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Interconnectedness of Ecosystem Services Potential with Land Use/Land Cover Change Dynamics in Western Uganda

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Abstract: Understanding the evolution of land use/land cover change (LULCC) and how it shapes current and future ecosystem services (ES) supply potential remains critical in sustainable natural resource management. Community perception of historic LULCC was reconciled with previous study via remote sensing/geographical information systems using recall data in the Budongo–Bugoma landscape in Uganda. Then, a CA-Markovian prediction model of a LULC situation in 2040 under business as usual (BAU) and forest restoration scenarios was constructed. Additionally, we assessed the perceived proximate and underlying drivers of LULCC, and how LULCC shapes ecosystem services potential using household surveys. The perceived LULCC trend for the past three decades (1990–2020) corresponded with previous studies showing grassland, bushland, tropical high forest, and wetland cover declined greatly, while subsistence farmland, commercial farmland, and built-up areas had a great increment. The predicted LULC under (i) the business as usual scenario showed a continued decline of natural LULC while anthropogenic LULC increased greatly, tending to cover half of the landscape area; (ii) forest restoration under different levels showed an improvement of forest cover and other native LULC classes with a decline in mostly subsistence farmland. The proximate drivers were in three principal components (soil infertility, subsistence farming, drought; infrastructural development, commercial farming, overstocking of livestock, pest and disease challenges; tree planting), while underlying drivers were in two principal components (technology adoption, corruption of environment stewards, policy implementation gaps; cultural gaps). Food and cash crops were perceived to be the most important ecosystem services in the landscape. Generally, the landscape ES supply potential was dwindling and predicted to continue with a similar trend under BAU, despite the increment in ES contribution of subsistence and commercial farmland. Forest restoration would slightly improve the landscape ES potential but would cause a decline in subsistence farmland, which would result in either a threat to food/livelihood security or a livelihood shift. We recommend combined interventions that seek to achieve a progressive frontier that achieves development needs and priorities based on national need such as food security through local level production with recognition for sustainable availability of ecosystem services.

Keywords: proximate drivers; underlying drivers; prediction; restoration; Budongo–Bugoma; landscape; trade-off

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1. Introduction

The current extents and intensities of global land use/land cover change (LULCC) are far greater now than ever in history [1]. LULCC is the human modification of the earth's terrestrial surface [2,3], and has a dynamic relationship with its drivers depending on prevailing socioeconomic and biophysical factors [4–6]. LULCC in the vast part of Sub-Saharan Africa is a result of one or a combination of population growth, high poverty levels, demand for settlement(s) land, increasing demand for fuel wood/charcoal production, and agricultural expansion [7,8]. There is a consensus between many researchers that understanding the drivers of LULCC is a perplexing question in global science, thus further research is indispensable [5,9,10]. The global and/or national assessment of spatiotemporal LULCC and its drivers needs to be scaled down to the local level in order to enable better strategic responses and natural resource use planning [11,12].

LULCC alters the landscape integrity by affecting species composition/diversity, species turnover, and ecosystem functioning [13–15], thus causing observable alteration of ecosystem services supply [16–18]. Ecosystem service(s) (ES) is a human-centred concept of the benefits derived from nature [19]. LULCC can influence ecosystem properties and increase the availability of certain ecosystem services while causing substantial decline in supply of others [20]. This phenomenon is called the ES trade-off because a few ES are optimized while causing deterioration of others [20–22]. It is also possible to have an increase or decrease in one ES, causing a similar effect in the other, a phenomenon called 'synergism' [21–23]. Therefore, LULCC interactions across space and time, and how they consequently shape ecosystem services supply potential across transforming landscapes, remain critical facets of land use planning [24]. It is also worthwhile to interrogate the likely ES synergies and trade-offs based on people's perceived ES changes [23]: this would facilitate devising effective measures to mitigate possible land use conflict [25]. This would also enable sustainable and optimal utilization of ecosystems and their services.

There is a plethora of studies on historical LULCC dynamics and ecosystem services at different spatial and temporal scales that have been done using remote sensing/geographical information systems [6,26,27]. Some of these studies have extended to involve community participation in classification of LULC but with limited emphasis on the temporal scale [28]. However, these approaches have helped to comprehend the interrelationship between people and natural resources, and have also provided more detail for reconciliation of the measured and perceived LULC situation [29]. LULCC studies have evolved to a level of making predictions using models, the simplest types being the cellular-agent based models, Markovian and cellular automata models [30,31], and DINAMICA-EGO and CLUE-S [32]. The integrated models, for instance cellular automata–Markov models, are robust and can accurately predict long-term spatiotemporal LULC changes [30,33].

In order to assess the interconnectedness of ecosystem services and LULCC, valuation is used, and the common methods can be broadly classified into two paradigms: biophysical methods and preference-based methods [34,35]. The preference-based method has been split more into three approaches, namely sociocultural methods [36,37], economics methods [17,38], and expert-based quantification that has been modified to involve a cross-section of stakeholders [15,39,40]. The scarcity of data in many regions, especially Sub-Saharan Africa, has been overcome by an improved ecosystem service matrix that is flexible, quick to implement, and also gives ecosystem service scores related to biophysical quantitative estimates [41]. In an attempt to measure and share ecosystem service values in a transparent manner, it is of paramount importance to categorize ecosystem services. The Common International Classification of Ecosystem Services (CICES V5.1) is one of the typologies frequently used by the global ecosystem service community that was developed through a highly consultative process, building on the typology suggested by Millennium Ecosystem Assessment [16], and refined to reflect key issues identified in the wider research literature [42,43]. This CICES typology is easy to customize and is a universal way of reporting ecosystem services [15,44].

The advance in research has enabled participatory study of the interconnectedness of spatiotemporal LULCC dynamics and ecosystem services, thus enabling adoption of the ES concept application in land use planning [45]. In the Budongo–Bugoma landscape located in mid-western Uganda (Figure 1), LULCC has occurred, with tremendous effects on natural LULC classes in order to increase agricultural production, infrastructural development, and human settlement [46]. To address the LULCC in Uganda, restoration of forests is one of the policy directions reflected in the country's Vision 2040 and the updated Nationally Determined Contribution of September 2022. However, it is not clear whether the perceived LULCC (1990–2020) by local community reconciles with LULCC recorded from remote sensing/geographical information systems. Besides, it is important establish the principal perceived drivers of LULCC, to predict the future LULC scenarios considering business as usual conditions as well as forest restoration, and determine the effect of historical and predicted LULCC on landscape ecosystem services potential. This would provide valuable knowledge and a reliable foundation for integration of the full range of ecosystem services into land use policy and planning for conservation, and participatory and sustainable management of natural resources at landscape scale. Ultimately, this would reduce the significant loss and trade-offs in ecosystem services that sustain human well-being.

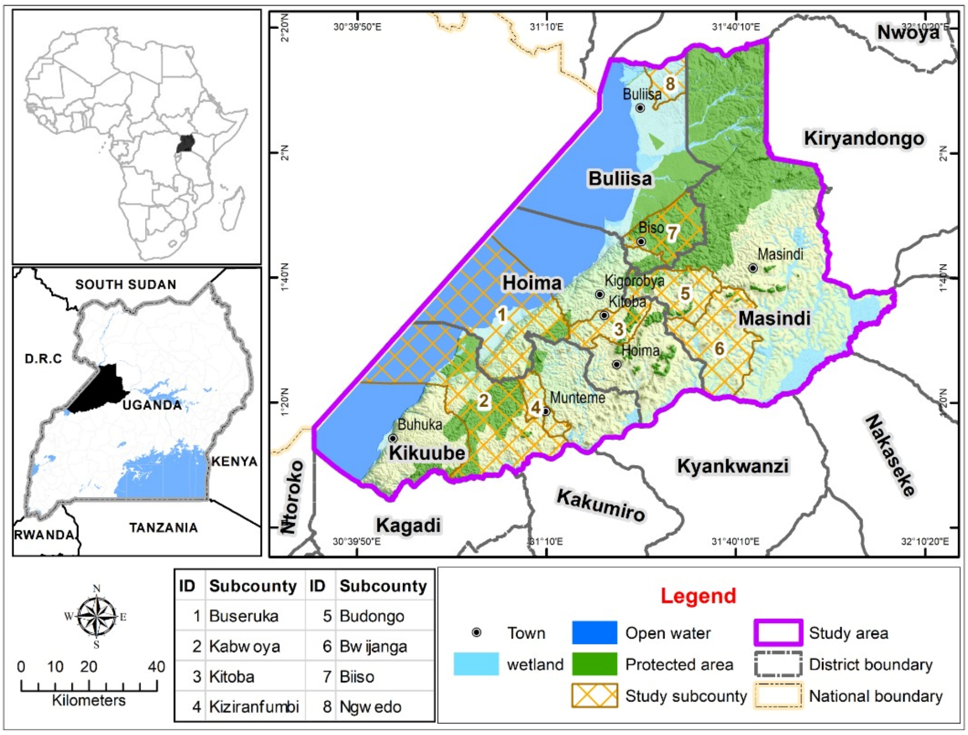

Figure 1. Map showing location of Budongo–Bugoma landscape in Mid-Western Uganda.

2. Materials and Methods

2.1. Study Area

The study was conducted in the Budongo–Bugoma landscape in Mid-Western Uganda, extending over four administrative districts of Masindi, Buliisa, Hoima, and Kikuube covering approximately 14,098.9 km^2 (Figure 1). The landscape forms the northern part of the Ugandan Albertine biodiversity hot spot, which has diverse avian species, rich floral diversity, and matchless endemic fauna diversity [47–49]. The landscape is densely populated (>200 people per km^2) with approximately 977,620 people in more than 211,821 households (excluding over 100,000 refugees) and a population growth rate of 4.3%, which is above the national rate of 3.3% [50]. An estimated 80% of the population practices subsistence agriculture, and around 78% of the population is rural-based [51]. There is a growth in commercial agriculture in the area, for instance of sugarcane production. There are also oil/gas exploration and ancillary activities that have been going on since the mid-2000s [52]. The area receives a bimodal rainfall pattern [48] with totals ranging from about 800 mm to 1500 mm per annum, and has significant surface water resources including Lake Albert and a network of rivers/streams. The landscape has LULC classes protected by national legislation totaling approximately 4305.8 Km^2 including *inter alia*; Budongo CFR (825 km^2), Bugoma CFR (411.42 km^2), open water (2866.21 km^2), wetlands (483.59 km^2), and Kabwoya Wildlife reserve (87 km^2). The methodological process followed for this study is summarized in a schematic diagram (Figure 2).

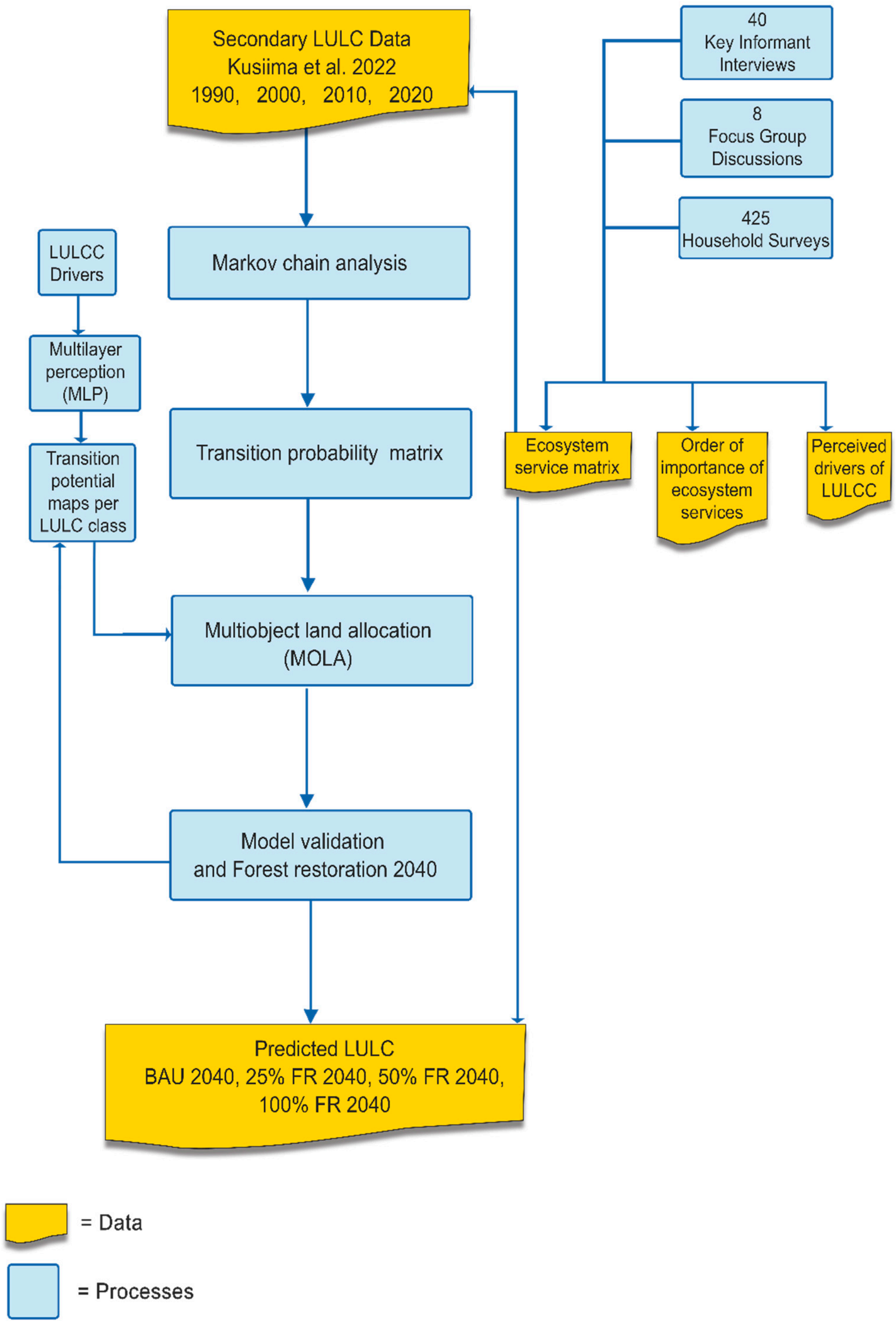

Figure 2. Schematic diagram of the research methods used in the study [46].

2.2. Prediction of Land Use Land Cover Change Using Secondary Data

Secondary data of historical LULCC were adopted from previous research [46] (Tables A1–A4, Figure A1) of authors who studied LULCC in the Budongo–Bugoma landscape between 1990 and 2020 using Landsat satellite imagery of single paths and rows (172/059); <10% cloud cover taken in the dry season was downloaded from USGS archive via Earth Explorer web-link http://earthexplorer.usgs.gov/16/05/2019 (accessed on 25 October 2022). The adopted study had used a reliable approach of supervised classification and a standard procedure for accuracy assessment by Congalton (1991) [53] was applied, giving an average accuracy coefficient of 0.84 (Table A3).

A hybrid cellular automata and Markov model [30] was used to predict the future LULC scenarios of Budongo–Bugoma landscape in 2040 using the Land Change Modeler in TerrSet Geospatial Monitoring and Modelling system [54]. The prediction was based on two scenarios: (i) business-as-usual (BAU) on the assumption that future LULC trends will be influenced by factors similar to the historical ones [55]; and (ii) restoration of forest cover at different levels (25%, 50%, 100%) inspired by the Vision 2040. The LULCC drivers used were based on three broad facets of natural environment, land use management, and socioeconomic activities [56] including distance from protected area, distance from drainage, rainfall, agricultural activities, and population. All the input spatial datasets were prepared in ArcGIS10.7; the output was then exported to TerrSet Geospatial Monitoring and Modelling System.

TerrSet's Land Change Modeler (LCM) is composed of the Multi-Layer Perceptron (MLP) neural network classifier, which consists of a set of three units (input layer, hidden layer of computation nodes, and output layer) that were used to model transitions [54]. The network of connections between components of MLP work as weights [30,31]. When a transition from a given LULC class to another occurred, a map of change potential was produced as a transition sub-model. This model environment allows multiple transitions under the same underlying driver variables and depends on the vulnerability of the LULC to change to other LULC classes, and resultant sub-models are combined into one transition suitability map for that LULC class [54]. A Markov model was used to simulate the land use in 2020 using the land cover image of 2000 as a reference and transition probability matrix. To spatially allocate the Markov transitions, the multi-objective land allocation (MOLA) and cellular automata built into the LCM were used. The validated LULC map of 2020 was used as a basis to predict LULC changes for 2040 under the CA-Markov prediction module in the LCM of TerrSet using Markovian transition areas, transition suitability images, and a standard 5×5 cellular automata filter. The transition matrix of 2020 to the business as usual (BAU) scenario of 2040 was used to fix the probability of restoration of wetland and forest towards attainment of the situation at base year considering 25%, 50%, and 100% restoration.

2.3. Key Informant Interviews and Focus Group Discussios

Key informant interviews (KIIs) and focus group discussions (FGDs) were adopted from previous related studies [6,40,57]. A total of forty (40) KIIs were identified based on their expertise and position of responsibility in the entire landscape, including agricultural extension workers, forestry officers, environmental officers, environmental activists, political/opinion leaders, business personnel, tourism professionals, fisheries staff, traditional leaders from Bunyoro Kitara Kingdom, oil and gas actors across the landscape, and eminent personnel in research/academia.

A total of 8 single focus group discussions (FGDs), each comprising 9–15 people including farmers, opinion leaders, business people, local leaders, fishermen, pit sawyers, private forest owners, and custodians of nature sites, were conducted across the landscape with one (1) FGD per selected sub-county [58]. The composition of FGDs was based on being knowledgeable about the study area and subject matter being studied [6].

Both KIIs and FGDs were used to collect data on LULCC and its drivers, relevant ES in the area, and ES supply potential for the different LULC classes.

Three broad classes of ES, provisioning, regulating, and cultural, were studied; selection was based on relevance and previous studies in the area (Treweek Environmental Consults 2016) and customized using the Common International Classification of Ecosystem Services (CICES) typology. Emphasis was on either what was used or experienced by the local people without any special consideration on its use pattern [15,44].

KIIs and FGDs were tasked with preparation of an ecosystem services matrix, which was later used to analyze the change in ecosystem services supply potential due to LULCC motivated by previous studies [15,26,59–61]. The y-axis of the matrix is for ecosystem service (ES) while the x-axis is the land use land cover types, and the intersection of LULC and ES, a score of production potential p_n^i (0 = no potential, 1 = very low relevant potential, 2 = low relevant potential, 3 = moderate relevant potential, 4 = high relevant potential, and 5 = very high relevant potential). We used LULC as a proxy to analyze the change in ecosystem service based on the generated ES matrix.

2.4. Household Survey

A household survey was conducted, guided by a questionnaire that was pretested to ensure achievement of a more precise tool for data collection providing insight into LULCC and its drivers [62]. Eight sub-counties, two parishes of each sub-county, and two villages of each parish were randomly selected. A total of 425 household heads who had lived in the landscape for more than three decades and were at least forty years of age (to ensure appropriate age for recall data) were selected randomly from lists given by village chairpersons. The thrust of the questionnaire was the perceived importance of relevant ecosystem services using a scale of 1 (less important) to 10 (most important), and the perceived trend/status of LULC classes in the past three decades using a scale of 1 (significant decrease) to 5 (significant increase). The questionnaire also interrogated drivers of LULCC, ranking the menu of proximate and underlying drivers described by Geist and Lambin [63] using a scale of 1 (no contribution to LULCC) to 5 (significant contribution to LULCC), and the observed change in ecosystem services supply potential of the landscape using a scale of 1 (significant decrease) to 5 (significant increase). The perceived status of LULC and ecosystem services supply potential was measured by taking recall information using the most memorable life history events associated with emotion/culture to enable interviewees to recall the situation [64]: the restoration of Bunyoro Kitara Kingdom in 1994, the promulgation of the Uganda constitution in 1995 to the millennium 2000, and post-millennium to date. The respondents were asked to start with the most recent event and proceed retrospectively as an attempt to produce better recall [64]. The recall periods considered did not coincide accurately with the time steps considered in remote sensing/GIS but strictly covered the historical study period.

2.5. Data Analysis

2.5.1. Perceived Land Use/Land Cover Change and Important Ecosystem Services

The perceived land use/land cover changes and the perceived importance of ecosystem services were subjected to descriptive statistical analysis to establish the general LULC situation as observed by people over the past three decades, and the order of importance of ecosystem services [65].

2.5.2. Perceived Land Use/Land Cover Change Drivers

The analysis of proximate and underlying drivers of LULCC was performed quantitatively using principal component analysis (PCA) in Stata 14.1 to establish the key drivers and how they combined to cause change [66,67].

2.5.3. Validation of Prediction Model

The simulated and actual LULC maps of 2020 were compared basing on Kappa variations generated from the Terrset validated sub-model in order to validate the CA-Markov model [68].

2.5.4. Implication of Historic and Predicted LULCC on Ecosystem Services

The historical (1990–2020) and predicted (2020–2040) changes in ecosystem services due to land use/land cover were analyzed using an approach adopted from a previous study [59,69]. The ecosystem services scores for a given category (provisioning, regulating, cultural) for all LULC classes (entire landscape) were summed up and divided by the total area of Budongo–Bugoma landscape to obtain ecosystem service value per hectare.

Potential production of the three (03) different categories of ecosystem services by all land use/land cover types i in the landscape was obtained via the following equation,

$$PPi = \sum_{n} p_n^i$$

Ecosystem service value (of a given category) per hectare = $PP_{ip} \div A$

With:

i = land use/land cover $\{$tropical forest, wetland, grassland . . . .open water$\}$;
n = ecosystem service $\{$food crop, . . . recreation$\}$;
p_n^i = level of production of the ecosystem services n by the land cover i $\{0, 1, 2, 3, 4, 5\}$;
PP_i = potential production of either provisioning, regulating, or cultural ES by the land use/land cover I;
A = total area of Budongo–Bugoma landscape in hectares.

The computed ecosystem service values per hectare were then multiplied by the area of the different LULC classes give the value of the different ecosystem service categories for historical periods and the predicted scenarios. The resultant values for the different periods/scenarios were compared and the difference was considered a proxy indicator for the effects of LULCC on ecosystem services. Stack plots were made to show the ecosystem services picture considering the three broad categories at different time periods per LULC class.

2.5.5. Relationship between Ecosystem Services

The community's perceived changes (increment or reduction) in ecosystem services availability in the past three decades were analyzed to establish competitiveness, trade-offs and synergies by conducting a pairwise correlation of food crops and the other ES for the base period and the current period [70].

3. Results

3.1. Perceived Land Use/Land Cover Change

An explicit strong association was observed between LULCC results obtained using remote sensing/geographical information systems analysis and community perceptions in the three-decade period of analysis (Figure 3). Both results showed that grassland, bushland, woodland, tropical high forests, and wetlands had decreased significantly over the past three decades owing to subsistence farmland, commercial farmland, and increase in built-up areas.

3.2. Predicted Land Use/Land Cover in 2040

The actual LULC map of 2020 was compared with the CA-Markov model-simulated 2020 LULC images in the validated model, which gave agreement and disagreement components that were further partitioned into 0.0071 (quantity disagreement) and 0.0087 (grid disagreement), implying that the main disagreement between the two images was due to allocation errors rather than quantity errors between simulated and actual LULC images. This was further confirmed by the strong agreement statistic of 0.2003 (quantity agreement) and 0.6838 (grid agreement). The overall accuracy of the prediction by CA-Markov was obtained from the Kno index, which is the standard kappa index of agreement. The KLocation index validates the simulation to predict the location. These indices are shown in detail in Table A5; the average value was 0.9837, which means that the LULC categories of the actual and simulated image were more than 98% similar.

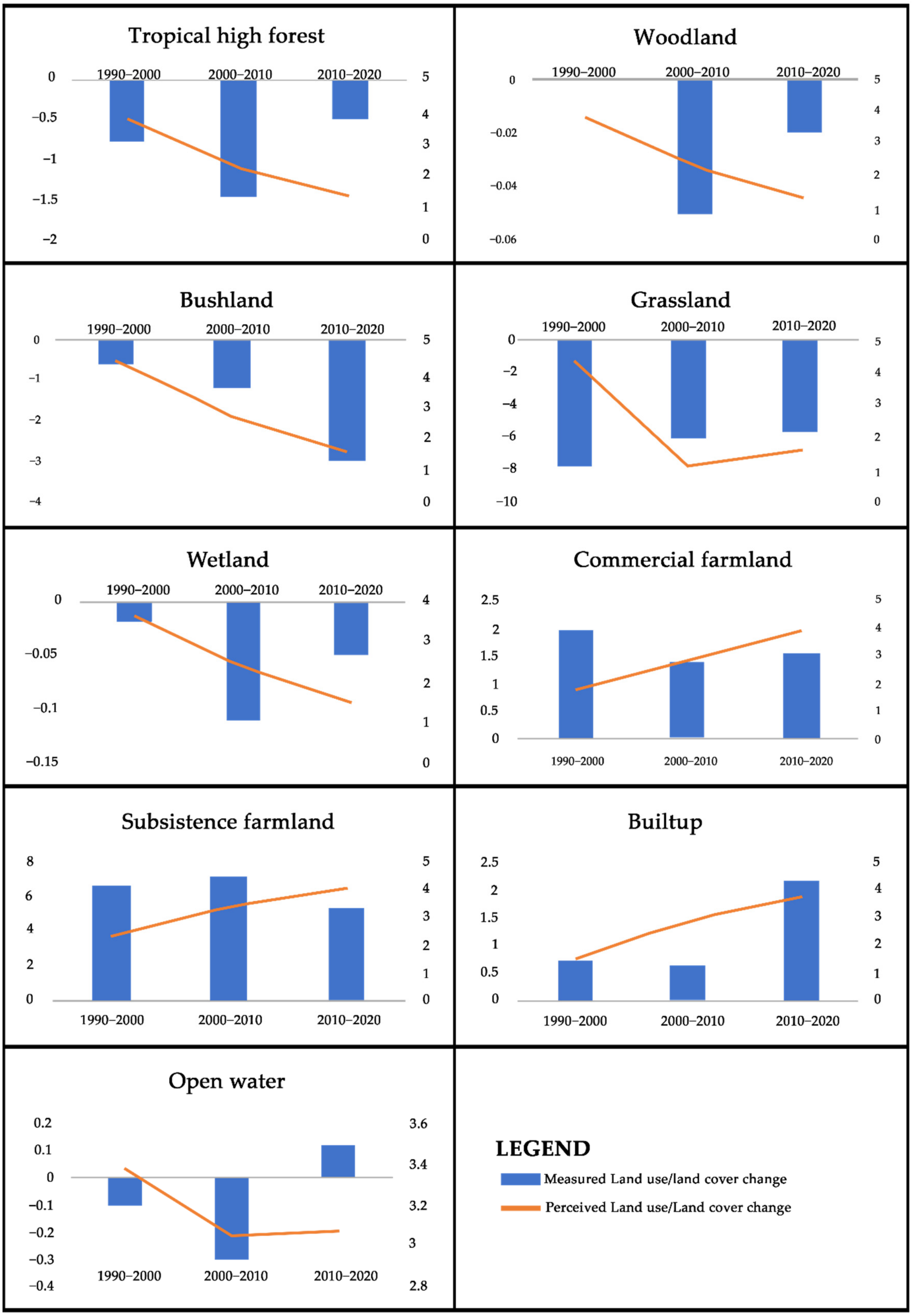

Figure 3. Combined plot of perceived and measured LULCC in Budongo–Bugoma landscape.

The predicted LULC situation in the year to 2040 (Figures 4 and 5) under the business as usual scenario revealed that subsistence farmland, commercial farmland, and built-up areas will continue to increase by 4.2%, 4.1%, and 4.3%, respectively. There will be a simultaneous decrease of grasslands, tropical high forests, wetland, and bushland by 11.3%, 0.6%, 0.5%, and 0.2%, respectively.

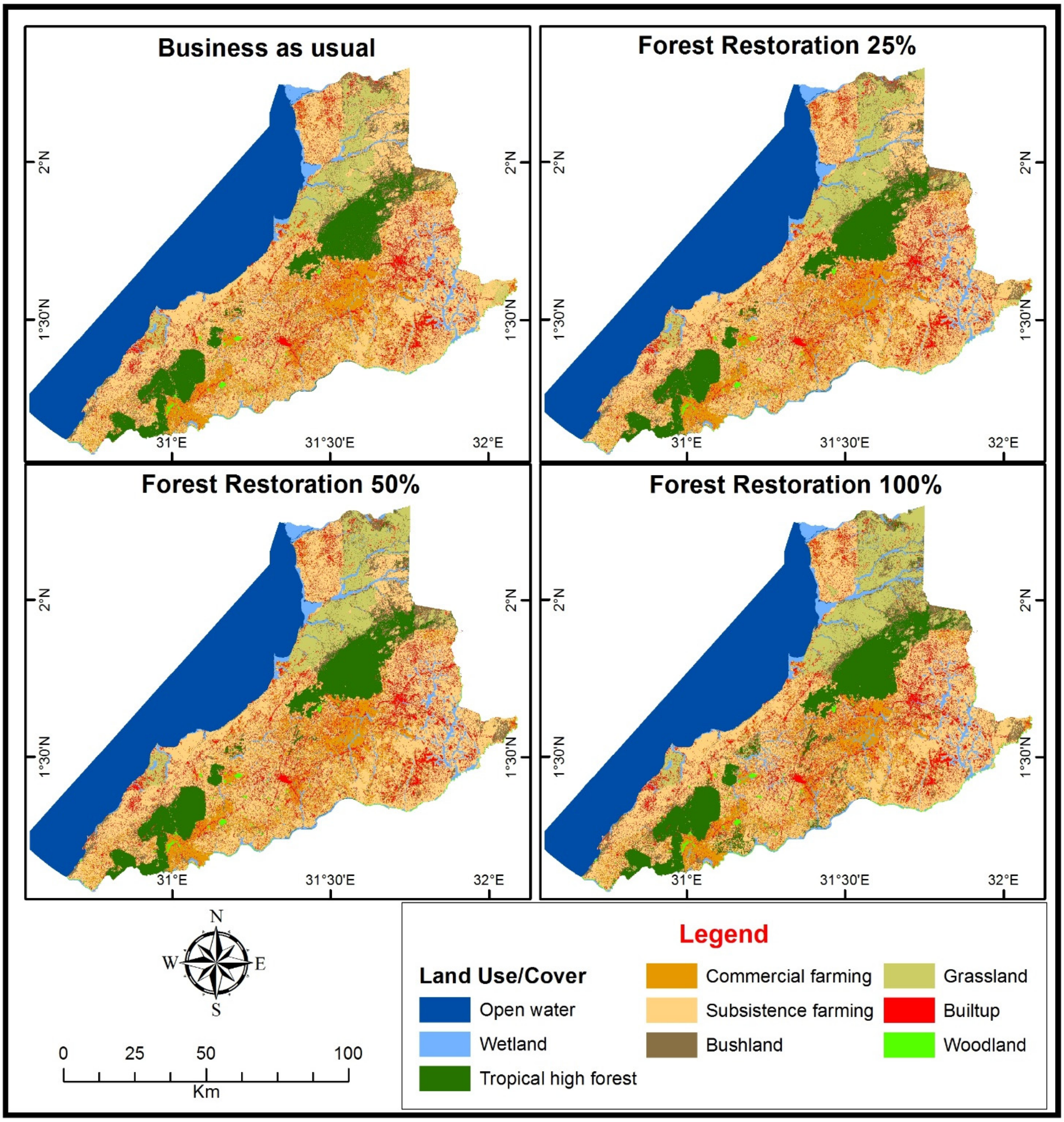

Figure 4. LULCC prediction maps for Budongo–Bugoma landscape under different scenarios in 2040.

The restoration of forests to 25% predicted an improvement in forest cover by 0.7%, with commercial farmland and subsistence farmland predicted to continue expanding but at nearly a quarter less than business as usual rates (2.7%, 3.9% respectively), while built-up areas would remain high at 4.2%. On the flip side, wetlands would be encroached on while grasslands would continue to be converted at rates of 0.7% and 10.7%, respectively.

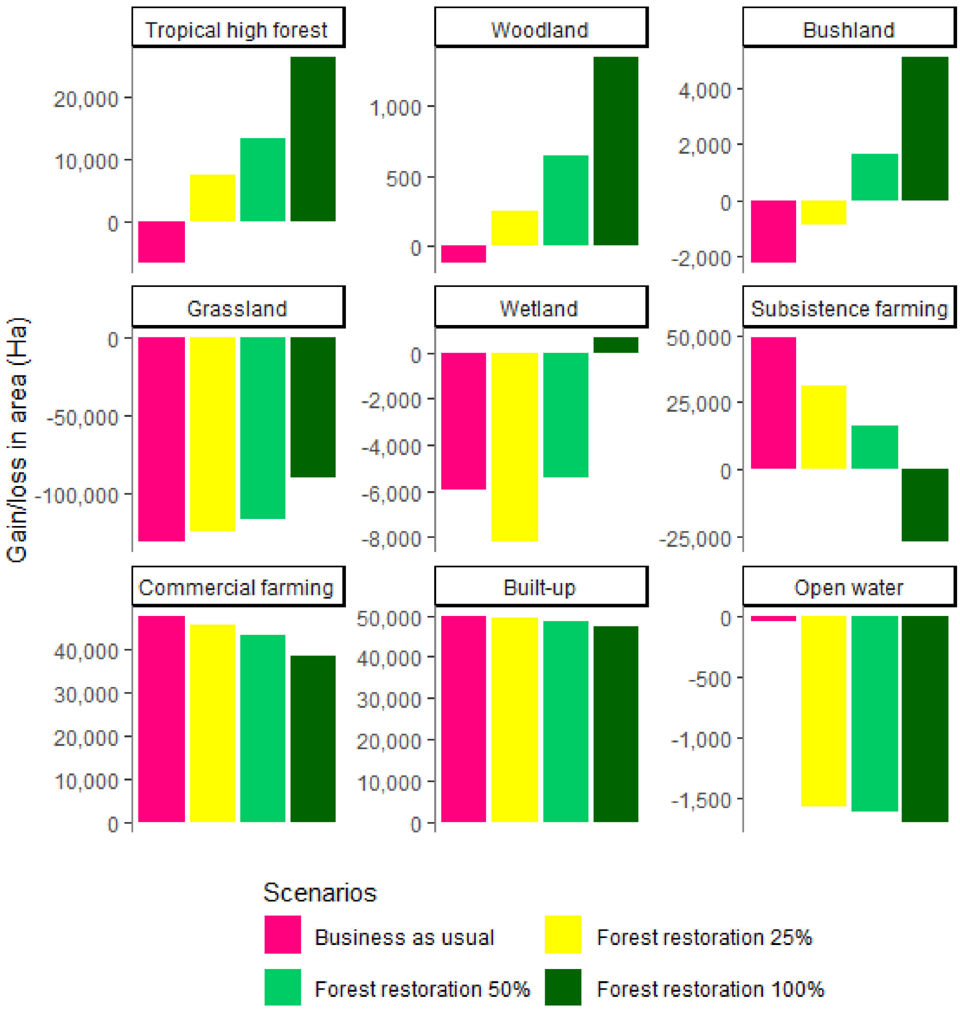

Figure 5. Predicted LULC gain and loss for Budongo–Bugoma landscape under different scenarios.

At 50% and 100% forest restoration, a continued positive trend of forest cover was notable; tropical high forest, shrubland, and woodland are likely to increase at levels of 2.3%, 0.4%, and 0.1%, respectively. The pressure on grassland and wetland would ease at >50% forest restoration with conversion of grassland reducing to 7.8% when compared with reduction under BAU; wetlands would improve by 0.1% under 100% forest restoration. The remarkable prediction under 100% restoration is subsistence farmland reducing by 2.3%; commercial farmland would still increase but by less than a quarter of BAU rates (3.3%), and built-up areas would still increase by more than 4.1%.

The prediction under BAU will entrench the threat to native LULC classes while forest restoration will most likely conflict with the need for food, livelihoods, and infrastructural development. The restoration of forest cover alone to the level of what existed in 1990 would not produce full recovery of landscape ecosystem service supply potential. An attempt to analyze the variance within and between LULC classes considering the different prediction scenarios showed there was indeed a difference within and between LULC classes.

3.3. Perceived Drivers of Land Use/Land Cover Change

LULCC was perceived to be a product of three (3) components, and two components (2) of proximate and underlying drivers, respectively (Table 1). Three components of proximate drivers were found to be causing LULCC in the Budongo–Bugoma landscape. Component one showed soil infertility, subsistence farming, and drought as the drivers of change while component two included infrastructural development, commercial agriculture, livestock keeping, and pest and disease challenges. The third component had only one LULCC driver, tree planting.

Table 1. Proximate and underlying drivers of LULCC in Budongo–Bugoma landscape.

Proximate Drivers				
Variable	Comp1	Comp2	Comp3	Unexplained
Infrastructure		0.5101		0.5723
Subsistence farming	0.4938			0.5287
Commercial agriculture		0.4559		0.6611
Livestock keeping		0.4405		0.4889
Soil infertility	0.5809			0.372
Drought	0.4673			0.3964
Pests and diseases		0.4196		0.4844
Tree planting			0.781	0.2663
Underlying drivers				
Variable	Comp1	Comp2		Unexplained
Population growth				0.5727
Technology adoption	0.4294			0.4448
Corruption of stewards	0.4247			0.4649
Urbanization				0.5043
Cultural factors		0.78		0.2251
Policy gaps	0.4333			0.3819
Industrialization		−0.4222		0.5204

The underlying drivers of LUCC were found to be in only two components. The first one had three drivers: technology adoption, corruption, and policy gaps in land management. The second component showed cultural factors as the drivers for LULCC.

3.4. Ecosystem Services

3.4.1. Importance of Ecosystem Services

A total of 21 priority ecosystem services, specifically ten (10) provisioning, nine (9) regulating, and two (2) cultural ecosystem services, were listed (Table 2). The importance of these priority ecosystem services based on respondents' perceived importance showed that provisioning ecosystem services, especially food crops, cash crops, and biomass for fuel, ranked highly followed by a mixture of regulating and other provisioning ecosystem services, while the only two cultural ecosystem services ranked least.

3.4.2. Landscape Ecosystem Service Matrix

The final ecosystem service matrix was obtained by comparing the individual matrices to detect any noticeable differences and calculating mean scores for each ES per LULC class. All the ES matrices were similar for the different ES scores, and the final matrix was obtained by computation of mean scores.

Wetland and subsistence farmlands had the highest number of ecosystem service scores, equal to nineteen (19), followed by four LULC classes, tropical high forest, woodland, bushland, and grassland, which had eighteen (18) scores each. Commercial farmland and open water had ten (10) scores each, while built-up areas had none (Table 3).

Table 2. Priority ecosystem services in the order of importance.

Ecosystem Services (ES)	Use	Rank	ES Type
Food crops	Crops for food meant hh consumption	1	Provisioning
Cash crops	Crops for revenue e.g sugarcane, tea, coffee	2	Provisioning
Fire wood/charcoal	Wood and charcoal for cooking, distilling, burning bricks	3	Provisioning
Clean air regulation	Maintaining air quality	4	Regulating
Rainfall formation	Good and reliable rainfall seasons	5	Regulating
Water supply	Water for domestic use, livestock, and watering crops	6	Provisioning
Cooling temperature	Making the ambient temperature conducive for man	7	Regulating
Soil fertility maintenance	Soils supporting crops optimally	8	Regulating
Herbal medicines	Treatment of common ailments	9	Provisioning
Soil erosion control	Holding soil/no runoff/no sedimentation	10	Regulating
Water quality control	Having clean and safe drinking water	11	Regulating
Wild foods	Mushrooms, berries, wild yams, vegetables etc	12	Provisioning
Crop pollination	Plants fruiting well and better harvest	13	Regulating
Pest Disease control	Minimal crop pest and diseases, and less use of chemicals	14	Regulating
Building materials	Poles, reeds, thatching grass, strings etc	15	Provisioning
Grazing pasture	Cattle and shoats grazing extensively	16	Provisioning
Flood control	Stopping stream/river banks from bursting	17	Regulating
Hunting Bushmeat	Edible rats, wild birds, small animals for bush meat	18	Provisioning
Wild fish capture	Fish from the lake, ponds, rivers, and swamps	19	Provisioning
Recreation & tourism	Tour to parks, wildlife reserves, cultural sites, esthetic views	20	Cultural
Education sites	Students going for study tours	21	Cultural

Subsistence farmland was perceived to have leading supply potential for the top three important ecosystem services, followed by commercial farmland and wetland. The native LULC classes (tropical high forest, woodland, bushland, grassland, and wetland) only contribute biomass for fuel when considering the most important ES in the landscape as perceived by the community. Generally, native LULC classes were perceived to have the highest supply potential of all ES, most especially the irreplaceable regulating ecosystem, and others irrespective of order of perceived importance.

Table 3. Ecosystem service matrix for different LULC classes in Budongo–Bugoma landscape.

	Provisioning											Regulating										Cultural		
LULC Classes	**Food Crops**	**Cash Crops**	**Fish Capture**	**Wildlife Population for Hunting**	**Open Access Grazing/Fodder**	**Woody Biomass for Firewood/Charcoal**	**Water Supply for Home & Livestock**	**Wild Foods**	**Building Materials**	**Herbal Medicines**	**Total Provisioning Ecosystem Services Potential**	**Clean Water (Quality) Regulation**	**Flood Control**	**Cooling Hot Temperatures**	**Rainfall Formation (Good Planting Seasons)**	**Soil Erosion Control**	**Soil Fertility Maintenance/Improvement**	**Non-Irritating Air for Breathing**	**Pollination of Crops**	**Absence of Crop Pests and Diseases**	**Total Regulating Ecosystem Services Potential**	**Recreation and Tourism**	**Environmental Education Sites for Students**	**Total Cultural Ecosystem Services Potential**
Tropical High Forest	0	0	0	5	2	5	4	3	5	5	**29**	4	4	5	5	4	4	5	4	5	**40**	5	5	**10**
Woodland	0	0	0	3	2	5	2	3	4	3	**22**	4	3	4	4	4	4	4	4	3	**34**	2	2	**4**
Bushland	0	0	0	3	2	2	3	3	4	3	**20**	3	3	3	3	3	3	3	4	3	**28**	2	2	**4**
Grassland	0	0	0	2	5	1	2	2	3	1	**16**	2	2	2	2	3	2	2	2	2	**19**	1	1	**2**
Wetland	2	0	5	2	4	2	5	1	3	2	**26**	5	5	4	5	3	2	3	3	2	**32**	3	3	**6**
Subsistence Farmland	5	3	1	0	2	2	2	1	1	1	**18**	1	1	2	2	3	3	3	3	3	**21**	1	1	**2**
Commercial Farm land	3	5	0	0	1	0	0	0	0	0	**9**	0	0	1	1	0	0	1	1	1	**5**	0	1	**1**
Built-up	0	0	0	0	0	0	0	0	0	0	**0**	0	0	0	0	0	0	0	0	0	**0**	0	0	**0**
Open Water	0	0	5	0	0	0	5	0	0	0	**10**	4	4	4	5	2	0	1	0	0	**20**	4	3	**7**
	10	**8**	**11**	**15**	**18**	**17**	**23**	**13**	**20**	**15**	**150**	**23**	**22**	**25**	**27**	**22**	**18**	**22**	**21**	**19**	**199**	**18**	**18**	**36**

3.4.3. Ecosystem Services Potential

The ecosystem service potential contribution of a given LULC class to landscape ES potential is a function of the spatial extent of that particular LULC class and not necessarily the number of ES it supplies.

During the base year of 1990, the ES potential contribution of all the broad categories of ES was in this following order: grassland, open water, tropical high forest, bushland, subsistence farmland, wetland, woodland, and commercial farmland (Figure 6).

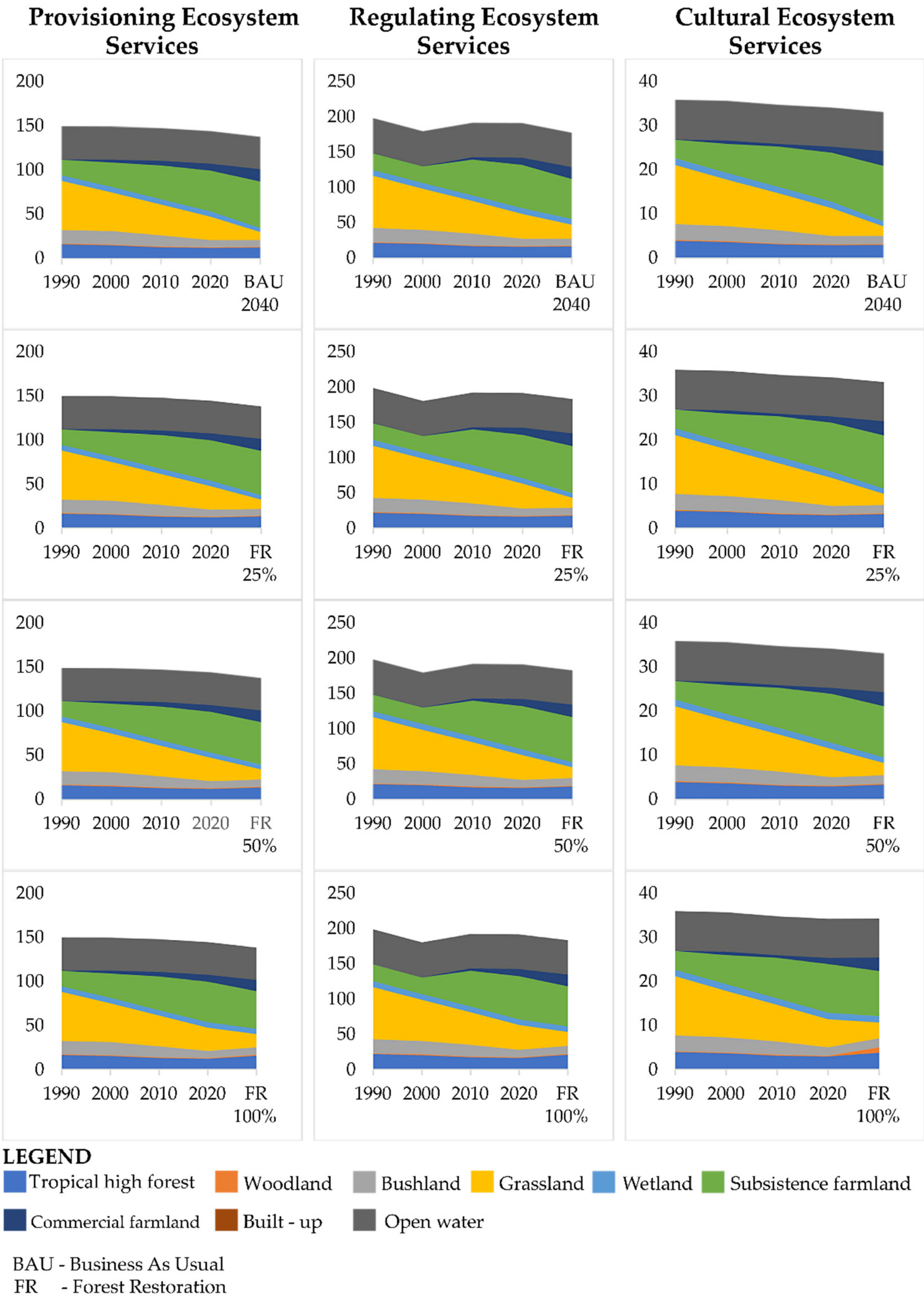

Figure 6. Historical and predicted ecosystem service potential for Budongo–Bugoma landscape.

In the three-decade period (1990–2020), the three categories of ES (provisioning, regulating, and cultural) were dwindling to landscape level. It is evident that contribution of open water maintained its level for the three broad ES because its area did not change much. Simultaneously, the contributions of grassland, tropical high forest, wetland, and woodland declined for all the ES while subsistence farmland and commercial farmland increased to nearly double that of the base year. This is related to the increase in area of the two LULC classes over the three decades.

The predicted ES potential situation under the BAU scenario shows that landscape ES potential will continue to dwindle despite a remarkable increment in contribution of subsistence and commercial farmlands. That aside, forest restoration at different levels would lead to a slight improvement in ES potential at landscape level but the base year situation would not be attained. A puzzlingpeculiar situation would be a decline in the contribution of subsistence farmland and persistent commercial farming, forecasting a clash of restoration with human socioeconomic demands of food, livelihoods, infrastructural development, and settlement space.

3.4.4. Relationship between Ecosystem Services

This study used correlation to determine the strength and direction of the linear relationship between various ecosystem services and food crop production as observed by the community. The choice of food crop was guided by the rank of importance as perceived by the community. The results (Table 4) generally indicate weakly negative but significant relationships between food crop production and other ecosystem services, except for tourism/recreation and education sites for students.

Table 4. Correlation between different ecosystem services. In bold are those correlations that have *p* values < 0.0001. The whole pairwise correlation matrix is in Table A6.

Other Ecosystem Services	Food Crop
Cash crop	**−0.1047**
Hunting bushmeat	**−0.2066**
Grazing pasture	**−0.2232**
Fire wood/charcoal	**−0.3504**
Water supply	0.019
Water quality purification	**−0.1543**
Flood control	0.0406
Air quality regulation	−0.0791
Rainfall formation	**−0.2231**
Soil erosion control	**−0.2101**
Soil fertility improvement	**−0.3304**
Cooling temperature	**−0.242**
Crop pollination	**−0.1547**
Pest and disease control	**−0.5056**
Ecotourism	**0.1771**
Herbal medicine	**−0.1772**
Education sites	**0.2047**
Wild foods	**−0.2519**
Fish capture	**−0.3548**
Building materials/timber	**−0.3168**

A moderately strong (correlation coefficient − 0.5) negative correlation was observed between food production and pest and disease control ES. This implies that as food production increases, the ability of the areas to provide pest and disease control will reduce. Additionally, there was a positive and significant correlation between increasing food production and increase in tourism/recreation and education sites for students.

3.5. Summary Content from KIIs and FGDs

In regard to all the above findings, the dominant narrative identified using content analysis of what was recorded during key informant interviews and focus group discussions was:

> *"There has been remarkable conversion of forests, grasslands, and wetlands to agricultural fields and settlement areas in the past three decades. This trend is expected to increase exponentially in the years ahead because of population growth, poverty, the oil/gas activities, and the exponential increase in sugarcane growing in this area. We are now witnessing low agricultural productivity, drying of wetlands, long dry spells, and hazards in form of heavy storm".*

4. Discussion

4.1. Land Use/Land Cover Change Dynamics

Land use change remains an important driver of landscape health [71,72]. Over the past three decades, LULCC in the Budongo–Bugoma landscape has been dynamic with progressive increase in subsistence farmlands, commercial farmlands, and built-up areas. Simultaneously, there has been a decline of natural LULC classes, especially grasslands, woodlands, and tropical forests. The LULCC in space and time agrees with the previous LULCC studies in the landscape that found significant conversion of forest land and other natural ecosystems to cultivated lands [46,73,74]. This pattern could be attributed to three fundamentals.

Firstly, the subsistence agriculture over Uganda, like elsewhere in Sub-Saharan Africa, is based on extensification for increasing agricultural production. This practice requires more land to be converted into cultivable land and these patterns have driven in part the considerable land cover conversion of the recent decades [31].

Secondly, the observed pattern could perhaps be related to the fact that extensification breeds continued extensification, as farmers see production increases (not necessary productivity) and associated income that further drives the insatiable need for increased production. This conforms to the Jevons paradox scenario [75]. The Jevon's paradox articulates that as the event that improved resource efficiency increases the profitability of activities the resource can be used for, it then expands, resulting in greater overall use [76]. We seem to be seeing this pattern in the current study region, especially among subsistence farmers, and it is being exacerbated by the finite nature of land as well as a decrease in soil fertility, causing cultivation of fresh fields [77,78]. This subregion has become a major food exporter, especially of maize to Kenya, South Sudan, and Rwanda, as well as internal consumption within Uganda.

Thirdly, as the country's population increases, the demand for more food, cultivable and residential land, and employment also grows. Over the past three decades, the subregion has seen an increase of population from around 615,401 people in 2002 to 1,132,700 people in 2018, with an annual population growth rate of 4.3%, yet the national figure is 3.3% [50]. Population growth in the area is not just a product of fecundity but also refugee influx [79] and people rushing into the subregion to acquire land as a strategic move to tap into the oil/gas industry opportunities [52]. The biggest share of the population (80%) in the study area and nationally are employed in agriculture, and the majority of them are subsistence farmers.

Generally, the perceived drivers of LULCC are also in agreement with the literature findings that agricultural expansion (both subsistence and commercial), lack of inclusion of local people in policies [78], corruption of environment stewards and political interference, overstocking of grazing livestock, and breakdown of cultural systems [77] are the major drivers of LULCC in Uganda.

Over the next 20 years to 2040, prediction results reveal a further dominance of agricultural land uses and built-up areas across the landscape and dwindling of grasslands, woodlands, and tropical high forests. Expansion of agricultural land should not come as a surprise because Uganda's population is projected to reach 115 million by 2050. The government of Uganda is currently pursuing a self-sufficiency food security policy based on the Global Food Security Strategy (GFSS) Uganda Country Plan (2018), and there is a strategic shift by the government to increase commercial agriculture with the argument that subsistence agriculture is not profitable for wealth creation, and hence cannot cause economic transformation. One of the commodities being promoted to eradicate the chronic poverty among smallholder farmers is sugarcane growing, despite evidence of it keeping smallholder farmers in poverty, dubbed "bitter sugarification" [80].

Commercial agriculture by its very nature is dependent on large-scale land clearance and facilitates commodity-centric landscapes. This is the reason for the trending land accumulation for large-scale agricultural and infrastructural development projects in Sub-Saharan Africa [81]. In countries such as Brazil that have taken a commercial agriculture path, significant land use change has been realized that has dramatically affected the quality of landscapes as well as the existing biodiversity [82,83].

However, the prediction of LULCC in 2040 considering restoration of forest cover scenario (at different levels) would cause an improvement in the spatial extent of tropical high forest, woodland, and partly wetland area, especially at 100% restoration to the base year situation, while commercial farmland and built-up areas would continue to grow. The forest restoration agenda would most probably affect the spatial extent of subsistence farmland, and actual decline would occur to a level below the current situation at 100% forest restoration. The shrinkage of subsistence farmland would linearly threaten food/livelihood security on the assumption that agricultural productivity is not improved. Additionally, the prediction of LULCC under the forest restoration scenario contributes to the trending debate on the permanence of restored forestlands [84], which might be hindered by a situation where it (restoration) conflicts with the reality of an exponentially growing population that needs food and settlement space. It is also on record that farming in Sub-Saharan Africa produces a reservoir of underemployed laborers [85], implying reduction of subsistence farmland would either exacerbate the problem or cause a livelihood shift to work on commercial farms, building work in the built-up areas, and industries, thus making good use of the abundant workforce. The latter would foster sustainable socioeconomic transformation across the landscape.

4.2. Relationship between LULCC Dynamics and Ecosystem Services Potential

LULCC decreases multi-functionality of the landscape [86] and creates immense environmental pressure that significantly affects ecosystem service potential at different scales [87,88]. LULCC is part of land system change that is listed among the nine planetary boundaries that have been transgressed, affecting carbon dioxide concentration, water flows, biodiversity, and ecosystems [89]. LULCC usually occurs in pursuit of one or a few of the most preferred ecosystem services at the expense others [90]. The perceived most important ES in the Budongo–Bugoma landscape are provisioning ES, especially food and cash crops, and woody biomass for fuel. This scenario was also observed in the Atacora highlands in Benin [91] and the rural communities in Nigeria [92]. As a consequence, there has been a steady increment in landscape potential to supply both food and cash crops, and an involuntary trade-off of a range of other ecosystem services, especially the irreplaceable regulating ES. The pursuit of food crops showed a negative correlation with a number of regulating ecosystem services, including soil fertility, pest and diseases control, reliable rainfall, and soil erosion control, which have been recorded as hinderances to optimal agriculture sector performance in Uganda [51,93]. In addition, the rainfall intensity for most agroecosystems of Uganda was around 8% lower between 2000 and 2009 compared to rainfall for the period of 1920–1969, and Western Uganda had a rainfall deficit for more than two decades [94]. The landscape is also prone to soil erosion, with the two iconic central forest reserves of Budongo and Bugoma on the national list of soil erosion threatened areas [95]. The adoption of forest restoration to improve LULC and ecosystem services potential of a given landscape would require complimenting it with application of agroecological techniques in agricultural lands, for instance agroforestry, which would cater for food and cash crops while causing synergism in ES supply potential whereby trees on the farm would contribute to both provisioning and regulating ES [96,97].

4.3. Limitations to the Study

The spatial data used in remote sensing and geographical information systems was of 30 m $\times$ 30 m resolution. This has the weakness of not being able to properly differentiate LULC classes that are closely related, thus compromising the accuracy levels of the spatial analysis results, but serves as a reliable foundation for future related studies.

Secondly, the use of the same ecosystem service scores for the past/present/future situations without any discounting or compounding was on the assumption that the hypothesized ecosystem services potential of given LULC classes did not change easily. In addition, prediction of the future did not cater for surprises and people's choices that would potentially impact on LULCC and ecosystem services potential.

5. Conclusions

Both the measured and perceived historical LULCC situation in Budongo–Bugoma landscape showed significant land system changes. Subsistence farmland, commercial farmland, and built-up areas increased steadily in that order as the natural LULC classes specifically; grassland, bushland, tropical high forest, wetland, and woodland declined. The perceived drivers of LULCC were soil infertility, agricultural (subsistence and commercial) field expansion, drought conditions, infrastructural development, overstocking of livestock, crop pests and diseases, technology adoption, corruption on the side of environmental stewards, and gaps in operationalization of environmental policies.

The predicted LULCC in 2040 under the BAU scenario showed an escalation of the historical trend while forest restoration at different scales showed an improvement in the spatial extent tropical high forest, woodland, and wetland. The built-up areas and commercial farmland would continue expanding while subsistence farmland expansion was predicted to slow down and even decline below the 2020 area at 100% forest restoration.

Generally, LULCC dynamics were highly interconnected with ecosystem services potential of the landscape, evidenced by the decline in ES service potential of the entire landscape except that of food crops, which was perceived as the most important ES and increased simultaneously with subsistence farmland. The predicted ES potential would improve slightly with forest restoration but would not restore the situation at the base year of 1990. The general reduction in ecosystem services supply potential was caused by conversion of natural LULC classes to subsistence and commercial farmlands, and exacerbated by expansion of built-up area.

The findings present an opportunity for better management of ecosystem integrity in the Budongo–Bugoma landscape through incorporation of ecosystem services in assessing LULCC at landscape level and appraisal of land use projects by physical planning committees at landscape scale, appreciation of the merits of combining remote sensing and GIS with people's perceptions, and foresight planning in land management. It is recommended that a combination of these techniques be embraced; land sparing, forest restoration through pursuit of the Vision 2040 targets and use of agroecological practices, for instance, agroforestry, greening of built-up areas, and population control policies. There is a need to establish the implications of declining ecosystem services potential born of LULCC for the well-being of the local community in the Budongo–Bugoma landscape.

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Appendix A

Table A1. Specifications for satellite data of Budongo–Bugoma landscape.

Year	Acquisition Date	Image	Satellite	Bands Combination
2020	15/01/2020	LC08_L1TP_172059_20200115_20200127_01_T1	Landsat 8	432
2010	17/01/2012	LE07_L1TP_172059_20120117_20161204_01_T1	Landsat 7	321
2000	06/01/2002	LE07_L1TP_172059_20020206_20170201_01_T1	Landsat 7	321
1990	22/01/1990	LT04_L1TP_172059_19901222_20170127_01_T1	Landsat 4	321

Table A2. Description of land use/land cover classes in Budongo–Bugoma landscape.

LULC Class	Description
Tropical high forest	Fully stocked with trees (natural and planted) forming closed canopies preventing sunlight penetration
Woodlands	Open trees and woody areas
Bush lands	Closed, open or very open shrubs
Grasslands	Graminoids, herbaceous area, may include scattered shrubs and thickets
Wetlands	Swampy and marshy areas
Subsistence farmlands	Mixed farmland, shrub and herbaceous crops on small fields
Commercial farmlands	Mono-cropped, both seasonal and non-seasonal farmland, e.g, sugarcane, tea of medium to large acreage
Built-up	Urban or rural built-up areas, roads, industrial parks
Open water	Lakes, rivers, ponds (stagnant and flowing water)

Table A3. LULC classification accuracy coefficients.

LULC	1990		2000		2010		2020	
	P *	U *	P	U	P	U	P	U
Open Water	90	90	90	100	90	90	100	90.91
Wetland	70.00	70	71.43	65.22	76.19	69.57	85.71	78.26
Tropical High Forest	83	86.36	83	82.61	78	90	91	95.45
Commercial Farming	83.33	92.11	80.65	80.65	83.87	78.79	93.55	87.88

Table A3. *Cont.*

LULC	1990		2000		2010		2020	
	P *	U *	P	U	P	U	P	U
Subsistence Farming	89.47	91.07	84.38	93.1	87.50	88.89	90.63	90.63
Bushland	78.26	78.26	78.26	75	78.26	81.82	86.96	86.96
Grassland	95.65	86.27	87.50	79.25	87.50	84	85.42	85.42
Built-up	96.77	96.77	90.63	96.67	84.38	96.43	84.38	100
Woodland	89.29	86.21	85.71	82.76	85.71	77.42	85.71	82.76
Overall Accuracy	87.50		83.93		84.29		88.5	
Kappa	0.857		0.815		0.819		0.869	

P * Producers Accuracy, U * Users Accuracy.

Table A4. LULC classification maps for Budongo–Bugoma landscape 1990–2020.

Land Use/Cover	1990		2000		2010		2020	
	Area (Ha^2)	Area (%)	Area (Ha^2)	Area (%)	Area (Ha^2)	Area (%)	Area (Ha^2)	Area (%)
Tropical high forest	126207	10.85	117254	10.08	100308	8.62	94416	8.12
Woodland	6800	0.58	6804	0.58	6218	0.53	5979	0.51
Bushland	116453	10.01	109918	9.45	96496	8.30	61446	5.28
Grassland	43214	37.15	341075	29.32	270544	23.26	205654	17.68
Wetland	48359	4.16	48215	4.14	46828	4.03	46325	3.98
Subsistence farmland	137491	11.82	213801	18.38	296594	25.50	358010	30.78
Commercial farmland	1981	0.17	25229	2.17	41498	3.57	60117	5.17
Built-up	3937	0.34	12266	1.05	19569	1.68	44727	3.84
Open water	289927	24.92	288733	24.82	285240	24.52	286621	24.64
Total	**1,163,295**	**100**	**1,163,295**	**100**	**1,163,295**	**100**	**1,163,295**	**100**

Table A5. Land use/land cover prediction model validation results.

Information of Allocation	Classification Agreement/Disagreement Information of Quantity No [n]	Medium [m]	Perfect [p]
Perfect [P(x)]	P (n) = 0.5245	P (m) = 0.9929	P (p) = 1.0000
PerfectStratum [K(x)]	K (n) = 0.5245	K (m) = 0.9929	K (p) = 1.0000
MediumGrid [M(x)]	M (n) = 0.5211	M (m) = 0.9842	M (p) = 0.9786
MediumStratum [H(x)]	H (n) = 0.1000	H (m) = 0.3003	H (p) = 0.3010
No [N(x)]	N (n) = 0.1000	N (m) = 0.3003	N (p) = 0.3010
Chance Agreement	0.1		
Quantity Agreement	0.2003		
Strata Agreement	0		
Gridcell Agreement	0.6838		
Gridcell Disagreement	0.0087		
Strata Disagreement	0		
Quantity Disagreement	0.0071		
Kappa No Information	0.9824		
Kappa Location	0.9875		
Kappa Location Strata	0.9875		
Kappa Standard	0.9774		

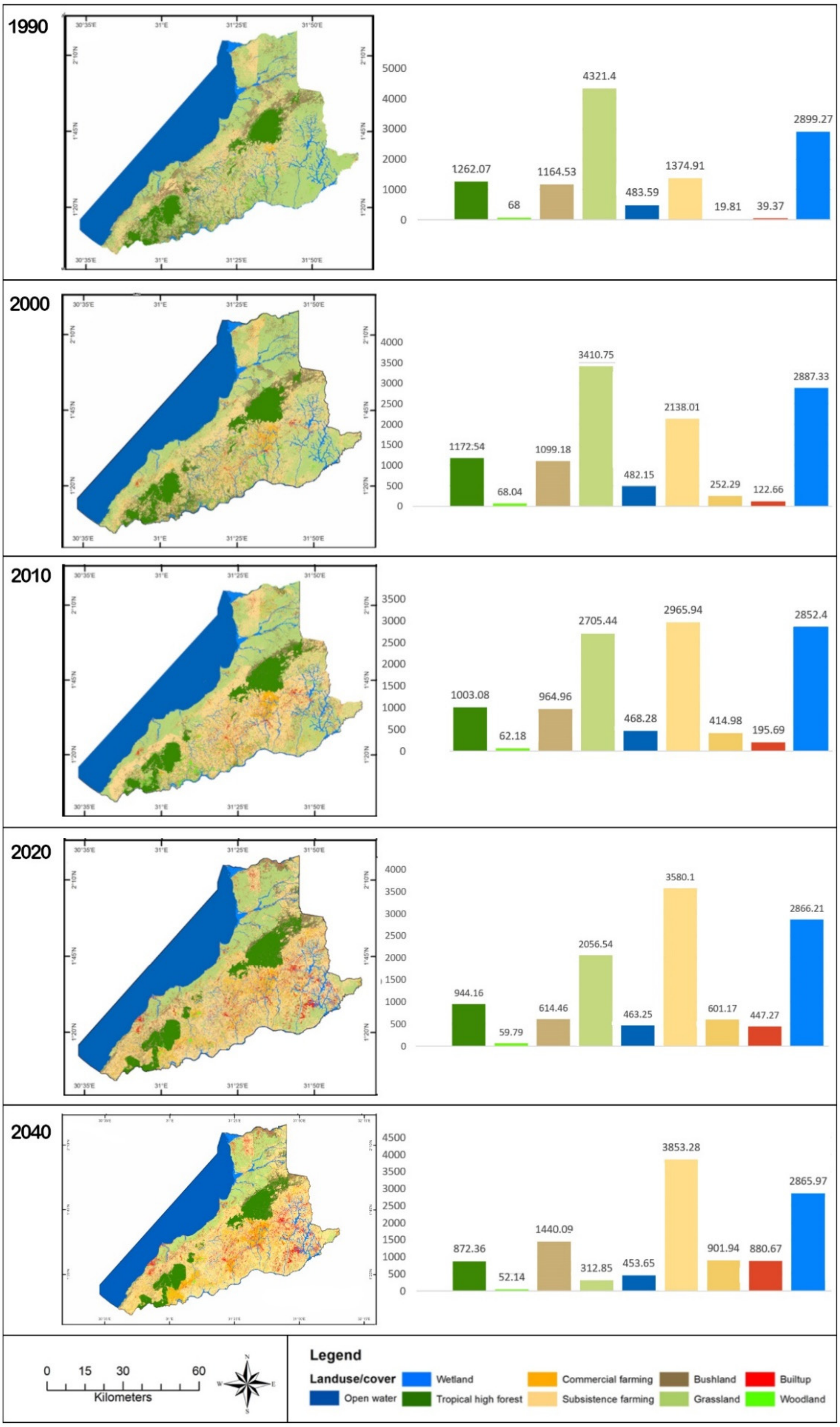

Figure A1. LULCC in the Budongo–Bugoma landscape using Landsat satellite imagery of single path and row (172/059).

Table A6. Results of ecosystem services pairwise correlation.

	1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Food crop	1																					
1.Food crop	−0.0199	1																				
	0.6817																					
2.Cash crop	−0.1047	0.5428	1																			
	0.0309	0																				
3. Hunting bushmeat	−0.2066	0.0192	0.1225	1																		
	0	0.6937	0.0115																			
4. Grazing pasture	−0.2232	0.2	0.3385	0.1878	1																	
	0	0	0	0.0001																		
5. Fire wood/chacoal	−0.3504	0.2791	0.2571	0.2093	0.3989	1																
	0	0	0	0	0																	
6. Water supply	0.019	0.0972	0.002	0.1183	0.3364	0.2946	1															
	0.6962	0.0452	0.9665	0.0147	0	0																
7. Water quality purification	−0.1543	0.1024	0.1054	0.0944	0.3332	0.2896	0.5763	1														
	0.0014	0.0348	0.0298	0.0517	0	0	0															
8. Flood control	0.0406	0.0727	0.2429	0.0744	0.153	−0.1852	0.0834	0.2331	1													
	0.4034	0.1346	0	0.1257	0.0016	0.0001	0.0861	0														
9. Air quality regulation	−0.0791	0.1246	0.0242	0.2389	0.1988	0.5187	0.4496	0.3717	−0.1055	1												
	0.1036	0.0101	0.6194	0	0	0	0	0	0.0296													
10. Rainfall formation	−0.2231	0.166	0.1427	0.2196	0.4051	0.547	0.3734	0.4121	0.0375	0.5618	1											
	0	0.0006	0.0032	0	0	0	0	0	0.4407	0												
11. Soil erosion control	−0.2101	0.0561	0.0894	0.1304	0.462	0.4682	0.4272	0.4173	0.0416	0.4556	0.6248	1										
	0	0.2483	0.0657	0.0071	0	0	0	0	0.3922	0	0											
12. Soil fertility improvement	−0.3304	0.1632	0.1426	0.1127	0.4477	0.6265	0.3655	0.3887	−0.0778	0.5287	0.6919	0.6817	1									
	0	0.0007	0.0032	0.0201	0	0	0	0	0.1094	0	0	0										
13. Cooling temperature	−0.242	0.1514	0.0935	0.2178	0.3175	0.5357	0.3758	0.3683	−0.0634	0.6792	0.6368	0.5371	0.6645	1								
	0	0.0017	0.0541	0	0	0	0	0	0.1918	0	0	0	0									
14. Crop pollination	−0.1547	0.2075	0.2537	0.0913	0.2063	0.3163	0.0526	0.2652	0.1066	0.278	0.3544	0.3578	0.3976	0.4585	1							
	0.0014	0	0	0.0601	0	0	0.2795	0	0.028	0	0	0	0	0								
15. Pest and disease control	−0.5056	0.116	0.2288	0.2095	0.3328	0.5327	0.0166	0.2575	−0.0617	0.2941	0.4687	0.4243	0.531	0.4574	0.4403	1						
	0	0.0167	0	0	0	0	0.7336	0	0.2043	0	0	0	0	0	0							
16. Ecotourism	0.1771	0.1142	0.1783	0.1684	0.0599	−0.0662	0.1705	0.1199	0.2039	−0.0207	−0.0199	0.0824	−0.0466	0.0468	0.0932	−0.114	1					
	0.0002	0.0185	0.0002	0.0005	0.2175	0.1733	0.0004	0.0134	0	0.6707	0.6822	0.0898	0.3376	0.3358	0.0548	0.0187						
17. Herbal medicine	−0.1772	0.0786	0.0752	0.3002	0.3342	0.5103	0.2626	0.1936	−0.206	0.4591	0.5094	0.4918	0.5594	0.5008	0.2761	0.4259	0.0904	1				
	0.0002	0.1056	0.1218	0	0	0	0	0.0001	0	0	0	0	0	0	0	0	0.0627					
18. Education sites	0.2047	0.1132	0.1424	0.2251	0.0266	−0.1296	0.1552	0.0604	0.2202	−0.0512	−0.0372	0.0348	−0.1189	−0.0163	0.0478	−0.1733	0.8964	0.0483	1			
	0	0.0196	0.0033	0	0.5849	0.0075	0.0013	0.214	0	0.2919	0.4437	0.4744	0.0142	0.7377	0.3254	0.0003	0	0.3201				
19. Wild foods	−0.2519	−0.0141	0.0642	0.2812	0.3399	0.4569	0.3115	0.2513	−0.1807	0.4447	0.4699	0.5187	0.5585	0.4887	0.2971	0.4286	0.0528	0.6993	−0.005	1		
	0	0.772	0.1863	0	0	0	0	0	0.0002	0	0	0	0	0	0	0	0.2775	0	0.9186			
20. Fish capture	−0.3548	−0.0478	0.1555	0.3324	0.4388	0.2788	0.2354	0.3328	0.0876	0.1673	0.357	0.3854	0.3963	0.2985	0.2582	0.4696	0.227	0.3827	0.1697	0.4866	1	
	0	0.3251	0.0013	0	0	0	0	0	0.0713	0.0005	0	0	0	0	0	0	0	0	0.0004	0		
21. Building materials/timber	−0.3168	0.2644	0.2477	0.261	0.377	0.4733	0.2442	0.3392	0.0399	0.3069	0.3936	0.3195	0.4158	0.3964	0.2973	0.4839	0.1348	0.4113	0.0872	0.385	0.4551	1
	0	0	0	0	0	0	0	0	0.4121	0	0	0	0	0	0	0	0.0054	0	0.0725	0	0	

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