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# Assessing How Land-Cover Change Associated with Urbanisation Affects Ecological Sustainability in the Greater Accra Metropolitan Area, Ghana

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**Abstract:** Intensive land-cover changes (LCC) driven by unplanned urbanisation continue to threaten the sustainability of ecological assets in many cities in Africa. Evaluating the nature and processes of these changes is key to understanding the extent to which ecological instability may be affecting sustainability futures. This study employed integrated remote sensing, GIS, land accounting techniques and utilisation of high-resolution Quickbird and Worldview 2 images to analyse actual (2008–2017) and future (2017–2030) LCC and explored implications for ecological sustainability in the Greater Accra Metropolitan Area, Ghana. After mapping and classifying actual LCC, multi-layer perception (MLP) neural network and Markov chain were employed to predict future LCC for the year 2030. The results indicate that the built-up area increased substantially from 27% in 2008 to 46% in 2017 and is expected to rise to 73% by 2030. In contrast, open-space (10%), forestlands (5%) and grassland/farmlands (49%) decreased progressively (2008–2030). In effect, these land-cover types experienced area turnover >100% during the actual and predicted period, indicating high vulnerability of natural land cover to urban growth, ecological degradation and resource depletion. The se findings highlight significant implications of LCC for ecological sustainability in the study area. A proactive land-cover/use management plan is necessary to ensure sustainable urban development and ecological land conservation.

**Keywords:** land-cover change; ecological sustainability; remote sensing; geographic information system; land accounting; Quickbird and Worldview-2

## 1. Introduction

Intensive land-cover change (LCC) is one of the most important factors leading to increasing concerns over global environmental change and sustainability across many cityscapes [1,2]. The rate and intensity of LCC pose several sustainability challenges particularly related to ensuring ecological sustainability, resource availability and management. The loss of ecological assets through the processes of land-cover changes is driven by rapid population growth and spatial expansion of cities, among other socio-economic drivers such as technology development. The se factors lead to a decline in land-cover types with high ecological values, thereby thwarting their capacity to sustain livelihoods and the well-being of people [2,3]. Global changes in land cover due to population growth urbanisation and expansion of human settlements have been estimated to be 4.89% between 1992 and 2015 [2]. This has resulted in a significant decline in the estimated value of major ecosystem assets, including their services and resources, ranging from US$ 4.3 to 20.2 trillion per year globally [4].

Analysis, modelling and prediction of the dynamics of LCC through remote sensing and geographic information system (GIS) tools and techniques and the utilisation of satellite-based and ground-truth data provides fundamental information for a better understanding of spatial change and transformation processes and trajectories [3,5,6]. In sustainability debates, up-to-date information on LCC is particularly relevant for identifying areas of vulnerability where long-term ecosystem functions and biodiversity are important for sustainability [2,7]. The lost land is often that used for ecological assets which help ensure a sustainable environment [1,8]. Thus, LCC often leads to the destruction of ecological landscapes, loss of biodiversity, diminished land productivity, land degradation and a depletion of freshwater and forest resources. Sustainable land use implies that land-related resources should be exploited to produce goods and services in such a way that, over the long term, the natural resource base is not damaged and that future human needs can be met [9]. Changes in the ecological landscape through human-nature interactions, particularly the influence of the former on the latter are a good indicator for sustainability [10].

The availability of the biosphere's resources, ecosystems and services is an important guarantee for sustainability. Current trends of rapid spatial changes, however, have led to increasing appropriation and degradation of ecological systems, which potentially undermine their capacity to sustain food production and natural resources. Since land-cover represents the resource base of our ecosystem, the dynamics of LCC invariably leads to the conversion of a natural ecological system into a social ecosystem [5,11,12]. In the light of this, assessing the implications of past, current and future LCC for ecological change and sustainability is becoming increasingly necessary.

The literature has generally identified two components of LCC relevant for understanding the implications of landscape changes for ecological sustainability [12–15]. Firstly, recent studies of LCC have largely built on the consensus that the magnitude of quantitative changes in land-cover types can seriously compromise the sustainability of a particular ecosystem [5,16–19]. Such changes lead to desiccation of the land, which can affect the quantity of biodiversity. In the context of African cities, land conversion especially through rapid urban sprawl characterised by uncontrolled real estate development, incremental building of single-family homes, and inner-city redevelopment (i.e., densification through high rise building) are some of the critical contributory factors of quantitative LCC [20–22]. A second line of research has focused on understanding qualitative changes taking place within stable land-cover elements that are critical for the sustainability of ecological systems and communities [1,15,23,24]. The se include inter alia, the processes through which changes occur and the underlying mechanisms for ecosystem function and provision of services [13]. In the context of African cities, such processes can include population growth, urban farming, informal developments, waste disposal and encroachment onto wetlands among others [16]. The se two strands of thought collectively draw attention to the fact that changes in the functions, resources and services provided by ecological systems can occur through both quantitative and qualitative changes in land-cover types [13,25].

Within this context, urbanisation constitutes one among many important forms of land-cover changes in major fast-growing African cities such as the Greater Accra Metropolitan Area (GAMA), Ghana. During the last decade, a rapid increase in population has taken place in GAMA [26]. Accordingly, there is a growing demand for vacant undeveloped land for housing development [27]. Subsequently, rapid expansion of rural and urban built-up land areas as well as infrastructure construction have occurred across formerly vegetation areas [27,28]. The patterns and distribution of this spatial growth, characterised by unplanned, uncontrolled, scattered and sprawling built-up areas, exert tremendous pressure on the natural landscape. The conversion of the natural landscape towards built-up areas in GAMA underscore the influences of LCC on ecological balance. The higher the level of land cover and land use changes, the more destructive the effects on ecological sustainability. Consequently, spatio-temporal changes in land cover and the impacts on ecological assets, systems and potential resource deficiency risk have become subjects of great concern [29].

There is a lack of research regarding how current and potential changes in land cover affects ecological sustainability within the GAMA region. Currently, a few satellite-based remote sensing studies have analysed land-use/cover (LULC) change dynamics in GAMA [20,30–32], revealing that that forest, grasslands, agricultural land, water bodies and wetlands are being rapidly replaced by contiguous built-up areas. Up until now, research which targets analysis of quantitative and qualitative LCC to unravel the implications of such changes for ecological sustainability is still absent. The studies shown in references [20,30,31] have only warned, based on their findings, that ongoing spatio-temporal changes in LULC may lead to resource deterioration and consequently have significant impacts on ecosystem services. A comprehensive analysis of both current and potential future spatial patterns and processes of LCC to show how such changes will affect ecological balance and sustainability is urgently needed.

Building on our previous research [20], the present study aimed at bridging the gap in knowledge by primarily analysing, modelling and predicting the spatio-temporal dynamics of LCC and subsequently highlighting the key implications of the changes for ecological sustainability of the GAMA region. We address these research objectives by integrating remote sensing, GIS, land accounting techniques and utilisation of very high spatial resolution (VHSR) imagery for 2008 and 2017. After mapping past LCC, future LCC is predicted for 2030. The statistical data derived from actual and predicted LCC is utilised to construct a land cover account [25,33] in order to evaluate the processes of land consumption and formation, vulnerability and/or persistence and the turnover rates of changing ecological land-cover types. The se data will aid in exploring the key implications of actual and predicted LCC for ecological sustainability of the GAMA regions. The outcomes of this study are expected to provide information on the state of ecological degradation, which is critical for defining policies targeted at ensuring proactive land management and spatial planning for sustainable trajectories of urban development and ecological land conservation.

The context and rationale of this study forms a key component of the WaterPower project's in-depth research on the collision of mega-trends in a West African coastal city [34]. With the main aim of contributing to current debates on society-nature relations by mapping, analysing and understanding processes that unfold in the urban water sphere, the WaterPower project (01.04.2014–30.09.2019) explored the intersections and dynamics of urbanisation, urban land expansion, the (mis-)allocation of resources and climate change, drawing on the example of water scarcity in the coastal city of Accra.

## 2. Materials and Methods

### 2.1. Study Area

The study was conducted in the Greater Accra Metropolitan Area. It is geographically located on the South-East Coast of Ghana on the Gulf of Guinea, which forms part of the Atlantic Ocean. It extends from latitudes 5°5′27″ N to 5°28′2″ N and stretches between longitudes 0°4′58″ E to 0°37′2″ W (Figure 1). GAMA covers a total area of 1497 km$^2$ and houses the capital city of Ghana (Accra) and the country's most prominent seaport (Tema), making it the major economic and political hubof the country. It has experienced a rapid population growth due to natural increase and in-migration from other regions and the rural hinterland. Correspondingly, the area is characterised by a high population density with a population of 4.6 million people as of 2016 and an average growth rate of 3.5% per annum. Projected growth shows that by 2040, the population of GAMA will double to 10.5 million [35]. A direct implication of the foregoing is that the region will be under significant pressure to urbanise more in the coming years.

GAMA has experienced rapid outward urban built-up expansion, which has led to frequent conversions from different land-cover types. The landscape is generally characterised by undulating lowland with pockets of inselbergs. Ecologically, GAMA comprises coastal scrubs, grassland and mangrove swamp, as well as small portions of guinea savannah and moist semi-deciduous forest. All of these are currently being threatened by urban land expansion.

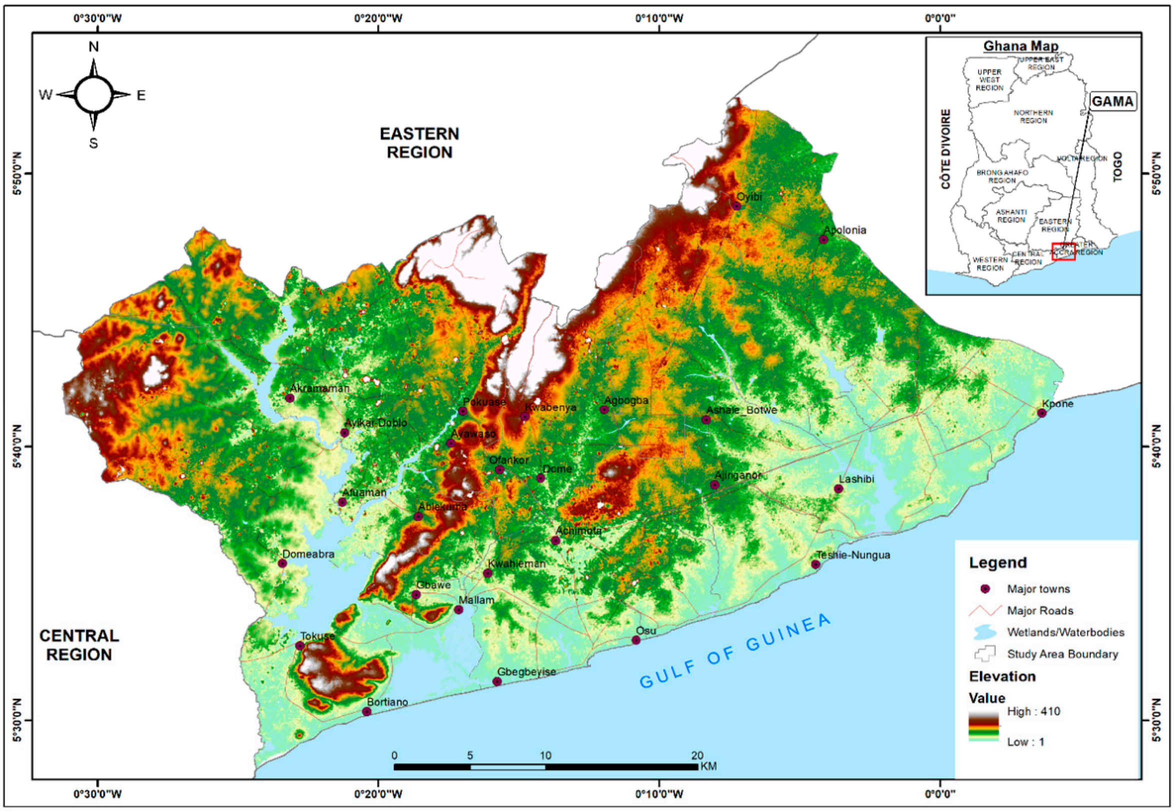



**Figure 1.** Study area location.

## 2.2. *Image Acquisition and Preproocessing*

DigitalGlobes's (now Maxar) Quickbird and Worldview-2 images were acquired for the study area from the European Space Agency (ESA). The se images were acquired as part of WaterPower project's work package, aimed at mapping and analysing urbanisation processes and their impacts on ecological systems in GAMA. The aforementioned images were requested for this study due to their high spatially-detailed information content which can help in overcoming the complexities associated with urban landscapes. Bearing this in mind, we placed an open order to the ESA for a cloud-free high resolution image and then supplied it with a region of interest (ROI) shapefile covering an area of 1495.07 km$^2$, the size of the study area. Following our request, a constellation of Quickbird and Worldview-2 images resampled at 1.5 meters' spatial resolution by the ESA were delivered in GeoTIFF format via a file transfer protocol (FTP) server from where the images were directly downloaded. The images comprised different image tiles captured by different sensors with slightly different acquisition dates. This is due to (1) unavailability of a complete VHSR image covering the study area and (2) the desire for cloud-free images that were acquired during the dry season (from November to April). The composite image with four spectral bands (blue, green, red, and near-infrared) for the two years consists of eight tiles of Quickbird + Worldview-2 for 2008 and seven tiles of Worldview-2 images for 2017. The specific dates on which images were acquired are presented in Table 1.

To remove distortions and errors produced during the imaging process, pre-processing techniques, both geometrical and atmospherical, were applied to all the images. The main image pre-processing applied in this study involves image mosaicking and homogenisation.

Due to the limitations of the imaging width or mechanism and the narrowness of sensors used to capture higher spatial resolution images [36], such as those acquired for this study, it was not possible to obtain a single image scene covering the full ROI. Thus, the multi-temporal and multi-sensor images (Table 1) were mosaicked into a single raster file covering the full ROI.

**Table 1.** Acquisition dates of the images of the time series.

| Year | Image ID | Sensor | Acquisition Date |
|---|---|---|---|
| 2008 * | P001 | Worldview-2 | 12/January/2008 |
| | P002 | Worldview-2 | 12/January/2009 |
| | P003 | Quickbird | 15/December/2008 |
| | P004 | Quickbird | 09/March/2009 |
| | P005 | Quickbird | 15January/2008 |
| | P006 | Quickbird | 31/January/2008 |
| | P007 | Quickbird | 18/February/2008 |
| | P008 | Quickbird | 26/January/2008 |
| 2017 * | P001 | Worldview-2 | 23/March/2017 |
| | P002 | Worldview-2 | 23/March/2017 |
| | P003 | Worldview-2 | 01/January/2017 |
| | P004 | Worldview-2 | 17/January/2017 |
| | P005 | Worldview-2 | 17/January/2017 |
| | P006 | Worldview-2 | 17/January/2017 |
| | P007 | Worldview-2 | 17/January/2017 |

* Image size—number of pixels per columns and rows: 2008 (43922, 30309), 2017 (44043, 30232).

Although the delivered images were already ortho-rectified, geometrically corrected and geo-referenced in the Universal Transverse Mercator (UTM) projection by the ESA before delivery, it was found out after mosaicking that the two different years of images had different dimensions, i.e., the number of columns and number of rows were not the same as can be seen from Table 1. To correct this, image-to-image co-registration [37,38] was performed using a register raster tool. In this process, the 2008 mosaicked image was used as a reference (base) to which the 2017 image was aligned. In addition to the 2017 image metadata including an off-nadir angle (0–25°) and cloud cover (0%), the 2008 image was referenced with a sample of 12 evenly distributed ground control points (GCPs) across the study area. GCPs such as highway intersection and road junctions were collected using Collector for ArcGIS. The se GCPs were collected because they are typically static features that have a defined location that can easily be recognised in both the 2008 and 2017 mosaicked images. Once the 2008 image was adequately referenced, it was used to rectify the 2017 image based on a polynomial function to achieve a uniform pixel dimensions.

Although most remotely sensed images are expected to undergo a primary task of atmospheric correction before classification and change detection, the correction for atmospheric effects in this study was considered unnecessary prior to image classification because the spectral signatures (training sites) characterising the desired land cover classes were derived from the same images for each year. As noted by Song et al. [39], as long as class training data is derived from the same image being classified, atmospheric correction is unnecessary for change detection based on classification of composite imagery in which multi-date images are rectified and spatially registered from different dates.

Given that the VHSR images were acquired by different multispectral sensors for both years, image homogenisation was required to reduce both spectral and geometric differences of the images. The procedure not only allows for direct comparison of the images acquired by the different sensors but also reduces change detection errors [40]. To ensure coherence among the different image tiles, a colour balancing technique [41] was initially used to minimise differences in visual appearance after mosaicking the images. This technique, however, did not yield perfect results since differences in image appearance were still visible. Thus, the first of the two-step image homogenisation approach presented by Solano-Correa et al. [40] was considered. The approach addresses radiometric, spectral and geometrical differences by extracting physical features that account for homogeneous areas and correspond to the land-cover classes that have been identified from the acquired images. The second step which involves change vector analysis (CVA) of spherical coordinates is often adopted where multiple changes in magnitude and direction variables are automatically separated by means of features that guarantee homogeneity across the different sensors.

*2.3. Image Segmentation and Classification*

An object-oriented image classification method was applied to classify the image data for the years 2008 and 2017 (see [20]). In this approach, the mosaicked images for each year were imported into eCognition and segmented based on a multi-resolution segmentation algorithm [42]. This was done to ensure spectral homogeneity across the images. The delineated spectrally homogenous polygons were combined with a set of training samples (objects) representing geographic features of the physical landscape to digitise the images (training) to the desired land cover categories. This exercise was reinforced by ground-truth data, the researchers' experience, physiographical and local knowledge of the study area.

The next major step after segmentation was classification and editing. Based on the derived segmented objects and ground-truth vector data, the image for both years were classified into five (5) main land-cover classes: open-space, forestland, grassland/farmland, urban built-up area and water bodies/wetlands. The delineation of these five land-cover classes was based on the internationally accepted Corine land-cover classification scheme [25].

Following classification, editing and reclassification was executed on the classified image output. This was an optimising task, executed by editing segments/polygons (objects) that may have been erroneously misclassified and re-assigning obvious objects to the land-cover classes they belong. This process was achieved by overlaying the exported shapefile on the respective images. The shapefile was then set in ArcGIS to have a transparent value of 70% so that the particular image could be seen below it. The final reclassified image output was then dissolved under the different land-cover classes to reduce the total number of segments.

Finally, a classification accuracy assessment was carried out for both 2008 and 2017 land cover maps based on Google Earth data (2008) and ground truth data (2017). A sample of 533 points were mapped from Google Earth images for the 2008/2009 image constellation and 754 ground-truth points and polygons were used to evaluate the 2017 classified image. The overall accuracies and Kappa for the extract land-cover maps of 2008 and 2017 were 92.5% (Kappa: 0.89) and 95.1% (Kappa: 0.93) respectively [20]. The se accuracy results indicate the suitability of the classified images for effective and reliable land-cover change analysis.

*2.4. Land-Cover Change Modelling and Prediction*

Predicting LCC is an effective way of gauging sustainability trajectories, which is deemed relevant for informing planning and environmental management interventions in order to ensure long-term ecological restoration continues to conform with sustainability goals. This study adopts Land Change Modeler (LCM) in Idrisi TerrSet to model and predict the LCC of the study area for the year 2030. LCM is an integrated geospatial monitoring and modelling software application for analysing past LCC, modeling the potential for change, predicting the course of change into the future and evaluating planning interventions for maintaining ecological sustainability [43]. The choice of this tool in this study rests on its capability in binding the strengths of statistical and spatially explicit models such as Markov chain to simulate dynamic spatial phenomena and particularly future LCC prediction based on their current state and potential driving factors. The resulting outputs are useful for inter alia, statistical constructions that are key to assessing ecological sustainability [43,44].

To setup the LCM model, we firstly imported 2008 and 2017 land-cover maps respectively as the base maps (input data). Secondly, we developed a transition potential sub-model (TPSM) using the multi-layer perceptron (MLP) neural network tool. A TPSM may consist of a single or group of land cover transition(s) that are presumed to have the same underlying driver variables. For the purposes of this study, four main transition potential maps were considered to determine the status of future LCC in the region. The se include open space to urban built-up, forestland to urban built-up, grassland/farmland to urban built-up and water bodies/wetland to urban built-up. In addition, two biophysical (slope and elevation) and three proximate (distance to built-up areas, distance to nearest roads and highways, and distance to water bodies) driver variables were used to model the change process and compute the transition potential map. The selection of these variables was informed by a literature review of similar studies [44]. Input vector data on urban built-up areas were derived from previously classified 2008 and 2017 land cover maps. The road network, stream, elevation (digital elevation model) and slope datasets covering the study area were computed from topographical sheets (obtained from the Survey Department, Accra-Ghana) and Google Earth maps.

Based on the prepared actual land-cover maps and TPSM, the Markov chain model within TerrSet was employed to predict the future LCC of the study area. Markov chain is a stochastic model widely used for quantifying the probability of land-cover change from current state to a future state [44]. The model calculates both quantities of conversion and rates of transfer among various categories of land-cover types. This process then estimates the precise quantum of land that would change from the base year to the specified prediction year based on the projected TPSM derived from the MLP neural network tool. Predicting the LCC is calculated as in Equation (1):

$$S(t+1) = P_{ij} \times s(t) \tag{1}$$

where $S(t)$, $S\ (t + 1)$ represent the status of the phenomenon or system at time $t$ or $t$ +1; $P_{ij}$ is the transition probability matrix in a state evaluated as in Equation (2):

$$P = P_{ij} = \begin{bmatrix} P_{11} & P_{12}\ldots & P_{1n} \\ P_{21} & P_{22}\ldots & P_{2n} \\ P_{n1} & P_{n2}\ldots & P_{nn} \end{bmatrix}, (0 \le P_{ij} < 1 \text{ and } \sum\nolimits_{j=1}^{N} P_{ij} = 1, (i,\ j = 1, 2, \ldots\ldots n) \tag{2}$$

where $P$ is the Markov transition matrix, $i$, $j$ is the LULC type in the first and second time, $P_{ij}$ denotes the probability of LULC type $i$ to change into type $j$, and $N$ refers to the number of LULC categories in the region. To validate the model and evaluate its reliability in predicting LCC for the projected year, 2030, the actual LCC maps for the years 2008 and 2017 were compared with the projected map for the same years. The 2030 predicted LCC map was evaluated using the validation module in LCM. This utilised a three-way cross-tabulation algorithm between the earlier land cover map (2008), the map of reality (2017) and the prediction map (2030). The output map, which portrays the quality and accuracy of the model, showed (a) areas which were correctly predicted, called *hits*, and (b) areas which appeared as predicted change but in reality did not change, called *misses*. Statistical assessment of the validation process between the actual and predicted land-cover map yielded a Kappa coefficient of 0.84—inferring a strong confidence [43] in our predicted 2030 map.

### 2.5. Land-Cover Change Detection Analysis

Post-classification change detection was performed in eCognition and ArcGIS 10.7 to deduce the temporal patterns of changes in land cover from 2008 to 2017 and 2017 to 2030. This was based on the computation results derived from segmentation, visual interpretation and subsequent classification of images for the study periods. The quantitative information generated from the classified images for the years 2008, 2017 and 2030 was used as input data to develop a land-cover account for the qualitative analysis of land-cover changes.

### 2.6. Land-Cover Accounting

The land-cover accounting technique, developed by Heines-Young and Weber (European Environmental Agency [25]), was employed to understand the qualitative characteristics and processes of actual and predicted LCC. A land-cover account is an ecological accounting tool which facilitates a better understanding of how changes in land-cover types may affect the integrity of natural resource systems and hence the output for measuring ecological sustainability [25,33]. For the purposes of this study, land 'stocks' and 'flows' were created by analysing and quantifying all the possible transitions between the five different land-cover classes. The processes are based on the determination of land loss and land gain (i.e., consumption and formation) to other land-cover types over a period of time.

Consumption expresses a loss in the area of a particular land-cover class to another whilst formation connotes a gain in area for a particular land cover class from other land-cover class(es) within the accounting periods (2008–2017 and 2017–2030). The constructed land-cover accounts shown in Tables 2 and 3 presents the initial losses of each land-cover type—labelled consumption (shown at the top of each table)—and the gain of new areas—labelled formation [13,25]. Addition of total area of consumption and the total unchanged area (i.e., 2008–2017 or 2017–2030) gives an estimate of the initial stock of each land-cover type obtained in each case. In addition, when the new area gained (formation) is added to the area that remain unchanged, the total amount of the final stock is produced. The difference between area consumed and area formed gives the net changes in each land-cover type. In relative terms, net changes (formation-consumption) are expressed as a percentage of the initial stock in the base year for each period, i.e., 2008–2017 and 2017–2030. The se processes of change show how the area loss is compensated for by area gained in the case of each land-cover type.

From the perspective of understanding whether changes in land cover over time and space affects ecological sustainability, the total amount of land turnover, also given in Tables 2 and 3, is as important as the net change. The output for land turnover is considered the key indicator for understanding the ecological sustainability of a given region [25,42]. In absolute terms, it is the summation of changes resulting from area loss and area gain (formation + consumption) between the initial and final year. In relative terms, the rate of land turnover is expressed as a percentage of initial stock that is lost or gained. A high turnover connotes intensive landscape transformation, which is also an indication that ecological land-related assets (such as biodiversity, ecosystems, habitats) are unstable and thus vulnerable to degradation [25]. On the other hand, the persistence of landscape pattern and processes implies such land-related assets have low turnover and are thus expected to persist, i.e., not susceptible to change indefinitely into the future [18]. Concerns about turnover land, and particularly the implications that it might have for ecological systems such as biodiversity, habitats, etc., are of critical importance from a policy perspective [33,45].

**Table 2.** Land-cover account for GAMA, 2008–2017.

| | **Open Space** | **Forest Land** | **Grassland /Farmland** | **Urban Built-Up Area** | **Water Body /Wetland** | **Total** |
|---|---|---|---|---|---|---|
| Land-cover, 2008 (km$^2$) | 155.1 | 181.56 | 713.02 | 411.45 | 35.94 | 1497.07 |
| Consumption of initial land-cover (km$^2$) | 136.83 | 102.69 | 367.75 | 51.04 | 6.95 | 665.26 |
| Formation of new land-cover (km$^2$) | 53.38 | 106.13 | 173.47 | 328.66 | 3.62 | 665.26 |
| Net Formation of land-cover (formation − consumption) (km$^2$) | −83.45 | 3.44 | −194.28 | 277.62 | −3.33 | 0.00 |
| Net formation as % of initial year | −53.80 | 1.89 | −27.25 | 67.47 | −9.27 | −20.95 |
| Total turnover of land-cover (consumption + formation) (km$^2$) | 190.21 | 208.82 | 541.22 | 379.7 | 10.57 | 1330.52 |
| Total turnover as % of initial year | 122.64 | 115.01 | 75.91 | 92.28 | 29.41 | 435.25 |
| No land-cover change (km$^2$) | 18.27 | 78.87 | 345.27 | 360.41 | 28.99 | 831.81 |
| No. of LCC as % of initial year | 11.78 | 43.44 | 48.42 | 87.60 | 80.66 | 271.90 |
| Land-cover, 2017 (km$^2$) | 71.64 | 185.01 | 518.73 | 689.07 | 32.62 | 1497.07 |

**Table 3.** Predicted land-cover account for GAMA, 2017–2030.

| | Open Space | Forest Land | Grassland /Farmland | Urban Built-Up Area | Water Body /Wetland | Total |
|---|---|---|---|---|---|---|
| Land-cover, 2017 (km$^2$) | 71.64 | 185.01 | 518.73 | 689.07 | 32.62 | 1497.07 |
| Consumption of initial land-cover (km$^2$) | 70.36 | 145.28 | 347.37 | 17.02 | 5.56 | 585.59 |
| Formation of new land-cover (km$^2$) | 5.83 | 59.73 | 94.75 | 425.13 | 0.15 | 585.59 |
| Net Formation of land-cover (formation−consumption) (km$^2$) | −64.53 | −85.55 | −252.62 | 408.11 | −5.41 | 0.00 |
| Net formation as % of initial year | −90.08 | −46.24 | −48.70 | 59.23 | −16.58 | −142.37 |
| Total turnover of land-cover (consumption + formation) (km$^2$) | 76.19 | 205.01 | 442.12 | 442.15 | 5.71 | 1171.18 |
| Total turnover as % of initial year | 106.35 | 110.81 | 85.23 | 64.17 | 17.50 | 384.06 |
| No land-cover change (km$^2$) | 1.28 | 39.73 | 171.36 | 672.05 | 27.06 | 911.48 |
| No. of LCC as % of initial year | 1.79 | 21.47 | 33.03 | 97.53 | 82.95 | 236.77 |
| Land-cover, 2030 (km$^2$) | 7.11 | 99.46 | 266.11 | 1097.18 | 27.21 | 1497.07 |

Table 3 presents the stock and change account for predicted land-cover between 2017 and 2030.

## 3. Results

This section presents outputs of LCC analysis as well as the land stock and flow account which highlight how land was transferred or exchanged between the different cover categories. This is particularly useful in answering some of the key questions that arise in the context of sustainability. Figure 2 below shows land-cover maps derived from classified images for the years 2008 and 2017 and land-cover change prediction modelling results for 2030.

Figure 3 below illustrates the spatial area distribution of the land-cover types identified in the study area. Grassland/farmland was the dominant land-cover type as of 2008, whilst the built-up area increased by 277 km$^2$ (67%) within the time period. This increase was largely due to the conversion of 83 km$^2$ (54%) of open space and 194 km$^2$ (27%) of grassland/farmland. Furthermore, the area of forestland and water body/wetland increased and decreased slightly by 5%. According to the predicted LCC distribution between 2017 and 2030, urban built-up area is likely to experience an increase of 408 km$^2$ (59%). On the contrary, open space, forestland, grassland/farmland and water body/wetland may decrease by 65 km$^2$ (90%), 86 km$^2$ (46%), 253 km$^2$ (49%) and 6 km$^2$ (17%), respectively.

The Sankey diagrams in Figure 4a,b below were used for visualising the size and direction of land-cover stocks and flows. The stacked bars represent the relative stocks or size of the land area of each cover category in 2008, 2017 and 2030, as shown in Figure 3. The height of each cover category in the vertically stacked bars is proportional to the relative stock of the represented land-cover category in the study area, and categories are also arranged vertically by spatial extent, from largest on top to smallest at the bottom (Figure 4a,b). The slightly darker shade of colour in the diagram represents transition lines for each land-cover category. Thus, Figure 4a,b [20] illustrate transitions showing the extent of each land-cover category as well as the size and change trajectories of the five land-cover categories.

As depicted in Figure 4a, between 2008 and 2017 the extent of grassland/farmland declined from 713.02 km$^2$ to 518.74 km$^2$. The area covered by grassland/farmland transformed mainly into urban built-up area (239.04 km$^2$) and forestland (90.11 km$^2$). Despite this net increase, the area forestland had been converted. As much as 72.60 km$^2$ and 26.61 km$^2$ of forested area transitioned to grassland/farmland and urban built-up area respectively. Thirdly, the area covered by open space reduced substantially. About 65.02 km$^2$ of open space transitioned to grassland/farmland, whilst 60.78 km$^2$ were converted to urban built-up area. The obvious increase in urban built-up area is largely due to the conversion of grassland/farmland (239.04 km$^2$), open space (60.78 km$^2$) and forestland (26.61 km$^2$). Quite interestingly, a total area of 50.9 km$^2$ of urban built-up area transitioned into grassland (34.08 km$^2$), open space

(11.51 km$^2$) and forestland (5.29 km$^2$). Finally, although two-thirds of the water body/wetland area remained unchanged, a marginal extent (2.23 km$^2$) transitioned into urban built-up.

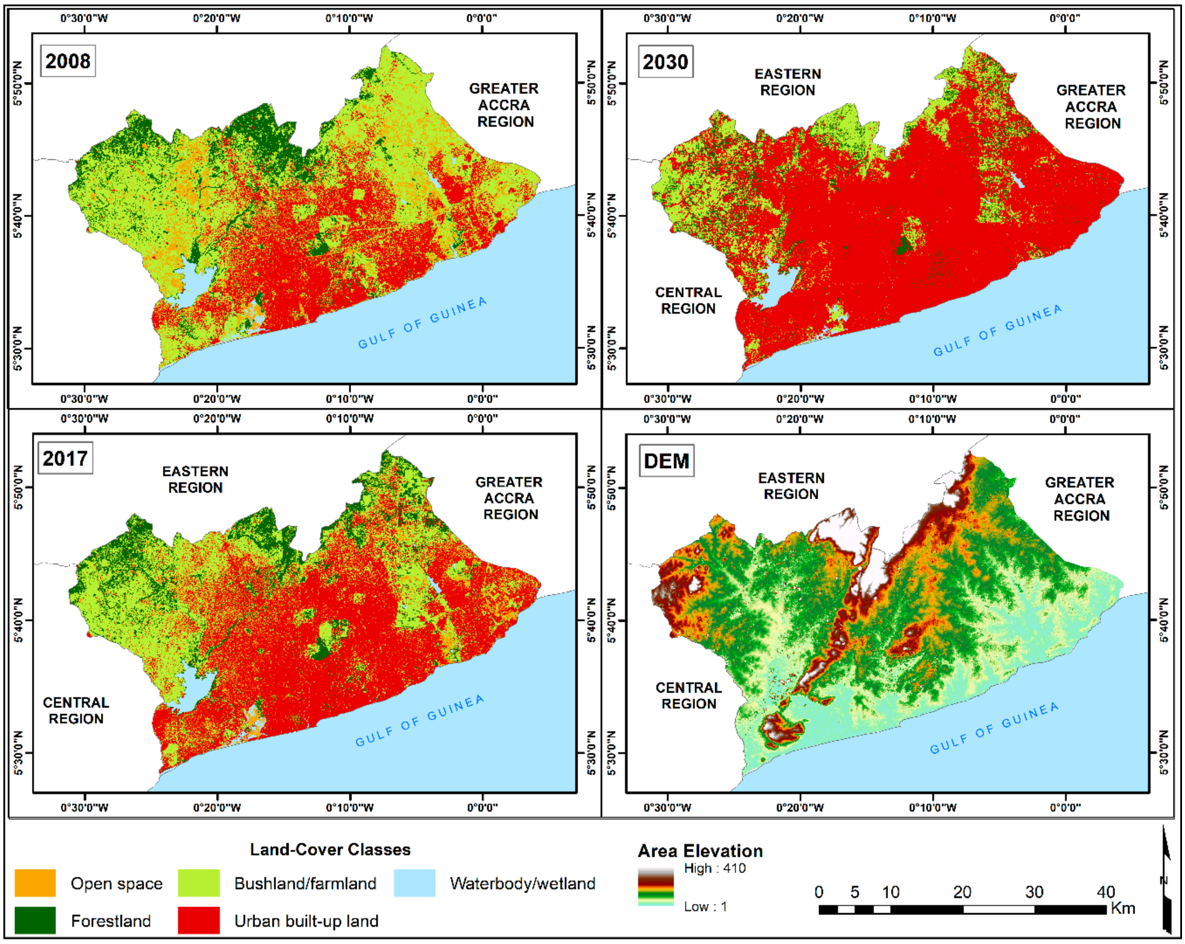



**Figure 2.** Actual land-cover maps for the years 2008 and 2017, predicted land-cover map for 2030 and elevation map of GAMA.

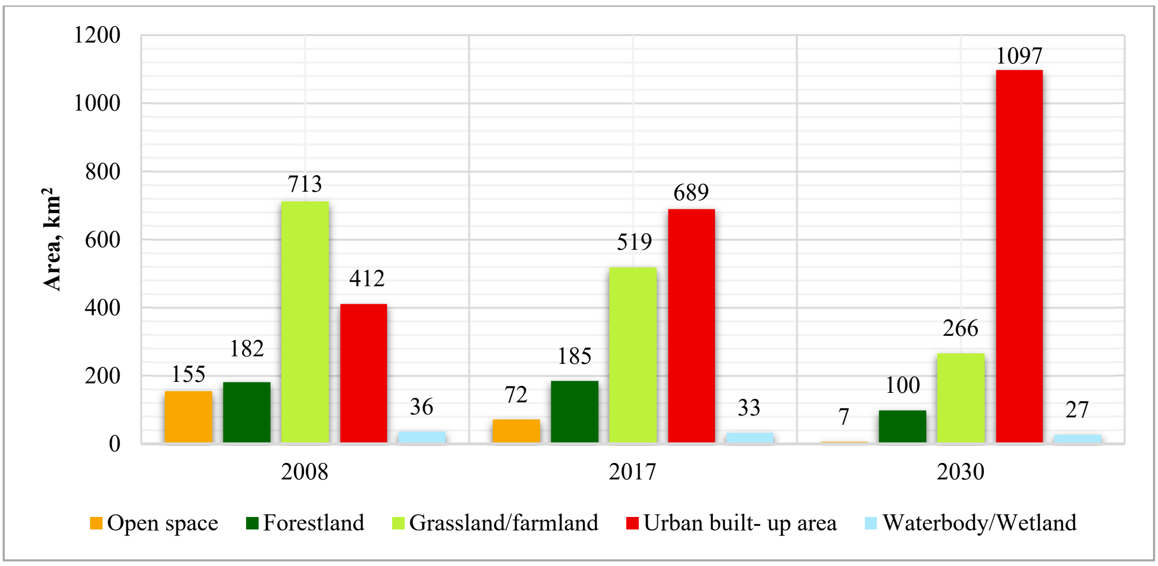
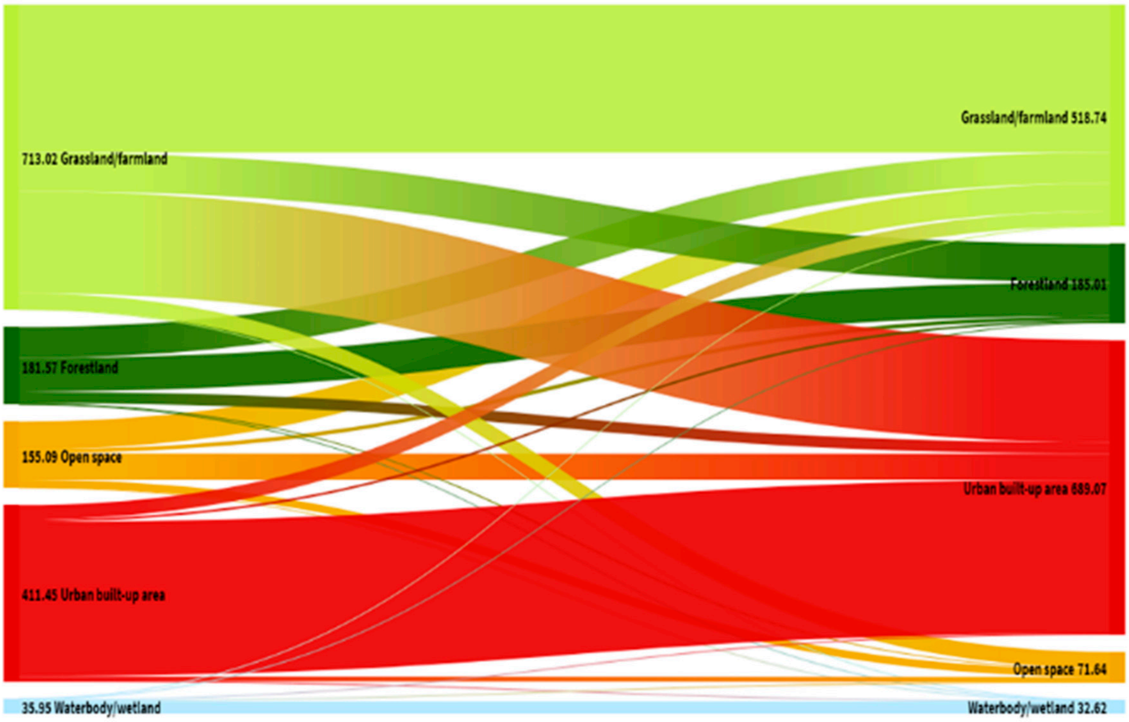
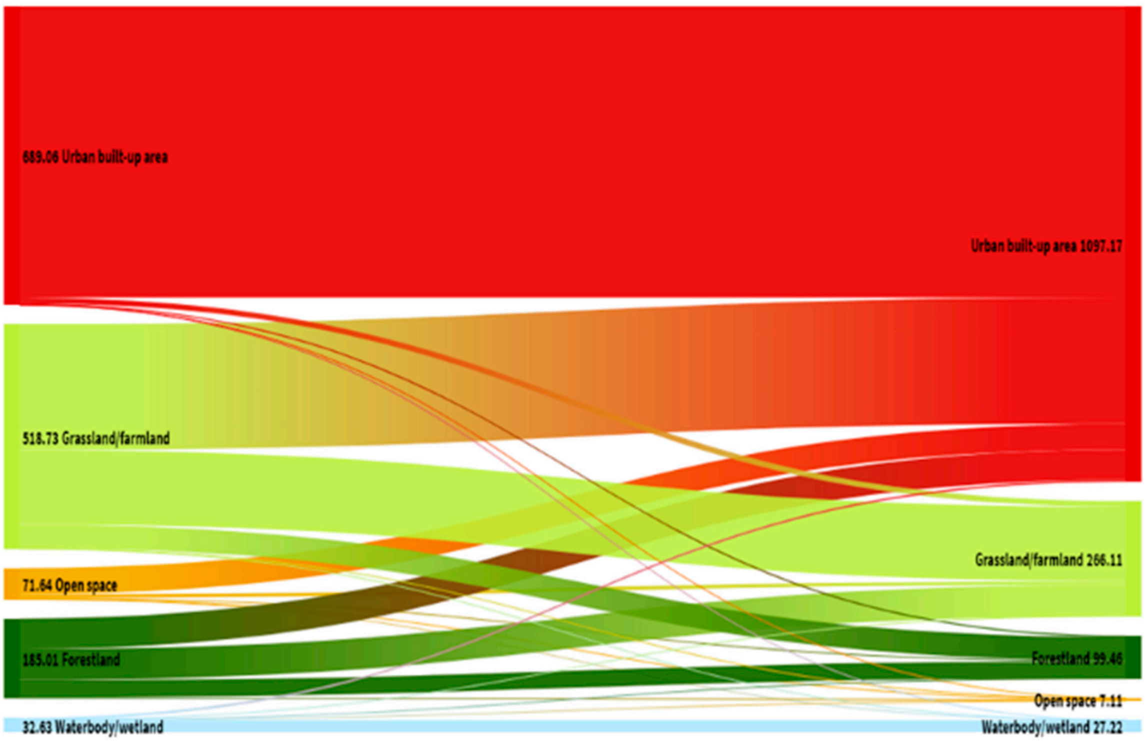



**Figure 3.** Estimated area of each land-cover class for the years 2008, 2017 and 2030.




(**a**)




(**b**)

**Figure 4.** Land-cover transition from one class to another. (**a**) Land-cover transition from one class to another (2008–2017) [20]. (**b**) Land-cover transition from one class to another (2017–2030).

Figure 4b illustrates how the predicted land-cover transitioned from 2017 to 2030. It is observed that urban built-up may expand by 408.11 km$^2$. This can be attributed mainly to the conversion of

290.77 km$^2$ of grassland/farmland, 70.29 km$^2$ of forestland, 59.79 km$^2$ of open space and 4.28 km$^2$ of water body/wetland. It is also interesting to note that by 2030, 71.89 km$^2$ of forestland and 13.65 km$^2$ of open space may transition into grassland/farmland. Overall, the results give an indication that between 2017 and 2030, rapid urban expansion may occupy a large area of ecological lands.

Having identified the dominant patterns of land-cover transitions across the study area, it was important to assess whether the consumption or loss of a given land-cover type is compensated for by the formation of new areas of the same type. This effectively presents information on land-cover persistence and vulnerability over time and space.

From Table 2, it can be observed that quite a substantial stock of most ecological land-cover types in 2008 was largely converted to urban built-up area as of 2017. It is interesting to note, however, that although open space, grassland/farmland and water body maintained some proportion of their original stock and also gained additional area, the proportion of the original stock that was consumed in each case were not compensated for by the formation of new areas. On the contrary, the original stock of forestland and urban built-up area that was lost from 2008 were fully compensated for in 2017. A marginal net formation and a much larger proportional increase in forestland and urban built-up area were observed. The importance of net formation is emphasised by the total amount of turnover for each land-cover type. The analysis of turnover revealed that with the exception of water body/wetland recording a low turnover, all the other land-cover types recorded relatively high turnover, implying the vulnerability of such land-cover types.

From the data, the area stock recorded for open space, forestland, grassland/farmland and water body/wetland in 2017 may decrease by 2030. As can be seen, the area stock each of these land cover categories may gain during the period might not be compensated for at all by 2030. In terms of stock turnover, open space and forestland may record a little over 100%, constituting a very high turnover. With a turnover of 85%, the farmland/grassland category is also expected to experience a relatively high stock turnover. The se expected turnover rates are an indication of the high vulnerability of these land-cover categories. All things being equal, the water bodies and wetlands category may experience a relatively low stock turnover (17%), indicating relative resistance to change.

Overall, the results reveal that ecological land cover lost a greater proportion of area compared with built-up land. Similarly, the changes experienced over the last decade are likely to continue into the future whereby urbanisation and urban growth may increase in GAMA by 2030. This suggests that as urban and rural settlements grow, the quantum of built-up areas increases. In constrast, ecologically significant land areas decrease, i.e., total land area – built-up area. Overall, the spatial distribution patterns of the predicted LCC are in accordance with the fact that the majority of current and future urban growth is concentrated around and expanding upon ecological areas.

## 4. Discussion

This study was initiated to examine how the magnitude and dynamics of LCC affect ecological sustainability in the GAMA city region. The analysis of land-cover data in this study has generated detailed quantitative and qualitative information that is particularly useful for understanding the impacts of LCC on the ecological condition and sustainability of the urban environment.

### *4.1. Dynamics of Land-Cover Change*

The dynamic changes of actual (2008–2017) and predicted (2017–2030) land-cover classes as presented above indicate that built-up land has rapidly increased and the probability of future increases is extremely high. It is observed that urban built-up areas are expanding rapidly into areas covered by natural land cover. This suggests that ecological support systems including biodiversity, natural resource reserves, freshwater, croplands and other natural ecosystem services and functions which provide goods and services essential for human survival are being destroyed and depleted through urbanisation and urban growth processes. The se findings tally with what previous studies [26,30,31] have independently reported. In sum, these studies showed that natural vegetative cover, ecosystems and resources are being degraded and lost mainly due to high urbanisation and urban growth in the area. The confluence of these findings point to the fact that the ability of ecological systems to sustain resource needs of future generations in the GAMA city region may be under threat.

The results shown by the land-cover accounts (Tables 2 and 3) reveal significant imbalances (i.e., negative net formation) between the land-cover classes, whereby the consumption of ecological land covers were not fully compensated for by formation. First, it is important to note that the area covered by water bodies/wetland recorded high persistence (81%) between 2008 and 2017, indicating relative stability (i.e., low turnover of ~29%). This is quite surprising, particularly because areas covered by water bodies/wetlands have been subjected to serious encroachment due to high pressure for housing and other developments [28]. Nevertheless, it is worth noting that whilst some water body/wetland areas may be drained and built upon, it is reasonable to assume that much of such areas cannot be converted unless rivers are all channeled into tunnels. Contrary to the foregoing, open space and grassland/farmland show moderate vulnerability (i.e., susceptible to urbanisation) due to the relatively high area stock turnover recorded between 2008 and 2017. It is quite disturbing to note that forestland may experience even higher vulnerability if the predicted future LCC between 2017 and 2030 proves to be realistic as per the relatively high stock turnover recorded for that category. It is also worth noting that the persistence or stability of the water body/wetlands area as revealed between 2008 and 2017 may be sustained during the predicted 2017–2030 period. This simply suggests that areas covered by water bodies and wetland might not be susceptible to development in the future. This affirms the increased land turnover rate observed between 2017 and 2030, which further gives an indication that most of the area covered by ecological land-cover will have declined, if not have been completely lost, by 2030.

The analysis of stock and flows from the land cover accounts underscores two fundamental issues. Firstly, the stocks (i.e., quantitative change) reflect the configuration of land-cover complexes in a typical African city where the disconnect between capital and labour is seen as significantly shaping the transformation of cities. From the lens of southern urbanism, Schindler [46] noted that the inability of the formal sector especially to absorb labour power through industrialisation has led to a profound landscape transformation of the cities in the South. In line with this, the findings of this study and other studies gives a distinct picture of how the natural landscape of the GAMA region is currently undergoing massive spatial transformation in response to meet the growing demand for housing, infrastructure, resources and social service needs of the ever-increasing urban population.

Secondly, the quantum of transitions between land stocks and flows (Figure 4a,b) may be highly contested due to competition from different land-cover categories (i.e., qualitative change). This competition develops according to the processes of change taking place in the GAMA region where intensive land uptake by urban development and new economic, industrial, and commercial sites and infrastructures results in dynamic flows that are often contested, rerouted and sometimes even blocked. This may explain some of the hidden underlying reasons for the everyday lived realities of the study area such as encroachment of water bodies/wetlands and semi-natural vegetated areas by informal and unregulated housing development. Such land uptake from natural areas may be courting decreased ecological potentials of already complex land systems. This raises concerns in relation to questions of sustainability when debates of maintaining an appropriate level of ecological capital are important. That being said, it is important to note that the processes underlying land-cover flows (i.e., qualitative change) are not politically neutral and have implications for unplanned and uncontrolled development across the region.

These findings provide insights regarding the impacts of population and spatial growth on the natural environment, which is widely acknowledged by several other scientific studies on LCC [6,8,29,47,48]. For instance, Attua [29] noted that tropical regions are experiencing the fastest land-cover transformations, involving the loss of forest and other natural ecosystem assets. Tetteh [49] also noted that the growth of Accra encroaches into ecologically sensitive and vulnerable natural areas. This also resonates with the predictions by Elmqvist [8] that urbanisation and urban growth in the coming decades may likely modify land-cover primarily by converting farmlands, forests, and savannas, reducing the area and other ecosystems of natural habitats, affecting ecosystem functioning and contributing to the loss of biodiversity. All of these findings raise important questions about ecological sustainability vis-a-vis the growth trajectory of cities.

### 4.2. Implications of Changing Patterns of Land Cover for Ecological Sustainability

From Section 4.1, the understanding of these dynamics is critical in unpacking the contemporary LCC problem space of GAMA and other similar cities of the Global South. Knowing and understanding the problem space can help unravel the different implications needed for ecological sustainability. As noted earlier, GAMA, like many other city regions in Sub-Saharan Africa, is confronted with a major challenge of making a "just transition" [50]. For ecological sustainability, the case of GAMA draws attention to a number to key implications.

Firstly, the findings of this study deepen the ongoing debate towards finding solutions to landscape sustainability [5,18,51,52], which involves questions pertaining to whether changes in land-cover dynamics driven by urbanisation and urban growth processes are compatible with the goals of sustainability. The findings of this study demonstrate a looming tipping point where ecological assets may not be able to sustain future generations. In view of this, it is necessary to have knowledge of where resource decreases are occurring if the overall implications of land-cover changes are to be fully understood. In this way, natural resource capital associated with land cover may be monitored and tracked to ensure that the extent of exploitation is compatible with the goals of sustainability.

Given the rates and magnitude of spatial LCC and, most importantly, loss of ecological assets, it is imperative for local governments to control urban growth and define critical thresholds for natural resource exploitation by improving inventorization of natural land cover through land change accounting. Within this context, land-cover accounts, such as those presented by this study, are quite useful to guide policy development and the remedial measures required to achieve resource sustainability. As discussed by Haines-Yong [13], the nature and magnitude of quantitative changes in an area of a particular land-cover type and the qualitative changes within land-cover elements are fundamental to determining the ecological sustainability. However, thresholds in guiding decision-making processes are particularly limited. Though such thresholds can be subject to revisions, they may nonetheless help in detecting critical tipping points of ecological assets.

Additionally, through threshold analysis, specific governance strategies for each stock type can easily be identified. Understanding how the qualitative characteristics of resources might be potentially affected by the processes of LCC can inform a range of targeted land-related policies designed to encourage positive change or to discourage an undesirable change in the context to conform with the goals of sustainability. Governance strategies could range from local government planning targeted at urban densification to sustainable management and governance of common urban ecological resources as well as conservation initiatives. Regulating and/or restricting rapid urban expansion into vulnerable ecological areas may be critical for ensuring ecological sustainability. Considering the dynamic nature of the land-cover stocks and flows, some areas of particular ecological significance may need to be conserved by relevant legislations. In addition, an integrated approach to sustainable ecological resources management through adaptive governance [53] strategies will be essential to safeguard ecological sustainability. Particularly, the data and information on land-cover turnover open up questions as to whether the process of change is consistent with the goals of sustainable forms of development. This is an important concern raised in recent contributions to adaptive governance debates arguing for transformative processes underlying sustainability.

The analyses and findings of this study underscore critical human-environment interactions advanced within the WaterPower project to explicate the relationship between biophysical and ongoing socio-environmental processes in Accra and the high threat being posed to the sustainability of the coastal environment. Given the complex and dynamic role that water plays as a natural resource within the wider context of rapid uneven urbanisation and environmental change, it may offer an entry point for understanding the sustainability of ecosystems and socio-economic systems. Particularly in view of the widening gap between science and policy, we contend that an integrated approach is needed to preserve ecological systems such as coastal wetlands and river systems. A sustainable urban metabolism requires that the complex interactions between human and environmental systems and between technology and society must be kept in balance. This will contribute to addressing critical urban-land challenges geared towards achieving resource security and sustainability [34].

## 5. Conclusions

This study explored the spatio-temporal dynamics of LCC and its implications for ecological sustainability in the GAMA. Following the analysis, modelling and accounting of actual LCC (2008-2017) and predicted LCC (2030), the study produced the following relevant findings. Firstly, the results revealed that between 2008 and 2017, there was a pervasive conversion and/or loss of ecological land including semi-vegetated open space, forestland, grassland/farmland, and water bodies/wetland due to a substantial increase in the urban built-up area. The general patterns and tendency of LCC in the region reveal that the trend of changes experienced between 2008 and 2017 is expected to continue into the future as per the predicted land-cover map for 2030. Overall, these results clearly showed a high degree of loss and vulnerability of ecological lands and by extension ecosystem assets, resources and services. This is a clear indication that the changing dynamics of land cover in the region does not represent a trend towards sustainability. While previous studies warned that ecological land deterioration could place the sustainability of many regions under threat, the findings of this study confirms the case of the GAMA region. Perhaps the predicted future LCC maps can serve as an early warning system for understanding the potential implications of LCC. The study's findings form the basis for proactive land use plans, policies and decisions that lay emphasis on sustainable management of current patterns of LULC change, resources and protection of ecologically sensitive areas. Thus, policy and decision makers, urban planning, land management organisations and natural resources managers should plan alternative conservation actions to develop improved LULC management practices for balanced sustainable trajectories of urban development and ecological land conservation.

The study reveals information that addresses one of the specific research questions of the WaterPower project on how the 'urbanscape' of rapidly growing coastal cities are at risk from local environmental burdens enforced by urbanisation and environmental change. The study synthesises impacts from urbanisation-driven LCC processes taking place on the coast environment of Accra and provides an understanding of the nexus between coastal urbanisation processes and a transformation towards sustainability.

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