in cities (Dadi et al., 2016). Our findings indicate that, between 1992 and 2022, Hawassa expanded from 620.37 ha (Wondrade et al., 2014) to 4,068 ha (a 236% increase), Dilla grew from 408 ha to 1,165 ha (186%), and Shashemene experienced a 287% increase in urban area. *Figure 9* highlights the competition between built-up and cultivated land in these cities.

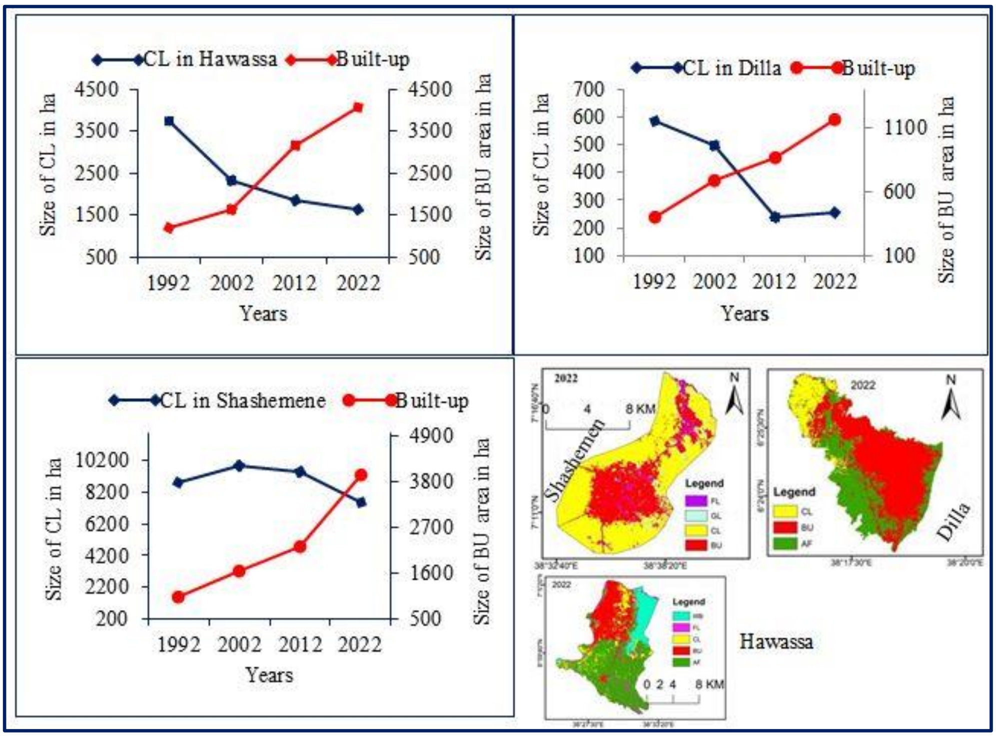

Figure 9. *Trends of Built-up (BU) area Vs Cultivated land (CL) between 1992 and 2022. Note: The picture at the right bottom indicate the maximum of CL (Yellow color) left and expanded BU area (Red color) for the year 2022*

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Our findings are consistent with those of Dadi et al. (2016); Cheng et al. (2023); Abebe (2024); and Koroso and Zevenbergen (2024), which emphasizes the competing demands of urban and agricultural land uses. Urbanization has received both praise and criticism regarding its impacts. While contributing significantly to GDP growth globally, expansion of urban presents unique challenges in developing nations like Sub-Saharan countries, where the socioeconomic gains do not fully offset losses in productive land and biodiversity (Aboye et al., 2024). This is a sore fact happening in Ethiopia, especially urban areas surrounded by permanent crops, such as coffee and fruit trees, as seen in Dilla and Hawassa. According to the World Bank Group (2022), cities contribute about 80% of global GDP. However, the share of urban development in a country's GDP depends on effective urban management (Benti et al., 2022). If managed well, urban development drives sustainable growth by boosting productivity, fostering innovation, and encouraging new ideas (UN-Habitat, 2022; World Bank Group, 2022).

In Ethiopia, cities contribute 38% of GDP despite only 15% of the workforce being urban (Alemayehu, 2019). In fact, the higher socioeconomic potential of urban areas remains untapped due to various factors, with the ineffectiveness of urban land management policies or lease policies being a primary one (Koroso and Zevenbergen, 2024). Meanwhile, the expropriation of farmers from their land without adequate compensation has been one of the main issues Ethiopia has faced over the past few decades (Abebe, 2024). Although this fact is undeniable, insufficient attention has been given to examining the impacts of urbanization (Benti et al., 2022; Abebe, 2024). In Ethiopia, land is a public resource owned by the state, and its allocation is solely managed by urban and regional governments. Urban land can be leased to individuals and companies, whether private or government-owned, in accordance with the country’s lease policy (FDRE., 2008; FDRE, 2011) to prevent urban land mismanagement. The problems that the government aimed to address through the proclamation remain persistent, particularly in cities where land shortages pose significant challenges. These issues are especially pronounced in areas administered by regional governments and cities (Koroso and Zevenbergen, 2024). Despite the introduction of the land lease proclamation, challenges such as land hoarding, urban sprawl, informal settlements, and illegal land capture continue to affect the study cities. These problems highlight the ineffectiveness of urban land management and utilization, contributing to urban land shortages, high prices, and unregulated and disordered settlements (urban sprawl) in Hawassa, Dilla, and Shashemene, Ethiopia.

The expansion of urban areas in Hawassa, Dilla, and Shashemene as a result of a complex interplay of factors, including urban population growth, economic development, and change in infrastructure (Aboye et al., 2024). Rural-to-urban migration often fuels urban expansion, leading to a high demand for housing in response to the growing urban population (Benti et al., 2022; Koroso and Zevenbergen, 2024). As the population increases in the urban areas, there is heightened demand for housing, which results in rapid urban sprawl (Dadi et al., 2016; Benti et al., 2022; Abebe, 2024; Koroso and Zevenbergen, 2024). However, this expansion has adverse effects, including the loss of green spaces, biodiversity, and productive agricultural lands, as well as increased pollution and cultural blending. In particular, urbanization encroaches on lands with permanent crops like coffee and fruit trees, as observed in Dilla and Hawassa. The healthiness of urbanization in Hawassa, Dilla, and Shashemene stems from the interplay of many factors, among which urban growth management plays a significant role. Expanding without sustainable urban planning—unchecked, uncoordinated, and

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unregulated-into productive lands is considered unhealthy. Therefore, it is essential to adopt a balanced approach to ensure that urban expansion contributes positively to the quality of life in these cities.

Urban sprawl as detected by Shannon entropy

Urban sprawl is a serious challenge that cause environmental and socioeconomic problems (Getu and Bhat, 2021) in the study cities. Population pressures and the failure of urban lease policies are the main causes of urban sprawl. The people movement to urban area is driven by a combination of push and pull factors (Melesse and Nachimuthu, 2017; Teshome and Belete, 2017; Abeje, 2021). Due to the current political instability in Ethiopia, most people feel that urban areas are safer for living compared to rural areas. In the past five years, armed conflict has been the main push factor in Ethiopia in general and the study cities in particular. Inter-communal conflicts have also caused many people to migrate to urban areas. In addition, ecosystem service degradation (provisioning, regulation, supporting, and cultural) (Melesse and Nachimuthu, 2017), landlessness and recurrent drought (Abeje, 2021), and inadequate social services are the major push factors that compel people to move toward cities (Hawassa, Shashemene, and Dilla). Meanwhile, economic reasons such as employment and job, better urban facilities and housing are significant pull factors that attract people to urban areas (Teshome and Belete, 2017). Due to these pull and push factors, the number of people in urban areas have been alarming increased with limited access to housing. As a result, people move to hinterlands to informally "*purchase lands*" from local farmers and build their own house using locally available wood. This result in deforestation, loss of biodiversity, and productive lands (Wubneh, 2018; Girma et al., 2019a; Koroso, 2020, 2023; Gemeda et al., 2020).

Population growth is directly correlated with built-up area expansion in the cities. The correlation coefficient (R^2) between population size and built-up area are 0.91, 0.93, and 0.99 for Dilla, Hawassa, and Shashemene, respectively, indicating a strong correlation between the two variables (*Figure 10*).

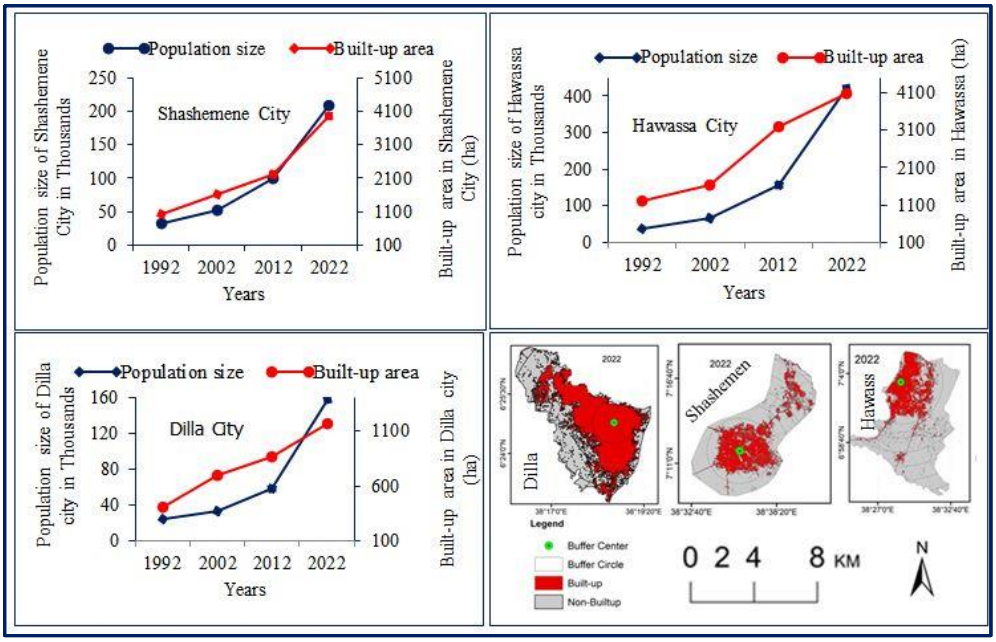

Figure 10. *Correlation between population and built-up area expansion in selected cities*

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Since cities have different morphologies, they exhibit different relative Shannon's entropy values. The Shannon's entropy values for Dilla, Hawassa, and Shashemene generally ranges from 1.05 to 2.19, indicating urban sprawl in these cities. The average Shannon entropy values obtained from each city are closer to the upper limit of log (n) (i.e. 1.79, 2.08, and 1.95), showing the degree of dispersion of built-up area in the cities (Deka et al., 2012). Entropy values close to upper limit indicate that the cities were undergoing urban sprawl (Deka et al., 2012; Dewa et al., 2022) and increasingly fragmented. The relative Shannon's entropy values (0.5-0.94) are similar to those of Bahir Dar city (0.45-.0.71) (Getu and Bhat, 2021), to Qom city, Iran (0.8-0.88) (Mosammam et al., 2017), Tripoli, Libya (0.74-0.90) (Alsharif et al., 2015), and Chennai, India (0.67-0.69) (Deka et al., 2012). The increased values of Shannon's entropy indicate a continuous increase in urban sprawl in the selected cities, which tend to become more dispersed and fragmented. The change in relative Shannon entropy values from 1992 to 2022 for Dilla was 0.33, followed by 0.34 for Hawassa and 0.44 for Shashemene. These values differ from the previous findings (Deka et al., 2012; Alsharif et al., 2015; Mosammam et al., 2017; Getu and Bhat, 2021), which reported entropy values of 0.16, 0.08, 0.16, 0.02, and 0.02, respectively. Our entropy values for the three cities are higher, indicating that the rate of urban sprawl in these cites was very high during the study period. Overall, from 1992 to 2022, Shannon entropy values indicates urban sprawl has been slightly increasing in each city, with sprawl being most prominent between 2012 and 2022, highlighting the need for effective plans and policies to manage the cities for sustainable growth and development. The ineffectiveness of control efforts in each city can lead to dispersed urban development, which negatively impacts sustainability. Both the government and the community need to work together to promote regulated urbanization and a healthy local environment in accordance with each city's spatial plan. Moreover, addressing the underlying "push-pull" causes of rural-to-urban migration in Ethiopia requires balanced development policies that improve rural livelihoods and infrastructures while managing urban growth sustainably.

Carbon sequestration analysis in relation to urban ecosystem services

A surge in built-up areas, driven by continuous urbanization and population growth in developing countries like Ethiopia, has led to urban sprawl at the expense of important land use types (Oertel et al., 2024). Urban sprawling disrupts the natural capital flow available in suburban areas, which is important to individual and community well-being (Costanza, 2014; Oertel et al., 2024), and negatively impacts ecosystem services such as carbon sequestration, primarily through the loss of vegetation cover.

In our study cities, forest coverage varies both spatially and temporally. For instance, in Dilla city, forestland cover has been completely disappeared due to informal settlements and land use modification, and instead, agroforestry land use now dominate the landscape. However, in Hawassa and Shashemene cities, the proportion of forestland appears to be lower compared to other land use types. Forestland increased in Hawassa, while it decreased in Shashemene city. In relation to urban green space establishment, Hawassa city tree cover has shown an increasing trends between 1992 and 2022**.** Government has focused on tree plantings in urban open spaces to enhance the aesthetic values of the area. A similar result was reported by Getahun and Yoseph (2022), indicating an increase in forest coverage from 14.62% in 1985 to 31.05% in 2017 in Hawassa city.

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Urban area contribute more than 70% of CO_2 emissions (Churkina, 2016) from various sources such as land use change, transportation, waste, and energy consumptions. In this case, the presence of forest in the city could play a significant role in offsetting the CO_2 emissions. For instance, in Hawassa city, 5.66 million t/ha and 1.82 million t/ha CO_2e has been sequestered using agroforestry and forestland use types. Between 1992 and 2022, 88.1% of CO_2e is sequestered in the city. This is a good practice that should be supported by strong policies and strategies to encourage individuals to pay due attention to urban forests and green spaces in the cities. However, the opposite occurred in Shashemene compared to Hawassa city. In Shashemene, forestland decreased as the built-up area of the city expanded between 1992 and 2022. As a result, 41.6% of CO_2 has been emitted to the atmosphere due to forest removal in the periphery of the urban area. This result is in contrary with the results of Hong et al. (2024) showing that a total increase in carbon sequestration of the urban area of Harbin Changchun urban agglomeration (HCUA), China. Forest area and green spaces are important sinks of CO_2 in cities by keeping carbon in the biomass through photosynthesis (Gratani et al., 2016; Tanhuanpää et al., 2017; Lu et al., 2021; Oertel et al., 2024; Fini et al., 2023; Escobedo et al., 2024).

In Ethiopia, until recent years, urban forests and green spaces have not been prioritized in urban planning (Eshetu et al., 2021). Preserving forested land in urban areas is not a luxury but a necessity for ensuring a healthy living environment (UN-Habitat, 2022). Urban forests play a crucial role in enhancing the quality of life in cities. However, the weak legal and regulatory framework in Sub-Saharan Africa has resulted in inadequate development and management of urban forests (Zakka et al., 2017; Eshetu et al., 2021). In Ethiopia, and specifically in the cities under study, there are policies and legal documents addressing the importance of maintaining forests and green spaces. However, there is a lack of commitments and quantitative guidelines and standards for their implementation and management in the cities (Eshetu et al., 2021).

Urban policy gaps for promoting regulated urbanization and healthy environment

In Ethiopia, land is a key driver of economic growth (Yusuf et al., 2009; Vongpraseuth, 2015; Koroso, 2020; Koroso et al., 2021). The urban land lease policy, introduced in 1993 and revised in 2011, aims to attract domestic and foreign investment for industries, housing, and other purposes (Koroso, 2020, 2023). However, weak enforcement has hindered its objectives, particularly efficient urban land utilization. Despite revisions to address these gaps (FDRE, 2008, 2011; Koroso, 2023), the challenges persist, and measures taken so far have been insufficient (Gemeda et al., 2020). Sustainable urban development requires the efficient use of land for its intended purposes from both socioeconomic and ecological perspectives (UN-Habitat, 2022).

As of today, Urban land lease proclamations remain ineffective in improving citizens' access to land, urban land utilization, and equity (Gemeda et al., 2020). Weak government and public commitment to curbing land speculation has hindered progress, allowing speculators to persist and land use efficiency to decline (Gemeda et al., 2020; Koroso et al., 2021; Koroso, 2020, 2023). As a result, there is land supply shortage, inflated land price, informal settlement/illegal occupation, land hoarding/stockpiling, corruption, and nepotism are currently nagging the cities. Different studies have raised the existence of such persistent problems in cities of Ethiopia and other Sub-Saharan countries (Yusuf et al., 2009; Koroso, 2020; Gemeda et al., 2020). Due to these problems, significant size of land has been taken from its productive use such as agriculture land and forest land to land speculators. The problems are among the main factors that promote urban sprawl in

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cities and reduce the collective efforts of government and non-government organization to promote regulated urbanization and health environments in cities. Green spaces, forest areas, and wetlands have been changed into settlement areas as a result of weak urban regulations. Cheleleka wetland is a typical manifestation of the impacts of unregulated urban growth in the case of Hawassa city.

Weak governance of land, including poor enforcement, has contributed to unregulated urbanization and unhealthy local environments. Engaging citizens in governance processes fosters transparency and accountability. However, the reality on the ground is different. Public participation in regulating urbanization and promoting a healthy environment is very low. As a result, community-led monitoring of urban sprawl in cities remains weak.

Promoting regulated urbanization and healthy environment: Recommendation

In Ethiopia, land related policy implementation issues are managed at municipal level, specifically by the Urban Land Development and Management Bureau (Koroso, 2023). As many scholar agreed (Wubneh, 2018; Koroso, 2023), these local officials hold considerable power to implement land-related policies in the cities, either to ensure proper land utilization or to fail in doing so. However, there is weak enforcement by local and regional governments in properly implementing the urban land lease policy in cities. Federal government intervention, influence and the limited capacity of local/regional governments-such as understaffing and a lack of qualified personnel-are among the main reasons for this low enforcement. The main solution is to provide technical capacity development, assigning skilled personnel, promote the use of technological, increase access to housing for individuals, and foster collaboration with the federal government. These measures can improve the management of urban land, enhance land use efficiency, and ultimately reduce urban sprawl.

It is well known that the population in cities is increasing alarmingly, while access to housing remains very limited. To minimize illegal settlements and urban sprawl, it is crucial to create options that enable individuals to own houses. This is an essential step toward halting or at least reducing urban sprawl into per-urban areas. Of-course, urban sprawl is not always a curse; it also presents opportunities, such as being a hub for innovation and economic activities (Dadi et al., 2016; Terfa et al., 2019). Preparing urban growth boundaries and properly implementing them can contribute significantly to controlling urban sprawl in cities (Oertel et al., 2024). Changing or modifying ineffective land acquisition rules, urban lease policies, and plans can help control, monitor, and govern urban expansion (Abdeljawad et al., 2022), and urban sprawl in cities. Capacity building, addressing resource constraints, and implementing techniques that enhance the commitment of local government staff would improve the efficiency of urban land utilization. On the other hand, promoting regulated urbanization and a healthy environment in cities requires a multifaceted approach that integrates urban land use planning, policy-making, community engagement, and sustainable practices. In line with these ideas, designing and implementing zoning policies (Dilla, Shashemene, and Hawassa) to separate industrial, residential, and green areas are crucial for promoting regulated urbanization and a healthy environment. Additionally, promoting smart city policies that focus on compact urban development can reduce urban sprawl and help achieve sustainable urban development. Furthermore, ensuring a healthy environment in cities involves implementing sustainable infrastructures, designing affordable housing initiatives, and fostering community participation. Similar suggestions have been made

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by various authors (Vongpraseuth, 2015; Wubneh, 2018; Koroso, 2020, 2023; Abdeljawad et al., 2022; Azadi, 2024) in studies conducted on different cities.

Limitation of the study

The study examines urban sprawl and its impact on carbon sequestration, focusing on promoting regulated urbanization and a healthy environment in Cities. Accurately determining urban sprawl using existing GIS platforms has been challenging due to urban expansion through formal leases and informal purchases from local farmers. Both land types have houses, but one is legally acquired, while the other is not. The absence of clear urban growth boundaries in the selected cities further complicates the analysis. To address this, we collected ground truth data and overlaid it on satellite images to identify unregulated urban expansion. Although we have solved the problems, still there might be wrongly placed areas in the built-up maps of the cities. Therefore, we encourage readers to interpret the map with caution. The other limitation relates to the application of Shannon entropy model to detect urban sprawl in the selected cities. In this case, we have calculated only relative values of Shannon entropy, so the index provides only the relative distribution of built-up area rather than the absolute amount. Readers should keep this issue in mind while reviewing the research findings. Moreover, in the case of the allometric equation (model), a general equation was used; however, specific equations for each tree type should have been applied. Additionally, urban sprawl-based carbon sequestration was prepared for the year 2022, but estimations were also made for the years 1992, 2002, and 2012. These estimations may not be entirely accurate due to physiological differences among trees between years. Therefore, we advise readers to take care during using the data.

Conclusion

This research examined urban sprawl and its impact on carbon sequestration in cities located in southern part of Ethiopia (Shashemene, Hawassa, and Dilla) using satellite image analysis and field measurements. The findings revealed that these cities have experienced significant, non-linear changes in LULC and urban sprawl over the past 30 years (1992-2022). The rate of urban expansion into peri-urban areas and productive land uses varies spatially and temporally between cities. While built-up areas have continuously increased, the size of other LULC classes has decreased over the past three decades. Cultivated land (CL), forest land (FL), and agroforestry (AF) are among the land use types that have declined in size. Hawassa city exhibited the highest rate of urban expansion compared to Dilla and Shashemene, primarily due to its status as the former capital of the former Southern Nation, Nationalities, and People’s Region. Unregulated and unordered urban expansion is a common feature of these cities. In Hawassa and Dilla, urban expansion has occurred at the expense of permanent crops such as coffee and fruit trees, unlike in Shashemene, where flat cultivated lands are more readily available.

The LULC change analysis, along with quantitative data analysis for the period of 1992-2022, suggests the presence of urban sprawl in the selected cities of Hawassa, Dilla, and Shashemene. The quantitative data analysis further indicates that all the three cities are leaning toward a more dispersed form of urban development. This trend is evident from the values of Shannon’s entropy, which show a continuous increase in urban sprawl, leading to a more dispersed urban structure. These findings highlight the urgent need for effective plans and policies to manage these cities for sustainable growth and development. Urban sprawl has negatively impacted ecosystem services, particularly

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through the loss of vegetation cover. Between 1992 and 2022, a significant amount of CO_2 was released into the atmosphere - 41.6% of CO_2 in case of Shashemene - due to deforestation. This has contributed to a significant loss of carbon sequestration in the city. Maintaining urban forests has not been a priority in urban planning in Ethiopia in the past years. Furthermore, the presence of a weak legal and regulatory framework has resulted in inadequate development and managements of urban forests.

The ineffectiveness of urban land lease policy has also contributed to the occurrence of urban sprawl in cities. Additionally, the level of commitment from government and the public to halt land speculation appears weak. As a result, the policy has done little to address the existing practices of land speculators in the cities. This is the major gap that persisted in urban area for decades. Consequently, there is a shortage of land supply, inflated land prices, land hoarding/stockpiling, and nepotism, all of which continue to affect cities. These problems are among the main factors contributing to urban sprawl and undermine the collective efforts of the government and non-governmental organizations to promote regulated urbanization and healthy environments in cities. Establishing a strong urban growth boundary and effectively implementing it can help control urban sprawl in cities. Changing ineffective land acquisition rules, re-visiting urban lease policies, and plans, can assist in controlling, monitoring, and governing urban expansion and urban sprawl in cities. Capacity building, addressing resource constraints, and implementing techniques to increase the commitment of local government staff would improve the efficiency of urban land utilization, help address urban sprawl, and reduce carbon footprint of cities. Moreover, strongly establish and enforce urban growth boundaries to limit the outward expansion of urban areas without prior consideration in urban planning. In addition, promoting affordable and sustainable housing, strengthening land use and environmental protections, and engaging communities in controlling unregulated urban expansion are important practices that help manage urban sprawl in the selected cities.

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APPENDIX

Appendix 1. *Area coverage of LULC classes of the three selected cities*

LU classes	Dilla Town							
	1992		2002		2012		2022	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
AF	1145.57	53.54	952.39	44.51	1030.74	48.18	718.11	33.56
BU	407.94	19.07	688.18	32.17	868.23	40.58	1164.82	54.44
CL	586.01	27.39	498.95	23.32	240.55	11.24	256.59	11.99
Total	2139.52	100	2139.52	100	2139.52	100	2139.52	100
LU classes	Hawassa Town							
	1992		2002		2012		2022	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
AF	6605.1	41.38	6331.92	39.67	6121.2	38.4	5676.33	35.6
BU	1211.85	7.59	1634.16	10.24	4562.6	28.6	5568.36	35.0
CL	3750.03	23.49	2341.03	14.67	1873.89	11.70	1636.65	10.20
FL	464.22	2.91	1186.58	7.43	1057.59	6.60	873.09	5.47
WB	2877.21	18.03	2800.72	17.55	2346.03	14.70	2206.89	13.83
GL	1052.91	6.60	1666.91	10.44	0	0.00	0	0
Total	15961.3	100	15961.3	100	15961.3	100	15961.3	100
LU classes	Shashemene Town							
	1992		2002		2012		2022	
	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
CL	8818.73	68.22	9906.36	76.63	9545.46	73.84	7591.72	58.72
BU	1023.51	7.92	1633.65	12.64	2239.32	17.32	3962.58	30.65
FL	1078.83	8.35	734.9	5.68	746.58	5.78	630.1	4.87
GL	2006.53	15.52	652.69	5.05	396.24	3.07	743.2	5.75
	12927.6	100	12927.6	100	12927.6	100	12927.6	100

CL = Cultivated land, AF = Agroforestry, BU = Built-up area, VG (FL) = vegetation or Forest land, GL = Grazing land, WB = water body

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Appendix 2. *Assessment of User accuracy (%) and the Kappa coefficient for each city*

LULC Classes	Hawassa Town							
	CL	**AF**	**WB**	**FL**	**BU**	**Total**	**User's Accuracy (%)**	**Kappa Coeff.(%)**
CL	70	6	0	0	0	76	0.92	-
AF	2	77	0	5	0	84	0.92	-
WB	0	4	79	3	0	86	0.92	-
FL	0	0	3	64	0	67	0.96	-
BU	11	0	0	0	104	115	0.90	-
GL	10	0	34	11	126	120	0.93	
Total	83	87	82	72	104	428	0	-
Producer's Acc. (%)	0.84	0.89	0.96	0.89	1	0.00	0.92	-
Kappa Coeff. (%)	-	-	-	-	-	-	0.00	0.90

LULC Classes	Shashemene Town							
	CL	**BU**	**FL**	**GL**	**-**	**Total**	**User's Accuracy (%)**	**Kappa Coeff. (%)**
CL	83	0	0	4	-	87	0.95	-
BU	7	38	0	0	-	45	0.84	-
FL	6	4	65	0	-	75	0.87	-
GL	4	0	10	95	-	109	0.87	-
Total	100	42	75	99	-	316	0	-
Producer's Acc. (%)	0.83	0.90	0.87	0.96	-	0	0.89	-
Kappa Coeff. (%)	-	-	-	-	-	-	-	0.85

LULC Classes	Dilla Town							
	BU	**AF**	**CL**	**-**	**-**	**Total**	**User's Accuracy (%)**	**Kappa Coeff. (%)**
BU	52	5	2	-	-	59	0.88	-
AF	0	47	3	-	-	50	0.94	-
CL	2	4	37	-	-	43	0.86	-
Total	54	56	42	-	-	152	0	-
Producer's Acc. (%)	0.96	0.84	0.88	-	-	0	0.89	-
Kappa Coeff. (%)	-	-	-	-	-	-	-	0.84

FL = Forest land, GL = grazing land, CL = Cultivated land, AF = agroforestry, WB = water body, and BU = Built-up area

Appendix 3. *Built-up area expansion in the selected cities*

Years	Total area (ha)	Urban Population size	Built-up area change in Dilla city		
			Area of built-up (ha)	**Area of built-up (%)**	**Change in built-up area (ha)**
1992	2139.52	30087	407.94	19.07	-
2002		42403	688.18	32.17	68.70
2012		82035	868.23	40.58	26.16
2022		158800	1164.82	54.44	34.16

Year	Total area (ha)	Urban Population size	Built-up area change in Hawassa city		
			Area of built-up (ha)	**Area of built-up (%)**	**Change in built-up area (ha)**
1992	15961.3	45464	1211.85	7.59	-
2002		60508	1634.16	10.24	34.85
2012		95975	3168	19.85	93.86
2022		422200	4068.36	25.49	28.42

Year	Total area (ha)	Urban Population size	Built-up area change in Shashemene city		
			Area of built-up (ha)	**Area of built-up (%)**	**Change in built-up area (ha)**
1992	12927.6	39633	1023.51	7.92	-
2002		65463	1633.65	12.64	59.61
2012		115890	2239.32	17.32	37.07
2022		208400	3962.58	30.65	76.95

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