Check for updates

Impact of land use/land cover dynamics on ecosystem service value—a case from Lake Malombe, Southern Malawi

Rodgers Makwinja (ID) **· Emmanuel Kaunda ·**
Seyoum Mengistou · Tena Alamirew

Abstract Lake Malombe ecosystem provides a vast range of services that are vital for the sustenance of the riparian communities. Understanding land use and land cover (LULC) dynamics, as well as the associated impacts on the multiple ecosystem service value (ESV), is extremely important in decision-making processes and effective implementation of an ecosystem-based management approach. This study analyzed the LULC dynamics from 1989 to 2019. The primary objective of the study was to assess its impact on ecosystem services (ES). The ESV was determined using LULC analysis and established global ESV coefficient. The LULC analysis showed a reduction in forest cover by 84.73% during the study period. Built-up, cultivated land, bare land, shrubs, and grassland increased considerably. Rapid population growth, climate change, government policy conflicts, and poverty were identified as the most important drivers of LULC dynamics. Based on ESVs estimations, the ES changes instigated by LULC dynamics in the study area result in an average loss of US$45.58 million during the study period. Within the same period, the lake fishery also recorded a net loss of US$8.63 million. The highest net loss of US$79.832 million was recorded from 1999 to 2019 due to increased loss of forest, a decrease in water bodies and marsh areas. The sensitivity analysis (CS) indicated that our estimates were relatively robust. This study findings provide a piece of empirical evidence that LULC dynamics in the Lake Malombe catchment have led to a significant loss of ESVs, with serious implications for the livelihoods of the local population.

Keywords Ecosystem service value · Land use/ land cover change · Lake Malombe · Riparian communities · Malawi

R. Makwinja (✉) · S. Mengistou
African Centre of Excellence for Water Management,
Addis Ababa University, P.O. BOX 1176, Addis Ababa,
Ethiopia
e-mail: makwinjarodgers@gmail.com; rodgers.
makwinja@aau.edu.et

R. Makwinja
Senga Bay Fisheries Research Centre, P. O. Box 316,
Salima, Malawi

E. Kaunda
African Centre of Excellence in Aquaculture and Fisheries
(AquaFish), Lilongwe University of Agriculture,
and Natural Resources, P.O. Box 219, Lilongwe, Malawi

T. Alamirew
Water and Land Resource Centre of Addis, Ababa
University, P.O. Box 3880, Addis Ababa, Ethiopia

Introduction

The LULC changes are key aspects of global ecological processes (Berihun, et al., 2019; Shiferaw, et al., 2019) and have significant implications on ecosystem services value (ESV) (MEA, 2005; Powers et al.,

2020). Millennium Ecosystem Assessment (MEA) (2005) report highlighted that the socio-economic and biophysical environment of the earth is rapidly changing as the result of socio-economic and biophysical drivers (Crespin & Simonett, 2016; Feng et al., 2012) such as rapid population explosion, agriculture expansion (Kindu et al., 2016), expansion of socio-economy (Makwinja et al., 2019), infrastructure developments, and climate change. The dynamic changes in the hydrologic cycle triggered by LULC dynamics and climate change have forced several aquatic species to migrate to alternative water bodies forcing other indigenous species to live in danger of being endangered, threatened, or even extinct. According to Haregeweyn et al. (2015), LULC dynamics significantly contribute to global atmosphere interactions, land degradation, forest fragmentation, and loss of biodiversity. IPBES (2018) report predicted that by 2050, Africa is expected to have a 2.5 billion population which will likely put severe pressure on the continent's biodiversity and ES. Estimates also show that about 13 million hectares of global forest lands are annually converted to cropland (Arowolo & Deng, 2018; Mendoza-González et al., 2012; Robertson & Swinton, 2005). At a global level, Costanza et al. (2014) estimated that about US$4.3 to US$20.2 trillion of ESVs are lost annually due to LULC changes. Sutton et al. (2016) also estimated that about US$ 6.3 trillion of ESV is lost in impairing ecosystem function instigated by LULC. In El Salvador, Crespin and Simonett (2016) estimated that LULC dynamics caused a 12% loss of natural biomes leading to a 2.6% decrease of ESVs. Many ES valuation studies using LULC changes in sub-Saharan Africa where Malawi is located have also pointed out that the region is under severe pressure of ES degradation with significant consequences for local populations (Arowolo & Deng, 2018; Kindu et al., 2016; Landell-Mills & Porras, 2002; Leh et al., 2013; Shiferaw et al., 2019).

In Malawi, freshwater ecosystems such as Lake Malombe provide multiple ES to the local population. However, LULC dynamics have negatively affected the lake ESs and promoted ecosystem disservices (EDs). Soil erosion and land use degradation triggered by the poor vegetative cover and continuous cultivation is cited as the most serious problem (Palamuleni et al., 2010) that has led to severe watershed deterioration and disruption of ES in many water bodies. In Lake Malawi

catchment, Chavula et al. (2011) estimated that savana/shrub/woodland has significantly declined almost by 90% from 1982 to 1995 due to LULC conversion. With the increasing human population, coupled with worsening poverty, marginal areas such as hilly slopes, rocky areas, marshes, lake periphery, originally left for natural vegetation to flourish are being converted into farmland and settlements (Malawi Government, 2013). Lake Malombe catchment is currently facing serious ecosystem degradation caused by both human activities and environmental drivers, leading to a decline in the ESs. Currently, loss and modification of natural habitats instigated by land-use activities are one of the leading threats to the lake's aquatic biodiversity (Hara & Njaya, 2016). For example, recent studies indicate that the annual soil loss in Lake Malombe catchment is estimated at 29t/ha/year above the national level (Mzuza et al., 2019), cultivated land has increased by 18% (Palamuleni et al., 2010). The lake area has dramatically decreased (Dulanya et al., 2013) and is currently experiencing accelerated eutrophication and catastrophic decline in fish stocks (Jamu et al., 2011; Njaya, 2007). Likoya (2019) further acknowledged that the areas around Lake Malombe catchment have been experiencing some worst ecological disasters through floods and droughts as well as periodic lake level fluctuations. Population explosion evidenced in 1966–1987, 1987–2000, and 2008–2018 in the area has further increased pressure on the land and causing further disruption of the lake ES (Government of Malawi, 2018). Currently, there is visibly severe land degradation in form of soil erosion and deforestation.

Although many LULC studies have been conducted in the Lake Malombe catchment (Dulanya et al., 2013; Palamuleni et al., 2010), they mostly focused on the dynamics of LULC changes and associated drivers, while little attention has been paid to the impact of LULC dynamics on ESVs. Involving various stakeholders to formulate strategies on how to manage the lake ecosystem through an ecosystem-based management approach has been perceived as the solution to Lake Malombe ES degradation. However, information on the extent to which ESV has changed in response to LULC dynamics is required. Unfortunately, no such studies have been conducted

in the Lake Malombe catchment to provide a comprehensive understanding of how LULC dynamics have impacted diverse ESVs. Thus, the objectives of this study are as follows: to quantify the LULC dynamics in Lake Malombe catchment from 1989 to 2019, to assign the specific coefficient of ESV to each land use category using the established unit-value transfer method, and determine the impact of LULC change on ESV. The coefficient of sensitivity is then assessed to estimate the uncertainty in the value coefficient. The significance of this study is to depict the current trend and vulnerability of each ES due to LULC dynamics to enhance policymakers and various stakeholders to take action and address the current lake ecosystem degradation.

Material and methods

Study area

The study was conducted in Lake Malombe catchment—geographical location between latitude 14° 21′ to 14° 45′ south and longitudes 35° 10′ to 35° 20′ east in the southern district of Mangochi (Fig. 1) (Makwinja et al., 2021). The catchment covers approximately 3387 km² stretching from Liwonde National Park, in the southeast to the upper Shire River (FISH, 2015). It lies entirely within the Great African Rift Valley system and is characterized by a series of major and minor faults (FISH, 2015) and calcimorphic soils, which occur along the rift valley floor (Malawi Government, 2013). Typical calcimorphic soils include mopanosols, which are dark grey, sandy-clay soils with a low permeability; and alluvial soils which are grey to brown. The eastern part of the catchment has a low risk of soil erosion as it is partially protected by the forest reserve and Liwonde National park (Kapute, 2018). The western part is deforested and is prone to soil erosion (Malawi Government, 2013). Lake Malombe is fed by water from Lake Malawi via a 19 km stretch of the Upper Shire River and shares the same aquatic ecology with Lake Malawi, including a high level of fish biodiversity, genetic plasticity, and endemism (Kapute, 2018). Hydrologically, Lake Malombe is a shallow, turbid, and nutrient-rich lake with shelving vegetated shores as compared to Lake Malawi (Dulanya et al., 2014). Fish diversity, though, is relatively lower than in

Lake Malawi, the biomass and productivity of the lake are higher probably due to nutrient-enriched water from inflowing streams from highly populated catchment areas and by recycling of nutrients in the sediments attributed to its shallow depth (Gondwe, 2009). The swampy shoreline of the lake is covered by *Phragmites australis*, *Typha domingensis*, *Cyperus papyrus*, *Vossia cuspidate*, *Penniseturm purpureum,* interspersed *Eichhornia crassipes,* scrubs, woodland, thicket, and scattered patches of mopane (FISH, 2015). The common crops grown in the surrounding flood plain include maize, groundnuts, rice, cotton, and tubers. The lake has approximately 47 species of fish belonging to families such as Anguillidae, Bagridae, Cichlidae, Claridae, Characidae, Cyprinidae, Mastacembelidae, Mochokidae, and Mormyridae which support the livelihood of the majority of the local population (Weyl et al., 2010). The lake has further diverse habitat types ranging from bottom substrate characterized by muddy, shallowest areas especially in the western and southeastern part of the shoreline, and dense beds characterized by oxygen weeds in the northeastern, and southwestern shoreline of the lake (FISH, 2015).

Satellite images pre-processing and land use classification

In this study, dry season Landsat images of LULC of 1989, 1999, 2009, and 2019 were produced from spectral Landsat imagery with a spatial resolution of 30 m retrieved from United States Geological Survey Website (USGS, http://glovis.usgs.gov/) using Worldwide Reference System Path 29 and Row 32. Before interpretation, atmospheric correction and geometrical rectification were performed including the resembling of a 1989 satellite image to match the pixel resolution. The criteria used to select Landsat imagery for the development of a land cover database for the Lake Malombe catchment was governed by existing multitemporal images, vegetation phenology, and image class (cloudiness, haze), and the catchment boundary. All images were captured in August and September during the dry season in Malawi to have clear distinctive phenology and diverse land cover characteristics. The individual catchment differentiation shapefile was used to sub-set the individual Landsat images. The area of the shapefile was revised from the location base map of the study area.
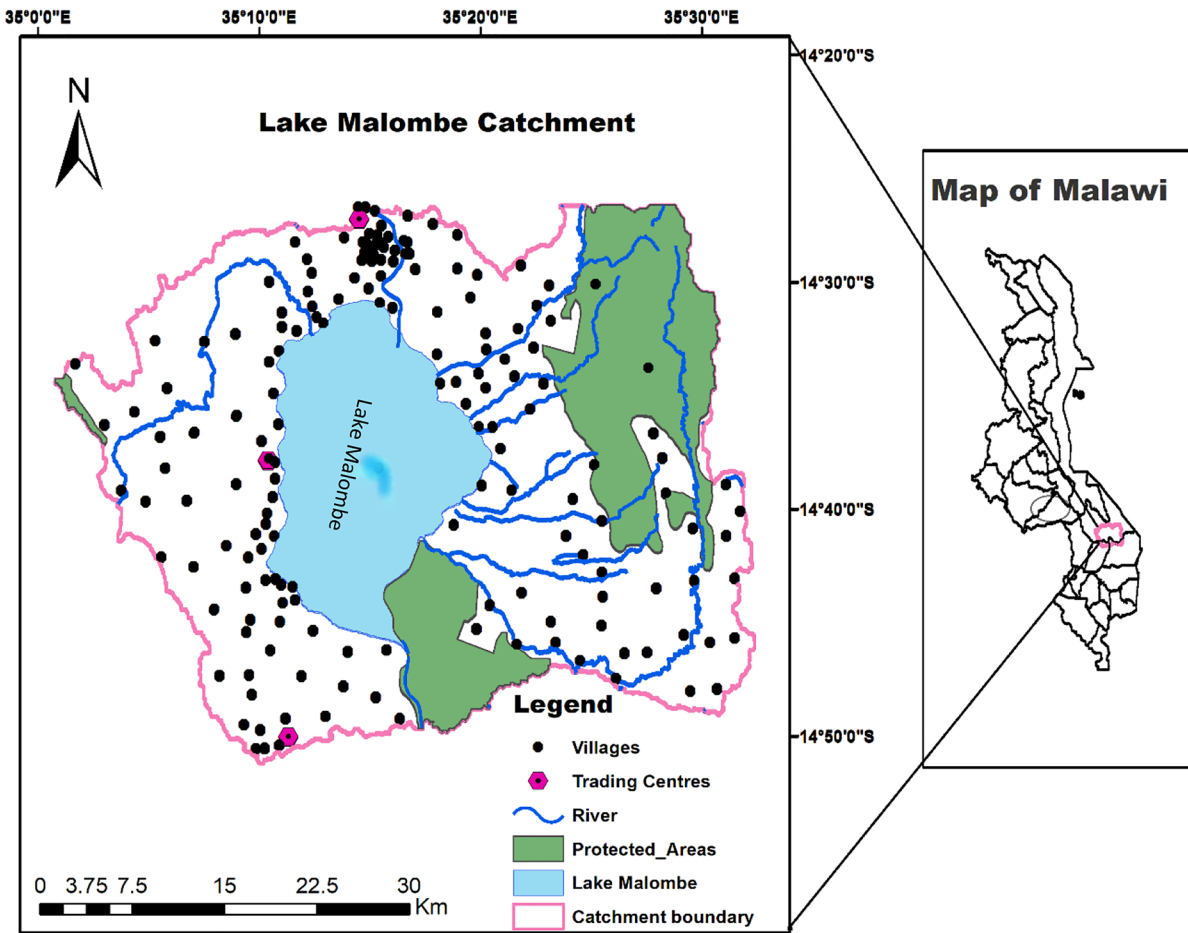
Fig. 1 Lake Malombe catchment

Data processing

Land cover mapping and subsequent quantitative change detection require geometric registration between image scenes and radiometric rectification to adjust for differences in atmospheric conditions, viewing geometry, and responses (Lillesand et al., 2007), and sensor noise. Landsat images were processed using ENVI 5.1 geospatial software. A multiband combination of Landsat images was done in preparation for research spectral characteristics of various types of LULC. Geometric correction of remote sensing images was done using Malawi DeM, Universal Transverse Mercator Projection, Arc 1960, and UTM zone 36S, based on 1:50,000 topographical map scale to fit

the Landsat images (Pettorelli et al., 2005) and eliminate errors of Landsat images which could probably be produced due to position of the sun and angle sensor.

Image enhancement

To check for applicability of the LULC classified map obtained after running the land classification tool in Arc Map 10.2, the location points of the current known LULC were compared with the classified map. Coordinates were captured for 30 different training points using a Garmin Etrex Venture HC, GPS. Observations were made on the current LULC for each point. With

a false-color composite, band combination of 4, 3, and 2 for Landsat 5, 7, and 8, various features in the imagery were identified. In this standard false composite, the vegetation appears shades of green, water blue, soil, and other dark grey. This TM band combination gives results similar to traditional color infrared aerial photography and highlights vegetation in green color thereby making them easy to visualize.

Normalized difference vegetation index

The normalized difference vegetation index (NDVI) was used to assess the presence of green vegetation and was computed as follows:

$$NDVI = \left(\frac{NIR - RED}{NIR + RED} \right) \tag{1}$$

$NIR = Near - infrared, \ RED = Red \ band$

NDVI values ranged from -1 to 1 means the higher the NDVI value, the higher the fraction of green vegetation present in the area. Landsat band 4 (0.8–9.94 mm) measured the reflectance in the NIR region and band 3 (0.63–0.69 mm) measured the reflectance in the red region. However, for Landsat 8, the NIR and red regions had different wavelength ranges. Therefore, they were computed using bands 4 and 5 for red and NIR respectively which resulted in values ranging from 0 to 200 and fit within an 8-bit structure. The green color showed the presence of vegetation and other colors show the absence of green vegetation. These attributes were useful in classifying the images.

Land use/land cover change image classification

The land in the study area was classified based on physiographical knowledge of the study area, visual interpretation using historical Google Earth images, supporting supplementary data, and the researcher's prior local knowledge of the study area. The study area was classified into six characteristics (Table 1) using the spectral signature. Stratified random sampling techniques were employed to collect 320 points for accuracy assessment. Land classes were verified by field observation in situ. Reference data was retrieved from Google Earth. Kappa coefficient and user accuracy derived from the error matrix were used in determining the accuracy assessment of the classification. The 2019 LULC imagery was subjected to a minimum of 80% overall accuracy and was used as a reference to classify historical images. The 2019 imagery was captured to compare phenological data during the study period and historical images (1989, 1999, 2009, and 2019) were further visually interpreted taking into account image tone, texture, shape, and class patterns. The LULC change analysis was further determined using the post-classification comparison (PCC) technique and was reported in a cross-tabulation matrix. Arc GIS software version 10.7.1 was used to compute LULC change-traditional matrix using overly procedure to quantify the area converted from a particular LULC class to another LULC category during the study period. The annual rate of change was determined as shown in the following equation:

$$r = \left(\frac{1}{t^{2-}t^1} \right) * \ln\left(\frac{S_2}{s_1} \right) \tag{2}$$

where r is the annual rate of change for each class, S_1 and S_2 are areas of each LULC class at a time t^1 and t^2, respectively.

Calculation of Lake Malombe ESV as a consequence of LULC dynamics

The benefit transfer approach (BTA) was used to estimate the values of ES of different LULC types and their dynamics (Niquisse et al., 2017). Since literature focuses on Lake Malombe's ESV is scarcely available, existing values and data from the study sites of similar locations were used (Kindu et al., 2016). Based on the global ESV coefficients proposed by Costanza et al. (1997), the equivalent value per unit area of ES for Lake Malombe was extracted. Using Costanza et al.'s indexes as a foundation, ESV per unit area for each land use attribute was assigned based on the equivalent coefficient value of the ES

Table 1 Description of land use/land cover categories

LULC types	Descriptions
Cultivated land	Agricultural production areas which include area prepared for cultivation, covered by crops, is practiced subsistence or commercial farming or grazing land during the dry season or rice scheme. Crop production includes maize widely adapted in both highland and lowlands and it is a staple food, rice, and vegetables dominated in the lowland areas of Lake Malombe, beans, cotton, and groundnuts in the upland
Forestry land	Areas with tall trees above 20 m or fewer shrubs with no undergrowth. Mangochi district has five gazette forest reserves dominated by miombo woodlands tree species and Palms. The Palm Forest reserve is dominated by *hyphae petersiana* (gwalangwa) and some valuable tree species such as (mbawa) *Khaya anthotheca* (Mlombwa) *Pterocarpus angolensis* (Ngwenya) *Adina microcephala* and (tsanya) *Colophospermum mopane*. Bare rock and/or coarse fragments. Areas that do not have an artificial cover as a result of human activities. These areas include areas with less than 4% vegetative cover
Bare land/shrubs, grassland	Bare land/shrubs, grassland include areas that do not have an artificial cover as a result of anthropogenic activities, have shrubs and permanent or seasonal grass
Build upland	These include areas used for settlements, permanent concentration buildings, and man-made structures and activities, ranging from large villages to town scale
Marshes	This is an area dominated by herbaceous rather than woody plant species. The marshes normally are found at the edges of the lakes and streams where they form a transition between aquatic and terrestrial ecosystems. They are mostly dominated by grasses, reeds, and rushes
Water bodies	Water bodies include permanent lakes, rivers, streams, seasonal or permanent wetland, intermittent pools, perennial marshy and man-made dams

(Table 2). The ESV of Lake Malombe catchment for each of the periods (1989, 1999, 2009, and 2019) was determined using the models described by Costanza et al. and recommended by Li et al. (2010) and Kreuter et al. (2001).

$$ESV_k = \sum_f A_k VC_{kf} \tag{3}$$

Table 2 Global Ecosystem service values (ESVf) per unit area for different land use categories (US$/ha/year (Costanza et al., 1997)

		Marsh/mangroves	Cultivated	Forest	Built-up	Water bodies	Grass/bare
Provisioning services	Water supply	7600	0	3	0	2117	0
	Food production	466	54	43	0	41	67
	Raw Materials	162	0	138	0	0	0
	Genetic resources	0	0	16	0	0	0
Regulatory services	Gas regulation	266	0	0	0	0	7
	Climate regulation	0	0	141	0	0	0
	Disturbance regulation	1839	0	2	0	0	0
	Hydrological regulation	30	0	2	0	5445	3
	Erosion control	0	0	96	0	0	29
	Biological control	0	24	2	0	0	23
	waste treatment	6696	0	87	0	666	87
Supporting services	soil formation	0	0	10	0	0	1
	Habitat	439	9	0	0	0	0
	Pollination	0	14	0	0	0	25
Recreation and culture	Recreation	491	0	66	0	230	2
	Culture	1761	0	2	0	0	0
Total		19,750	101	608	0	8499	244

$$ESV_f = \sum_k A_k VC_{kf} \qquad (4)$$

$$ESV = \sum_k \sum_f A_k VC_{kf} \qquad (5)$$

where ESV_k, ESV_f, and ESV represent the ESV of land use type k, service function f, and the total ESVs, respectively (in the unit of US$). The A_k is the area of land use type k (ha) and VC_{kf} is the value coefficient for land use type k with ecological service function type f. The sensitivity analysis (CS) was also performed to verify the changes in the ESV for a given change in the coefficient. Using the standard economic theory of elasticity as an indicator of how well an economic variable responds to another economic variable, the CS was calculated as:

$$CS = \frac{ESV_j - ESV_i}{VC_{jk} - VC_{ik}/VC_{ik}} \qquad (6)$$

where ESV refers to the estimated ESVs, VC refers to the value coefficient, i and j represent the initial and adjusted values, and k is the land type.

Exploratory survey and assessment of perceived drivers

To identify the perceived drivers of LULC dynamics, eight focus group discussions (FDG), comprising an average of fifteen members per group were conducted. The FDG was coordinated by a single facilitator to maintain consistency in question delivery, timing emphasis, and reactivity (Maxwell, 2013). The FGDs consisted of young and elderly of local communities in the Traditional Authority Chimwala, Chowe and Mponda, group village headman Changamile, Changali, Mpinganjira, Mtambo, Chowe, Nalikolo, Kadewere, Dimu, Chapola, with a balanced composition in terms of gender. Questions focusing on LULC dynamics that have occurred over the past years and reasons why such dynamics occurred were presented to each group. The drivers identified by the communities were ranked based on their degree of importance using a Likert scale from 1 to 5 (1 = least important and 5 means most important). Six key informant interviews targeting chiefs, government officials, NGOs, leaders of environmental conservation groups, village beach committees, village elders, and fish traders were also conducted. The key informant interviews were conducted using a phenomenological research approach (Patton, 1990) to triangulate different data sources to improve validity. The open-ended questions were used to allow the local communities to discuss and elaborate more on their experiences (Maxwell, 2013). Data collection procedures followed high ethical principles recommended by Levy and Lemeshow (1999). The FGDs and the key informant interviews were conducted between October and November 2020.

Statistical analysis

Geospatial LULC Landsat satellite data were analyzed using GIS and remote sensing approaches. ArcGIS version 10.7.1 and ENVil 5.4 software were used. Some qualitative and quantitative data were analyzed using descriptive and inferential statistics. STATA version 15 was used in the data analysis.

Results

Table 3 presents the results of the confusion matrix for accuracy assessment of LULC classification of the years 1989, 1999, 2009, and 2019. With Kappa coefficiency of 87% in both 1989 and 2019, the confusion matrix produced overall very good accuracies for the six classification points and the defined LULC classes. Both class-specific user accuracies and producer's accuracies were at least 80%, suggesting that a considerable percentage of pixels were correctly classified. The LULC dynamics from 1989 to 2019 derived from image classification are presented in Fig. 2. The changes in the size of six land use categories are presented in Table 4. Comparing the land use of 1989, 1999, 2009, and 2019, there was an obvious change in LULC. Built-up, shrubs/grass/bare land, and cultivated land progressively increased over the study period. The built-up area increased by 11.5% in the period (1989–1999), 27.6% in the period (1999–2009), and 30.7% in the period (2009–2019). The overall increment of the built-up area in the study period was 149%. Cultivated land increased from 52,932 ha to 62,852 ha in the period (1989–1999) translating to an 18.7% increase, slightly increased by

Table 3 Accuracy assessment of classified image

1989	Forest	Built-up	Marshes	Cultivated land	Shrubs/Grass/bare land	Waterbody	User accuracy
Forest	96.15	0.00	0.00	7.86	0.00	0.00	82.83
Built up	0.33	97	1.76	7.39	39.71	0.00	87.06
Marshes	0.25	0.00	97.08	0.20	0.37	0.00	98.49
Cultivated land	1.04	2.97	0.00	84.55	0.02	0.00	95.08
Shrubs/grass/bare land	2.23	0.00	0.17	0.00	59.75	0.00	88.47
Water body	0	0.00	0.17	0.00	0	100	99.95
Producer accuracy	96.15	97.03	97.08	85.28	59.75	100	
Overall accuracy = 90.24%							
Kappa coefficient = 0.875							

1999	Forest	Built-up	Marshes	Cultivated land	Shrubs/Grass/bare land	Waterbody	User accuracy
Forest	99.82	0.00	0.00	000	0.00	0.00	82.83
Built up	0.00	71.13	0.42	3.48	9.75	0.00	87.06
Marshes	0.18	7.64	99.11	8.48	0.72	0.18	98.19
Cultivated land	0.00	21.23	0.00	85.28	0.80	0.00	95.08
Shrubs/grass/bare land	0.00	0.00	0.00	2.76	88.73	0.00	88.47
Water body	0.00	0.00	0.47	0.00	0.00	99.82	99.95
	100	100	100	100	100	100	
Producer accuracy	96.15	97.03	97.08	85.28	59.75	100	
Overall accuracy 90.24%							
Kappa coefficient = 0.88%							

2009	Forest	Built-up	Marshes	Cultivated land	Shrubs/Grass/bare land	Waterbody	User accuracy
Forest	85.01	0.00	0.18	0.00	0.00	0.00	80.07
Built up	0.00	82.15	5.9	4.45	9.00	0.00	52.24
Marshes	0.05	2.75	92.8	0.00	0.22	6.06	83.25
Cultivated land	0.00	14.65	0.53	90.05	0.83	0.01	95.73
Shrubs/grass/bare land	14.94	0.45	0.42	5.50	89.95	0.00	86.2
Water body	0.00	0.00	0.17	0.00	0.00	93.93	99.31
	100	100	100	100	100	100	
Producer accuracy	99.62	87.36	79.06	83.38	79.1	100	
Overall accuracy = 89.33							
Kappa coefficient = 0.85%							

| 2019	Forest	Built-up	Marshes	Cultivated land	Shrubs/Grass/bare land	Waterbody	User accuracy
Forest	79.9	0.02	2.83	4.14	0.00	0.00	99.86
Built up	12.27	79.06	8.63	8.25	7.56	0.00	82.69
Marshes	4.65	5.30	83.26	0.25	0.10	0.38	80.54
Cultivated land	3.18	15.62	2.10	87.36	2.8	0.00	81.09
Shrubs/grass/bare land	0.00	0.00	3.18	0.00	89.54	0.00	99.85
Water body	0.00	0.00	0.00	0.00	0.00	99.62	84.35
	100	100	100	100	100	100	
Producer accuracy	85.01	89.93	92.8	90.05	93.93	82.15	
Overall accuracy = 89.36							
Kappa coefficient = 0.87							
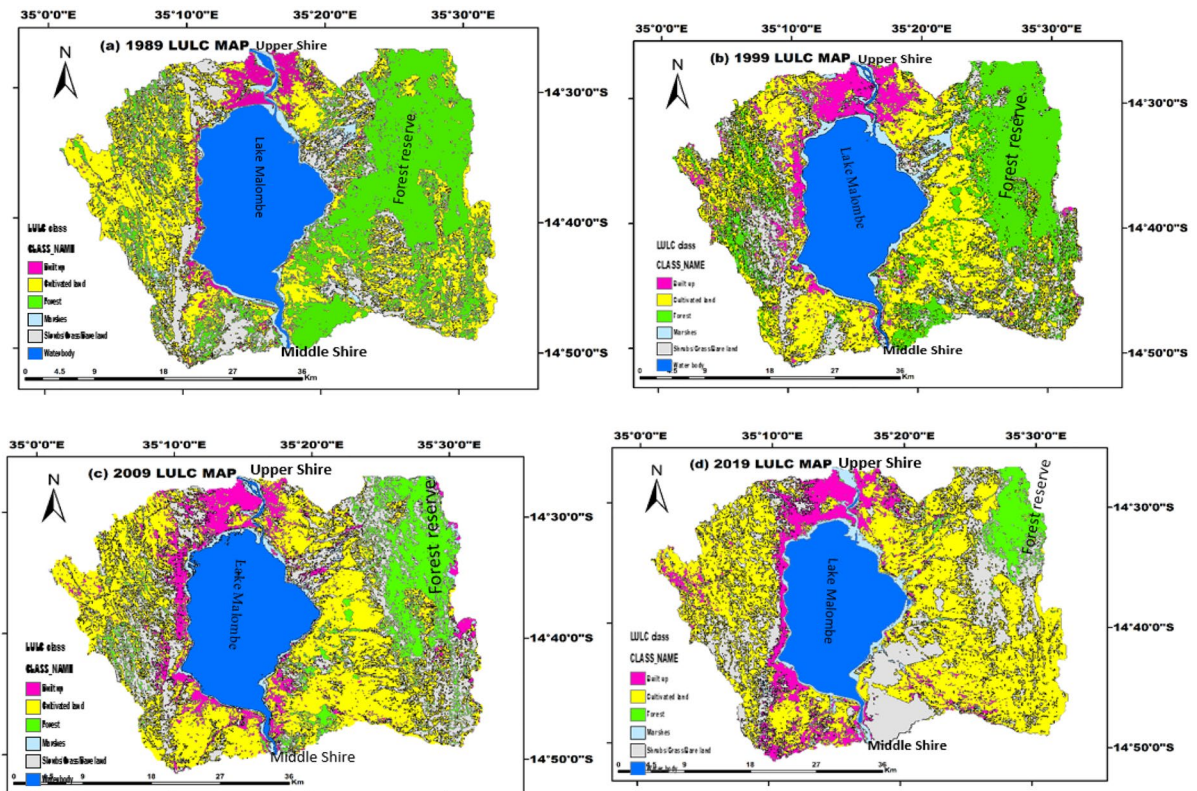
Fig. 2 Land use/land cover classes

6.96% in the period (1999–2009) and then 17.48% in the period (2009–2019). A similar trend is observed in shrubs/grass/bare land with a percentage increase of 11.5% in the period (1989–1999) and a sharp increase of 27.6% in the period (1999–2009) and then a very slight increase of 3.07% in the period (2009–2019). Overall, the increment of the cultivated area was 49.2% and shrubs/grass/bare land 46.72% during the study period. The total area of forest land was reduced from 56235 to 8585 ha during the study period translating to an 87.3% decrease and the value was the highest of its negative dynamic index among

all land use classes suggesting an increased rate of deforestation in the lake catchment. Other land-use classes such as water bodies and marshes showed mixed results. Waterbody decreased by 5.99% period (1989–1999), slightly increased by 1.93% period (1999–2009), and then dropped by 4.47% period (2009–2019). Overall, the water body showed a negative trend of 8.46% throughout the study period. Marshes increased by 42.8% in the period (1989–1999), significantly decreased by 48.27% in the period (1999–2009), and then fluctuated positively by 36.96% in the period (2009–2019). Overall,

Table 4 Absolute area coverage

LULC class	Area coverage (ha)				Cover change between period (%)		
	1989	1999	2009	2019	1989–1999	1999–2009	2009–2019
Shrubs/grass/bare land	29,550	32,961	42,063	43,358	11.5	27.6	3.07
Built up	7054	13,364	16,286	17,595	89.5	21.86	8.03
Cultivated land	52,932	62,852	67,229	78,983	18.7	6.96	17.48
Water body	33,300	31,306	31,911	30,483	−5.99	1.93	−4.47
Forest	56,235	36,152	23,069	8585	−35.71	−36.19	−62.79
Marshes	5691	8127	4204	5758	42.8	−48.27	36.96
Total	184,762	184,762	184,762	184,762	120.8	−26.11	−1.72

Fig. 3 Drivers for land use/
land cover changes
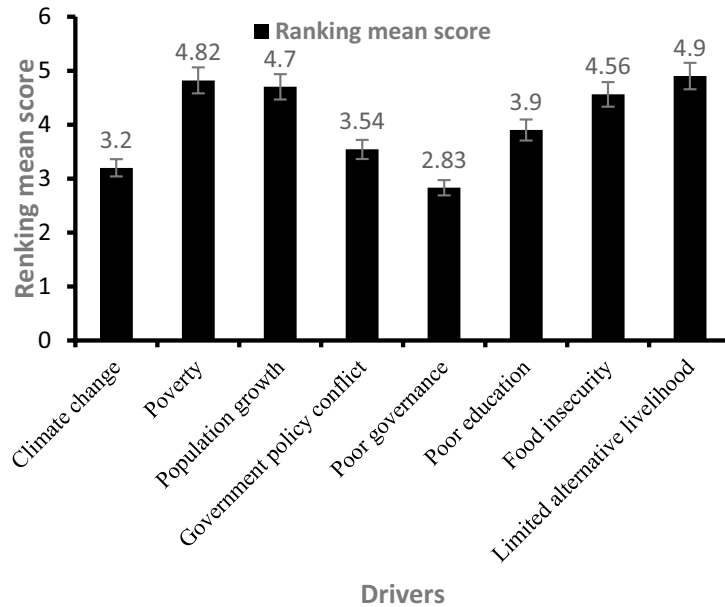
Note: low score means less important drivers while higher score means the most important driver

the area covered by marshes slightly increased by 1.18% throughout the study period. The major perceived drivers for LULC dynamics were rapid population growth, climate change impact, poverty, government policy conflicts, poor governance, poor education, food insecurity, and limited alternative livelihood (Fig. 3). Limited alternative livelihood was ranked the highest followed by poverty, population growth, food insecurity then poor education. Climate change, poor governance, and other associated drivers were ranked the lowest. The fluctuation of water bodies was strongly linked to the impact of climate change (Table 5) defined within the context of high temperatures and declining rainfall patterns in the catchment. The decrease in forestry land was linked to increased rapid population growth, government policy conflicts, and poverty. An increase in the built-up area was also highly linked to an increase in human population suggesting that as the population increases more land for settlements is required at the expense of forest land.

Lake Malombe ecosystem services

Considering ESV changes across the different time intervals (1989–1999, 1999–2009, 2009–2019), ESV

for forest land displayed a negative trend whereas the ESV for shrubs/grass/bare land increased (Table 6). For marshes and water bodies, the ESVs were mixed up. The ESV for marshes increased in 1999–2009 interval, decreased in 1999–2009, and then increased in 2009–2019. Waterbody's ESV on the other hand increased in 1999–2009 and then decreased between the 2009–2019 interval. For cultivated land, shrubs, bare land, and grassland, the ESVs have been increasing across different intervals. The net ESVs between 1989 and 1999 increased by US$20.77 million and decreased by US$ 79.83million between 1999–2009 and slightly increased by US$13.48 million. The increase in net value between 1999–2009 time intervals was due to an increase in marshes as the lake level declined. On the other hand, the dramatic reduction in ESV observed between 1999–2009, was due to the high rate of conversion of marshland into cultivated as well as a fishing ground. It was difficult to estimate the ESV value for build-up areas, though the rural houses played an integral part of the lake landscape matrix and had an impact on ES provisioning. Table 7 presents the estimates of sixteen ES categorized as provisioning, regulating, supporting, recreation, and culture. In terms of the estimated ESV for provisioning services, water

Table 5 Lake Malombe LULC dynamic drivers' correlation matrix

| Factors | LULC classification | | | | | |
	Built up	Cultivated	Water bodies	Forestry	Marshes	Shrubs/grass/bare land
Rainfall	−0.865	−0.928	0.699	0.94	0.507	−0.848
Max temp	0.999	0.944	−0.882	−0.982	−0.196	0.785
Poverty	−0.95	−0.771	0.783	0.852	0.12	−0.53
Population growth	0.188	0.500	−0.569	−0.35	0.432	0.745
Government policy conflict	0.134	0.876	0.364	0.803	0.02	0.543

supply registered a significant net loss of US$28.5 million between 1999–2009 and a slight gain of ESV values of US$14.23 million and US$8.75 million between 1989–1999 and 2009–2019. Overall, there is a general net loss of water supply ESV of about US$ 5.5 million during the study period. The ESV net gain for food production slightly increased by US$0.16 million throughout the study period. The ESVs for raw materials and genetic resources have been declining throughout the study period with a total net loss of US$6.56 million and US$ 0.76million. The regulatory services such as gas regulation and biological control experienced a slight net gain of US$0.12million and US$0.85million. Climate regulation had a net loss of US$6.72 million, disturbance regulation (US$0.3 million), hydrological regulation (US$15.46 million), erosion control (US$4.18 million), and waste treatment (US$4.37 million). Supporting services such as soil formalization had a net gain of US$0.03 million, habitat (US$ 1.31 million), and pollination (US$0.71 million). The ESV values for recreation and culture services were reduced with a net loss of US$3.73 million for recreation services and US$4.26 million for culture. Table 8 shows the coefficient of total ESVs and the coefficient of sensitivity (CS). The CS is defined as the ratio of the percentage change in the estimated total ESVs and the percentage change in the adjusted valuation coefficient. In this study, the CS in all analyzed LULC classes were less than one with the highest (0.708) reported in the waterbody class after adjusting the value coefficient for these land use categories by 50%. The CS for the water body was the highest because of the highest ESVs coefficient. The CS greater than 1 means that ESV is elastic to the coefficient while less than 1 means that ESV is

inelastic. The greater the proportional change in the ESVs relative to the proportional change in the valuation coefficient, the more critical it becomes to use the ESV coefficient. The results from this study indicate that the total ESVs estimated in the study area were relatively inelastic to the ecosystem value coefficients, suggesting that the ESVs used in this study were practical and robust.

Discussion

Analysis of LULC dynamics

The LULC dynamics for the Lake Malombe catchment from 1989 to 2019 were computed. The analysis showed a massive expansion of built-up areas and cultivated land. The forest cover decreased during the period (1989–2019). This is in line with many studies in Malawi (Chavula et al., 2011; Dulanya et al., 2013; Gondwe et al., 2019; Haak et al., 2015; Jamu et al., 2003; Mawenda et al., 2020; Munthali & Murayama, 2015; Pullanikkatil et al., 2016) and other countries around the global (Bone et al., 2017; Duraisamy et al., 2018; Hailu et al., 2020; Kabanda, 2019; Käyhkö et al., 2011; Kilic et al., 2006; Kindu et al., 2016; Landell-Mills & Porras, 2002; Mtui et al., 2017; Mucova et al., 2018; Phiri et al., 2019; Ritse et al., 2020; Teucher et al., 2020). The major perceived drivers for LULC dynamics were rapid population growth, climate change impact, poverty, government policy conflicts, poor governance, poor education, food insecurity, and limited alternative livelihood. Kindu et al. (2015) also identified similar drivers as the main cause of LULC dynamics in the Munessa-Shashemene landscape of the south-central

Table 6 Change in Lake Malombe ESV (million US$)

Change in ESV in Lake Malombe catchment (million US$)

LULC class	1989		1999		2009		2019		Change in ESV between periods (million US$)		
	ESV	ESV (%)	ESV	ESV (%)	ESV	ESV (%)	ESV	ESV (%)	1989–1999	1999–2009	2009–2019
Marshes	112.4	25.42	160.51	34.67	83.03	21.67	113.72	28.68	48.11	−77.48	30.69
Cultivated land	5.34	1.21	6.35	1.37	6.79	1.77	7.98	2.01	1.01	0.44	1.19
Forestry	34.19	7.73	21.98	4.75	14.025	3.66	5.219	1.32	−12.21	−7.955	−8.806
Built up	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water bodies	283.02	64.01	266.07	57.48	271.211	70.79	259.08	65.33	−16.95	5.141	−12.131
shrubs/grass/bare land	7.21	1.63	8.02	1.73	8.042	2.10	10.58	2.67	0.81	0.022	2.538
Total	442.16	100	462.93	100	383.098	100	396.579	100	20.77	−79.832	13.481

highlands of Ethiopia. Limited alternative livelihood option was ranked the highest because most of the vulnerable local population in Lake Malombe catchment live at the margins of the cash economy and have very limited choices for generating an income (Bulirani, 2003). Without access to land and marketing, ES generally offers the greatest option for sustenance (Stringer et al., 2020). Consequently, these vulnerable individuals who live close to the lake ecosystems such as fishers, hunters, and small-scale farmers are increasingly pushing forest land and the lake biodiversity to the verge of extinction as the result of deforestation, agriculture expansion, and overexploitation (Woodruff, 2010). Behind direct threats to the lake ES, complex factors such as high rates of illiteracy, poor governance, social-economic, and rapid population growth interact (Hall et al., 2017).

Mangochi district (where Lake Malombe is located) is ranked as one of the districts in Malawi with high illiteracy rated at 65.9% (NSO, 2012). Increased unregulated sand mining, illegal charcoal production, brick molding, and kilning that lead to massive deforestation, reduction in aesthetic beauty, and high rate of erosion are adopted by the poor with a low level of education (Government of Malawi, 2014). The main challenge of the high illiteracy rate is that the local communities are held back in terms of accessing knowledge on the value of ES (FISH, 2015). For example, continuous overexploitation of biodiversity in the Lake Malombe catchment is attributed to the fact that local communities lack knowledge on how to embrace an effective governance system to achieve sustainable ES management (Makwinja et al., 2019). There is further limited knowledge on the development of sustainable adaptation strategies as well as alternative livelihood options. This consequently leads to unsustainable exploitation of the scarce ES. The unsustainable exploitation of the ES leads to ecosystem disservices. Ecosystem disservices often breed conflict over the limited resources. Conflict leads to resource scarcity through habitat destruction, over-exploitation of natural resources, pollution, and breakdown of environmental programs (Nagoli et al., 2016). Lake Malombe provides the best example. The onshore and offshore aquatic vegetation has dramatically declined due to the high level of deforestation instigated by the wide

Table 7 Values of Lake Malombe ecosystem service functions (million US$)

		1989		1999		2009		2019		Change in ESV per time interval		
		ESV	ESV (%)	ESV	ESV (%)	ESV	ESV (%)	ESV	ESV (%)	1989–1999	1999–2009	2009–2019
Provisioning services	Water supply	113.92	34.31	128.15	37.99	99.57	34.85	108.32	37.59	14.23	−28.58	8.75
	Food production	11.28	3.4	12.23	3.63	10.71	3.75	11.42	3.96	0.95	−1.52	0.61
	Raw materials	8.68	2.61	6.31	1.87	3.86	1.35	2.12	0.73	−2.37	−2.45	−1.74
	Genetic resources	0.9	0.27	0.58	0.17	0.37	0.13	0.14	0.05	−0.32	−0.21	−0.23
Regulatory services	Gas regulation	1.72	0.52	2.39	0.71	1.41	0.49	1.84	0.64	0.67	−0.98	0.43
	Climate regulation	7.93	2.39	5.1	1.51	3.25	1.14	1.21	0.42	−2.83	−1.85	−2.04
	Disturbance regulation	10.58	3.19	15.02	4.45	7.78	2.72	10.61	3.68	4.44	−7.24	2.83
	Hydrological regulation	181.69	54.72	170.87	50.66	174.05	60.92	166.23	57.69	−10.82	3.18	−7.82
	Erosion control	6.26	1.88	6.94	2.06	3.43	1.2	2.08	0.72	0.68	−3.51	−1.35
	Biological control	2.06	0.62	2.34	0.69	2.63	0.92	2.91	1.01	0.28	0.29	0.28
	Waste treatment	67.75	20.4	81.28	24.1	55.07	19.27	63.38	22	13.53	−26.21	8.31
Supporting services	Soil formation	0.1	0.03	0.39	0.12	0.27	0.09	0.13	0.05	0.29	−0.12	−0.14
	Habitat	2.97	0.89	4.13	1.23	2.45	0.86	3.24	1.12	1.16	−1.68	0.79
	Pollination	1.48	0.45	1.7	0.5	1.99	0.7	2.19	0.76	0.22	0.29	0.2
Recreation and culture	Recreation	14.22	4.28	13.64	4.04	11	3.85	10.49	3.64	−0.58	−2.64	−0.51
	Culture	14.42	4.34	14.38	4.26	7.45	2.61	10.16	3.53	−0.04	−6.93	2.71
Total		332.04	100	337.3	100	285.72	100	288.15	100	5.26	−51.58	2.33

Table 8 Percentage changes in estimated ESV and CS resulting from a 50% adjustment in VC

Change of value coefficient	1989		1999		2009		2019	
	Percentage	CS	Percentage	CS	Percentage	ESV (%)	Percentage	CS
Marshes VC ± 50%	0.254	0.254	17.336	0.347	10.837	0.217	14.34	0.29
Cultivated land VC ± 50%	0.012	0.012	0.686	0.014	0.886	0.018	1.01	0.02
Forestry VC ± 50%	0.077	0.077	2.374	0.047	1.830	0.037	0.66	0.01
Built up VC ± 50%	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.00
Water bodies VC ± 50%	0.640	0.640	28.738	0.575	35.397	0.708	32.66	0.65
Shrubs/grass/bare land VC ± 50%	0.016	0.016	0.866	0.017	1.050	0.021	1.33	0.03

expansion of agriculture, high demand for firewood and charcoal production. Fishery resources have been overexploited due to human pressure putting human-wellbeing at risk (FISH, 2015; Malawi Government, 2010). There is a general piece of evidence that large four endemic *Oreochromis species-Oreochromis shiranus*, *Oreochromis karongae*, *Oreochromis squamipinnis*, and *Oreochromis lidoles* have almost vanished from the lake due to among other reasons being recruitment overfishing, destruction of habitats, increasing silt-load, and disappearance of weed areas in the Lake (FISH, 2015; Hara & Njaya, 2016). This is also a case in many African Great Rift Valley lakes (Ogutu-Ohwayo et al., 1997) such as Lake Victoria (Kolding et al., 2008; Matsuishi et al., 2006), Lake Malawi (Bootsma & Hecky, 1993), Lake Chilwa (Jamu et al., 2003), Chia lagoon (Makwinja et al., 2019), and other lakes in Africa (Kafumbata et al., 2014).

Poverty is one of the major drivers for the unsustainable exploitation of ES. Malawi is a small but densely populated country in sub-Saharan Africa with 62% of the population live on less than US$ 1.25 a day and 89% lives below the US$ 2 a day threshold (FISH, 2015; NSO, 2005). The majority of the poor are heavily reliant on the low-input production of maize on small landholdings where the soil is degrading (Sanchez, 2002). Agriculture is the major source of income for rural households (63.7%) but land productivity is generally low. Most farmers rely on rain-fed farming or limited forms of irrigation (Nagoli et al., 2017; Pullanikkatil et al., 2015). In Lake Malombe catchment, increased the rate of poverty is evidenced by an increased percentage of households experiencing food shortages annually (Fig. 4a) which is instigated by increased drought cases, crop damages due to pest and diseases, lack of inputs

such as fertilizers, excessive rain (Fig. 4b), low level of education, high rate of youth unemployment, limited livelihood options, land scarcity for farming and social conflicts (FISH, 2015; Hartzell & Hoddie, 2003). Lake Malombe catchment is surrounded by hills in the west bank, 3–7 km away from the lake, bordered by the Mangochi hills on the eastern part and the Liwonde National park in the southeast banks trapping the fishing communities within the narrow strips of land along the lake at a high population density of 500/km^2 (Bell & Donda, 1993). Charcoal burning and fishing are the main sources of livelihood while farming is done in the steep slopes, rocky areas, flood plain, wetlands, and around the lake periphery. Poverty is forcing the fishing communities to remove trees for cultivation and income generation (Government of Malawi, 2014). It further forces them to seek different unsustainable coping strategies that have serious implications for ES (Fig. 4c). The endangered tree species such as *Percopsis angolensis*, *Terminalia sericea*, *Colophospermum*, *Pterocarpus angolensis* in the forest reserve are being cleared out for charcoal production (plate 1). The decline in marshes in the period of 1999–2009 is linked to the shifting of riparian communities' coping strategies from fishing to farming systems to avert the shock (FISH, 2015; Salas et al., 2010). Many fishing households diversified their livelihood through cultivating upland areas and steep slopes a few meters away from the lake. Flood plain cultivation and small-scale irrigation are also common during the lake recession leading to a high rate of conversion of marshland into cultivated.` The situation reported in Lake Malombe also applies to other Malawian inland lakes such as Lake Chilwa, Lake Chiuta, and Chia lagoon (Jamu et al., 2003; Makwinja et al., 2019; Mzembe, 1990; Nagoli et al., 2016; Palamuleni et al., 2010).

The government policy conflict is also one of the major drivers for LULC dynamics. For example,
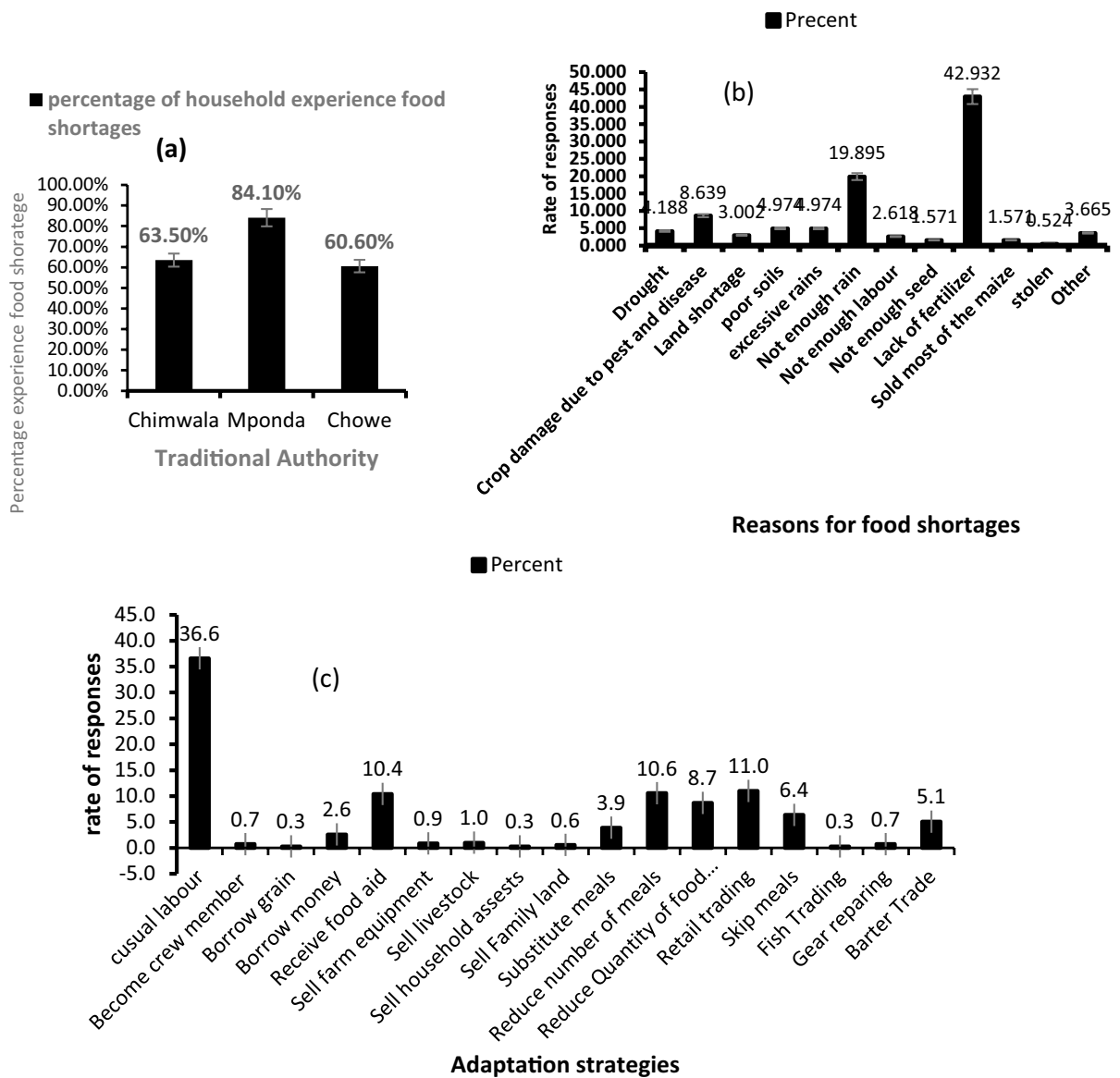
Fig. 4 The rate of food shortages, the reasons, and coping strategies

the National Forest Policy of 1996, considers the forest as life-sustaining as it provides watershed protection and enhancing water resources (Malawi government, 1996). However, this contradicts the food security policy of 2006, the land policy of 2002, and agriculture policy which promote a market-oriented approach as a response to the national economic development agenda. The later policies do not explicitly explain how economic development and ES should be balanced in the face of

unprecedented population growth and economic activities. Agriculture policy priority also contradicts other related policies such as fisheries, land policy, environmental policy, and water policy as it focused much on transformative utilization of land for the farming system to increase agricultural production (Government of Malawi, 2016). The increasing demand for agricultural areas affects a wide range of ES, including forest, water quality, soil retention, carbon sequestration, biodiversity

Fig. 5 Rainfall and temperatures of Lake Malombe catchment
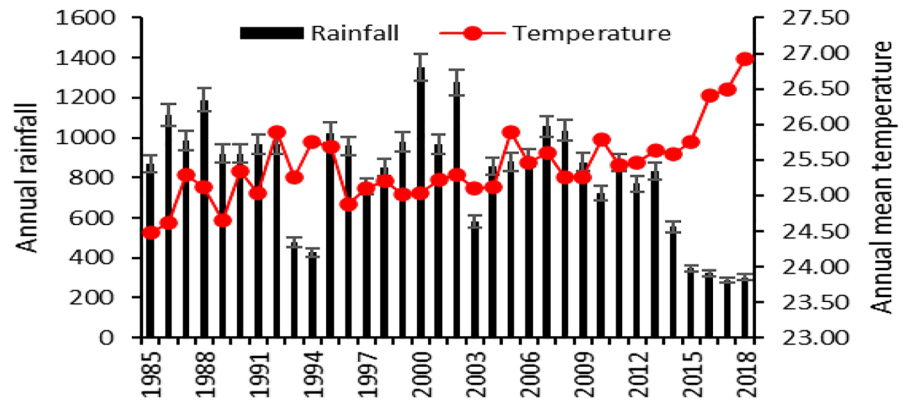
conservation, and nutrient cycling (Dale & Polasky, 2007). Agriculture policy also does not explicitly explain how to balance between these two. Malawi's National Water Policy of 2005 prohibits river bank cultivation and encourage buffers along river banks as one way of protecting marsh/mangroves, while agriculture and irrigation policies on the other hand are framed to promote small scale irrigation, river bank cultivation, thereby increasing the conversion of marshland into cultivated—a scenario which is depicted in 1999–2009 where 48.27% of the marshland in Lake Malombe catchment were lost. In developing countries such as Malawi, irrigation is seen principally as a tool for social-economic development, poverty alleviation, and enhancing food security (Sanmuganathan, 2000). Malawi's irrigation policy of 2016 emphasizes the need to effectively use the freshwater ecosystem for irrigation development to serve human needs such as food, nutrition, and income (Government of Malawi, 2016). Despite the significant contribution of irrigated agriculture to increasing food production and overall socio-economic development, irrigation has come under increasing criticism over the past decade for concerns over increasing environmental problems such as siltation, reduction in vegetative land, decrease in water bodies, and water quality degradation (Alauddin & Quiggin, 2008). In Pakistan, evidence shows that increased irrigated agriculture is associated with increased salinity and depletion of water resources in lakes, rivers, and reservoirs (Qureshi et al., 2008). Malawi's irrigation policy does not explain how these problems should be addressed to achieve a sustainable freshwater ecosystem. The Malawi customary land laws also

offer legal rights on the land if the household converts forest land or buffer zone into farmland. This encourages farmers to legally or illegally covert forest land and buffer zone into cultivated (Government of Malawi, 2002). This policy weakness has also been identified by many researchers in various tropical countries (Green et al., 2013; Muleta et al., 2020; Shiferaw et al., 2019; Solomon et al., 2019; Tendaupenyu et al., 2017; Tolessa et al., 2017).

Climate change is also ranked as a major driver for LULC dynamics in the Lake Malombe catchment. Malawi has experienced severe droughts for the past years notable among these occurred in 1948/49, 1991/92, 1996/97, and 2001/02 seasons (Chavula, 1999). In Malawi, the observed climate changes are evidenced by the changes in the rainfall season, pattern and temperature, and changes in the frequency of droughts and floods (Mkanda, 1999) as well as significant variations in the lake and river levels (Calder, 1995). The historical data (Fig. 5) shows that there have been increasing in maximum temperatures over the past years while total annual rainfall has been declining with negative consequences on Lake Malombe water levels (Likoya, 2019; Ngongondo et al., 2020). Waterbody fluctuated negatively in 1989–1999 and then slightly fluctuated positively between 1999 and 2009 and later declined between 2009 and 2019 (plate 2). This fluctuation is linked to climatic forces such as El Niño/Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) as previously confirmed by Dulanya et al. (2013). Malawi government report states that the Shire River Basin where Lake Malombe is located has been facing significant extreme weather events with severe

drought conditions in 1991–1992 (the same period which corresponds to the decline in water bodies) (Malawi Government, 2013). The report suggests that prolonged droughts that have been experienced in Lake Malombe catchment over the past years are responsible for a decline in water levels, complete drying up of rivers (plate 2) and marshes, decline in fish production, land degradation, loss of soil fertility, loss of forest through the fire, losses in biodiversity, and migration of mammals and other animal species (Malawi Government, 2013). Lake Malombe catchment is further experienced extreme flash floods in the 2000–2001—the period which corresponds to the increase in water bodies. The extreme flash floods led to the loss of agricultural land, low crop production with serious implications on ES and local communities. The marshland also increased in the subsequent years. The increase in marshland was attributed to increased lake siltation and low lake levels that exposed lake beds to sunlight and encouraged the growth of herbaceous grass (Keim et al., 2012).

Lake Malombe ecosystem services

The sensitivity analysis undertaken to test the robustness of our estimation showed that our ESV was reliable which confirms the other previous findings such as those of Tolessa et al. (2017), Leh et al. (2013), Li et al. (2007), Hao et al. (2012), Kindu et al. (2016), and Gashaw et al. (2018). The LULC dynamics were described as the most important driver of change in Lake Malombe ES. The overall ES of the study area experienced a net loss of US$45.58 million during the study period. The value ES loss due to LULC dynamics is greater than the estimated total annual ES benefit generated from Lake Chilwa which is estimated at US$21 million (Malawi Government, 2010), Lake Chuta estimated at US$17 million (Zuze, 2013), and less than the economic benefit generated from Lake Chad (US$750 million) (Kafumbata et al., 2014) and Lake Naivasha (US$613–640 million) (Mekonnen & Hoekstra, 2010). On the other hand, Msofe et al. (2020) reported a total ESVs net loss of US$811.5 million in Kilombero Valley Floodplain, Southeastern Tanzania, over 26-year period—a value which is higher than the one reported in this study. On the other hand, Kindu et al. (2015) reported slightly

lower net loss ranging from S$ 19.3 million to US$ 45.9 million in Munessa–Shashemene landscape of Ethiopia than the current net loss value reported in Lake Malombe. The highest ES net loss value of US$79.832 million was recorded from 1999 to 2019 due to increased loss of forest and marsh areas, which is in line with other research findings in other countries around the globe (Badamfiroo & Mousazadeh, 2019; Hasan et al., 2020; Hu et al., 2008; Li et al., 2007; Muleta et al., 2020; Tolessa et al., 2017; Wang et al., 2006; Zhang et al., 2011). When disaggregated based on ES functions, the provisioning services had a net gain of US$13.16 million in the period of 1989 to 1999 and dramatically experienced ES net loss of US$33.74million and then a slight net gain of US$7.92 million in the period of 2009–2019. Cumulatively, the ES provisioning services from 1989 to 2019 had a net loss of US$ 12.68 million suggesting that the lake ecosystem is degrading and is losing its economic value. The regulatory ecosystem services have been fluctuating since 1989 with the highest net loss of US$36.32 million recorded between 1999 and 2009. The cumulative net loss of ESV for regulations from 1989 to 2019 was US$29.73 million. In terms of supporting services, Lake Malombe catchment had a cumulative net gain of US$1.01million though with a net loss of US$ 1.51 million in the period of 1999 to 2009. Culture and recreational value also cumulatively declined by US$7.99 million during the study period and this could be attributed to the loss of biodiversity and degradation of water quality in the lake. Our results are in line with other research findings in the tropical region (Cawthorn & Hoffman, 2015; Kindu et al., 2016; Li et al., 2010; MEA, 2005; Wangai et al., 2016). Figure 3 b on the other hand shows that the total fish biomass has also been dramatically declining from 13,000 metric tons registered in the early 1980s to approximately 4575 metric tons as of 2019 (Fig. 6a) with the corresponding decline in economic benefit (Fig. 6b) from US$14.32 million recorded in 1982 to about US$5.69 million as of 2019 translating to 60.3% net loss. The value of net economic loss from Lake Malombe fishery is less than the total annual economic benefit generated from Lake Chilwa fishery estimated at US$ 18 million (Malawi Government, 2010) but higher than (US$4.7million) reported in Lake Chiuta (Zuze, 2013).
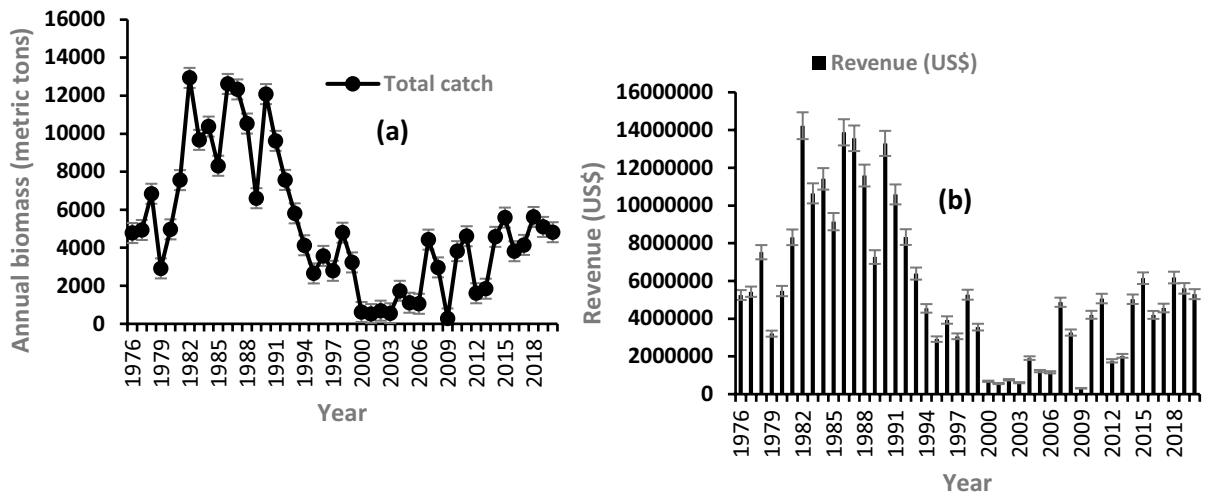
Fig. 6 Total fish biomass and total revenue within the period from 1976 to 2020

Conclusion

The ESV estimation based on LULC analysis is very vital within the landscape and ES. It demonstrates how much ES changed in responses to anthropological activities and ecological stress on spatial and temporal scales. Such estimation is of paramount importance in influencing decision-making processes through modifying national accounting systems to reflect the true value of ES that will ultimately be used as a basis for substantial and sustainable developmental activities within the catchment. We found that forest land was significantly reduced to other land uses by 84.73% during the period while other land classes such as built-up areas and cultivated increased. The overall ESV decreased by US$45.58 million during the study period. The highest ES net loss value of US$79.832 million was recorded from 1999 to 2019 due to increased loss of forest and marsh areas. Within the same period, the lake fishery also recorded a net loss of US$8.63million. The CS for water body was the highest among all land uses throughout the study period indicating a higher ESV coefficient assigned to the water body. This study suggests that the only way to avoid ecosystem disservices in the catchments of tropical shallow lakes such as Lake Malombe is by reducing the impact of anthropogenic and ecological stressors within acceptable levels to maintain ecosystem functions. This can be achieved by firstly understating the strategies on how the local population around the lake have survived over the years from the shocks and stress triggered by the loss of ESVs and develop an incentive economic model for the lake ES based on the data generated from the study of this nature to support local population livelihoods which are currently at the greatest risk due to increased LULC dynamics and other associated stressors such as poverty and environmental threats. The economic incentive models should include the introduction of integrated agriculture–aquaculture in the upland areas to reduce pressure on the capture fishery, improve the income generation through income diversification and agroforestry, introduction of cage culture, fish restocking program, fish habitat, and sanctuaries to improve income generation, promoting village savings, climate-smart agriculture, and freshwater ecosystem marketing approach to reduce poverty, improve food security and livelihood of the local population. However, the success of this approach depends on an effective multi-sectoral collaborative effort at a grass root level from various partners to convince the local population who are predominately fishers and small-scale farmers the economic incentives of adopting these approaches as compared to capture fishery and the traditional farming systems. Joint efforts should also be made to address the conflicts that exist among the various government policies. There is an urgent

need to harmonize various multi-sectoral conflicting policies and projects to ensure that there are synergies among them. There is also a need to enforce the buffer zones of about a 10 m radius around the lakeshore and riverine corridors as stipulated in the water resources act through a co-management approach to provide greater protection of the mangroves as well as marshes. Capacity-building among local governance structures especially on the integrated ecosystem-based management approach to ensure that they understand the value of the lake ES and a need to conserve for the future generation is also required. The combined initiatives from both local and national could promote conservation of forest as well as marshland. The current study findings show that Lake Malombe catchment is at a high rate of ES loss due to several underlying and proximate causes of LULC dynamics. Of the LULC within the Lake Malombe landscape, our results indicate that marshland, forest, and water bodies provide a higher level of ES than others due to the relatively larger coefficient assigned to them as well as larger area in case of forest and hence a reduction in these land classes significantly hamper the balanced flow of ES.

Limitations

We noted that coefficient ESV developed by Costanza et al. (1997), however, had some limitations. For example, the unit values derived from one area of a specific good were based on a generalization of average unit value in all areas with an assumption that ESV within the entire LULC categories was homogeneity (Kindu et al., 2016) which may not be true in reality. Despite this limitation, the Costanza et al. coefficients have been widely used by several environmental scientists, ecosystem managers, and policy analysts for timely assessment of various ES at multiple geographical scales (local, national, regional, and global) when primary data is scarcely available (Wong et al., 2015). Another limitation was that studies of ESV are very scarce in Malawi and our context was based on ESV global indexes after perfectly and accurately adjusted them to reflect local ecosystem conditions (Song & Deng, 2017). Given the location of Lake Malombe which falls within East African Great Rift Valley systems, the ESV estimation using LULC and established coefficient is extremely

important where ground data collection is expensive, land degradation is pervasive and the historical land uses data for rural areas is scarce. It provides the best alternative and robust data for decision-making processes at the local level and a similar study can be applied in other parts of the country's freshwater ecosystem.

Declarations

Conflict of interest The authors declare no competing interests.

References

Alauddin, M., & Quiggin, J. (2008). Agricultural intensification, irrigation and the environment in South Asia: Issues and policy options. *Ecological Economics, 65*(1), 111–124.

Arowolo, A., & Deng, X. (2018). Landuse/land cover change and statistical modeling of cultivated land change drivers in Nigeria. *Regional Environmental Change, 18*(1), 247–259.

Badamfiroo, J., & Mousazadeh, R. (2019). Quantitative assessment of land use/land cover changes on the value of ecosystem services in the coastal landscape of Anzali International Wetland. *Environmental Monitoring and Assessment, 191*, 694. https://doi.org/10.1007/s10661-019-7802-8

Bell, R., & Donda, S. (1993). *Community participation consultancy report*. Lilongwe, Malawi: Fisheries Department.

Berihun, M., Tsunekawa, A., Haregeweyn, N., Meshesha, D., Adgo, E., Tsubo, M., ... & Yibeltal, M. (2019). Exploring land use/land cover changes, drivers and their implications in contrasting agro-ecological environments of Ethiopia. *Land Use Policy, 87*, 104052. https://doi.org/10.1016/j.landusepol.2019.104052

Bone, R., Parks, K., Hudson, M., Tsirinzeni, M., & Willcock, S. (2017). Deforestation since independence: A quantitative assessment of four decades of land-cover change in Malawi. *Journal of Forest Science, 79*, 4269–4275. https://doi.org/10.2989/20702620.2016.1233777

Bootsma, H., & Hecky, R. (1993). The major socio-economic benefits from these three major African conservation of the African Great Lakes: A Limnological Perspective. *Conservation Biology, 7*(3), 644–656.

Bulirani, A. (2003). The challenges of developing an integrated approach to the management of Lake Malawi/Niassa and its catchment resources. In A. Wright, & J. Chafota, *Lake Malawi/Niassa/Nyasa Ecorg\egion, report on donors and partners meeting*. WWF Ecoregion Conservation Programme.

Calder, I. (1995). The impact of land-use change on water resources in sub-Saharan Africa: A modeling study of Lake Malawi. *Journal of Hydrology, 170*(1–4), 123–135.

Cawthorn, D., & Hoffman, L. (2015). The bushmeat and food security nexus: A global account of the contributions, conundrums, and ethical collisions. *Food Research International, 76*, 906–925.

Chavula, G. (1999). The potential of using community-based small-earth dams for irrigation development. *Regional Consultation-Africa/Middle East on Large dam and their alternatives* (pp. 883–895). Cairo: Egypt.

Chavula, G., Brezonik, P., & Baue, M. (2011). Land use and land cover change (LULC) in the Lake Malawi drainage basin, 1982–2005. *International Journal of Geosciences, 2*, 172–178.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., ... & van den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature, 387*(115), 254–260.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S., Kubiszewski, I., ... & Turner, R. (2014). Changes in the global value of ecosystem services. *Global Environmental Change, 26*, 152–158.

Crespin, S., & Simonett, J. (2016). Loss of ecosystem services and the decapitalization of nature in El Salvador. *Ecosystem Services, 17*, 5–13.

Dale, V., & Polasky, S. (2007). Measures of the effects of agricultural practices on ecosystem services. *Ecological Economics, 64*(2), 286–296.

Dulanya, Z., Croudance, I., Reed, J., & Trauth, M. (2014). Palaeolimnological reconstruction of recent environmental change in Lake Malombe (S. Malawi) using multiple proxies. *Water SA, 40*(4), 11–18.

Dulanya, Z., Reed, J., & Trauth, M. (2013). Mapping changing shorelines in the Malombe and Chiuta lakes of Malawi—environmental effects of recent climatic variations. *Catena, 104*, 111–119.

Duraisamy, V., Bendapudi, R., & Jadhav, A. (2018). Identifying hotspots in land use land cover change and the drivers in a semi-arid region of India. *Environmental Monitoring and Assessment, 190*(9), 1–21.

Feng, X., Luo, G., Li, C., Dai, L., & Ln, L. (2012). Dynamics of ecosystem service value caused by land-use changes in Manas River of Xinjiang, China. *Journal of Environmental Research, 6*(2), 499–508.

FISH. (2015). *Environmental Threats and Opportunities Assessment (ETOA) of Four Major Lakes in Malawi*. USAID/FISH Project, Pact Publication.

Gashaw, T., Tulu, T., Argaw, M., Worqlul, A., Tolessa, T., & Kindu, M. (2018). Estimating the impacts of land use/land cover changes on Ecosystem Service Values: The case of the Andassa watershed in the Upper Blue Nile basin of Ethiopia. *Ecosystem Services, 31*, 219–228.

Gondwe, M. (2009). *Environmental impacts of cage aquaculture in the southeast arm of Lake Malawi: Water and sediment quality and food web changes*. University of Waterloo.

Gondwe, M., Cho, M., Chirwa, P., & Geldenhuys, C. (2019). Land use land cover change and the comparative impact of co-management and government-management on the forest cover in Malawi (1999–2018). *Journal of Land Use Science, 14*(4–6), 281–305. https://doi.org/10.1080/1747423X.2019.1706654

Government of Malawi. (2014). *Mangochi District State of Environment and Outlook*. Mangochi: Mangochi District Council.

Government of Malawi. (2002). *Land Policy*. Lilongwe: Malawi Government.

Government of Malawi. (2018). *2018 Malawi Population and Housing*. Zomba: National Statistical Office.

Government of Malawi. (2016). *National Irrigation Policy*. Lilongwe: Ministry of Agriculture, Irrigation and Water DevelopmentDepartment of Irrigation.

Green, J., Larrosa, C., Burgess, N., Balmford, A., Johnston, A., Mbilinyi, B., ... & Coad, L. (2013). Deforestation in an African biodiversity hotspot: Extent, variation and the effectiveness of protected areas. *Biological Conservation, 164*, 62–72.

Haak, B., Mahabir, R., & Kerkering, J. (2015). Remote sensing-derived national land covers land use maps: A comparison for Malawi. *Geocarto International, 30*(3), 270–292. https://doi.org/10.1080/10106049.2014.952355

Hailu, A., Mammo, S., & Kidane, M. (2020). Dynamics of land use, land cover change trend and its drivers in Jimma Geneti District Western Ethiopia. *Land Use Policy, 99*, 105011. https://doi.org/10.1016/j.landusepol.2020.105011

Hall, C., Dawson, T., Matthews, R., & Smith, P. (2017). The impact of population growth and climate change on food security in Africa: Looking ahead to 2050. *International Journal of Agricultural Sustainability, 15*(2), 124–135. https://doi.org/10.1080/14735903.2017.1293929

Hao, F., Lai, X., & Ouyang, W. (2012). Effects of land use changes on the ecosystem service values of a reclamation farm in Northeast China. *Environmental Management, 50*, 888–899. https://doi.org/10.1007/s00267-012-9923-5

Hara, M., & Njaya, F. (2016). Between a rock and a hard place: The need for and challenges to implementation of rights-based fisheries management in small-scale fisheries of southern Lake Malawi. *Fisheries Research, 174*, 10–18.

Haregeweyn, N., Tesfaye, S., Tsunekawa, A., Tsubo, M., Meshesha, D., Adgo, E., & Elias, A. (2015). Dynamics of land use and land cover and its effects on hydrologic responses: a case study of the Gilgel Tekeze catchment in the highlands of Northern Ethiopia. *Environmental*

Monitoring and Assessment, 187, 4090. https://doi.org/10.1007/s10661-014-4090-1

Hartzell, C., & Hoddie, M. (2003). Institutionalizing Peace: Power Sharing and Post-Civil War Conflict Management. *American Journal of Political Science, 47*(2), 318–332. https://doi.org/10.1111/1540-5907.00022

Hasan, S., Shi, W., & Zhu, X. (2020). Impact of land use land cover changes on ecosystem service value– A case study of Guangdong, Hong Kong, and Macaoin South China. *PLoS One, 15*(4), e0231259. https://doi.org/10.1371/journal.pone.0231259

Hu, H., Liu, W., & Cao, M. (2008). Impact of land use and land cover changes on ecosystem services in Menglun, Xishuangbanna, Southwest China. *Environmental Monitoring and Assessment, 146*, 147–156. https://doi.org/10.1007/s10661-007-0067-7

IPBES. (2018). *The IPBES regional assessment report on biodiversity and ecosystservices for Africa.* Bonn, Germany: IPBES Secretariat.

Jamu, D., Chimphamba, J., & Brummett, R. (2003). Land use and cover changes in the Likangala catchment of the Lake Chilwa basin, Malawi: Implications for managing a tropical wetland. *African Journal of Aquatic Science, 28*(2), 123–135.

Jamu, D., Banda, M., Njaya, F., & Hecky, R. (2011). Challenges to sustainable management of the lakes of Malawi. *Great Lakes Research, 37*(1), 3–14.

Kafumbata, D., Jamu, D., & Chiotha, S. (2014). Riparian ecosystem resilience and livelihood strategies under test: lessons from Lake Chilwa in Malawi and other lakes in Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences, 369*(1639), 20130052. https://doi.org/10.1098/rstb.2013.0052

Kabanda, T. (2019). Land use/cover changes and prediction of Dodoma, Tanzania, African. *African Journal of Science, Technology, Innovation, and Development, 11*(1), 55–60. https://doi.org/10.1080/20421338.2018.1550925

Kapute, F. (2018). The role of the Liwonde National Park in conserving fish species diversity in the upper Shire River, Malawi. *Aquatic Ecosystem Health & Management, 21*(2), 132–138. https://doi.org/10.1080/14634988.2018.1457389

Käyhkö, N., Fagerholm, N., Asseid, B., & Mzee, A. (2011). Dynamic land use and land cover changes and their effect on forest resources in a coastal village of Matemwe, Zanzibar, Tanzania. *Land Use Policy, 28*(1), 26–37.

Keim, R., Izdepski, C., & Day, J., Jr. (2012). Growth Responses of Baldcypress to Wastewater Nutrient Additions and Changing Hydrologic Regime. *Wetlands, 32*, 95–103. https://doi.org/10.1007/s13157-011-0248-6

Kindu, M., Schneider, T., Teketay, D., & Knoke, T. (2016). Changes of ecosystem service values in response to land use/land cover. *Science of the Total Environment, 547*, 137–147.

Kindu, M., Schneider, T., Teketay, D., & Knoke, T. (2015). Drivers of land use/land cover changes in the Munessa-Shashemene landscape of the south-central highlands of Ethiopia. *Environmental Monitoring and Assessment, 187*, 452. https://doi.org/10.1007/s10661-015-4671-7

Kolding, J., Van Zwieten, R., Mkumbo, O., Silsbe, G., & Hecky, R. (2008). Are the Lake Victoria fisheries

threatened by exploitation or eutrophication? Towards an ecosystem-based approach to management. In G. Bianchi & H. Skjoldal (Eds.), *The Ecosystem Approach to Fisheries* (pp. 309–355). CABI Publishing.

Kreuter, U., Harris, H., Matlock, M., & Lacey, R. (2001). Change in ecosystem service values in the San Antonio area, Texas. *Ecological Economics, 39*(3), 333–346.

Kilic, C., Evrendilek, F., Berberoglu, S., & Demirkesen, A. (2006). Environmental monitoring of land-use and land-cover changes in a Mediterranean region of Turkey. *Environmental Monitoring and Assessment, 114*, 157–168. https://doi.org/10.1007/s10661-006-2525-z

Landell-Mills, N., & Porras, I. (2002). *Silver Bullet or Fool's Gold? A Global Review of Markets for Forest Environmental Services and Their Impact on the Poor.* IIED.

Leh, M., Matlock, M., Cummings, E., & Nalley, L. (2013). Quantifying and mapping multiple ecosystem services change in WestAfrica. *Agriculture, Ecosystems and Environment, 165*, 6–18.

Levy, P., & Lemeshow, S. (1999). *A sampling of populations: Methods and applications*. Wiley.

Li, J., Wang, W., Hu, G., & Wei, Z. (2010). Changes in ecosystem service values in Zoige Plateau, China. *Agriculture, Ecosystems and Environment, 139*, 766–770.

Li, R., Dong, M., Cui, J., Zhang, L., Cui, Q., & He, W. (2007). Quantification of the impact of land-use changes on ecosystem services: A case study in Pingbian County, China. *Environmental Monitoring and Assessment, 128*, 503–510. https://doi.org/10.1007/s10661-006-9344-0

Likoya, E. (2019). *Change in the context of changing land use and cover: Case study of the Shire River basin flood of 2015, MSc Thesis.* Cape Town: University of Cape Town.

Lillesand, T., Kiefer, R., & Chipman, J. (2007). *Remote sensing and image interpretation*. Wiley.

Makwinja, R., Kaunda, E., Alemiew, T., Phiri, T., Kosamu, I., & Kaonga, C. (2021). Modeling of Lake Malombe annual fish landings and catch per unit effort (CPUE). *Forecasting, 3*(1), 39–55. https://doi.org/10.3390/forecast3010004

Makwinja, R., Kosamu, I., & Kaonga, C. (2019). Determinants and values of willingness to pay for water quality improvement: Insights from Chia Lagoon, Malawi. *Sustainability, 11*, 4690. https://doi.org/10.3390/su11174690

Malawi government. (1996). *The national forest policy of Malawi.* Lilongwe: Ministry of Natural Resources.

Malawi Government. (2010). *Malawi State of Environment and Outlook ReportEnvironment for Sustainable Economic Growth: Environment for Sustainable Economic Growth.* Lilongwe: Ministry of Natural Resources, Energy and Environment.

Malawi Government. (2013). *Shire River basin Management Programme (Phase I) Project: Final Environmental and Social Assessment Report.* Lilongwe: Ministry of Water Development and Irrigation.

Matsuishi, T., Mkumbo, O., Budeba, Y., Njiru, M., Asila, A., Othina, A., & Cowx, I. (2006). Are the exploitation pressures on the Nile perch fisheries resources of Lake Victoria a cause for concern? *Fisheries Management and Ecology, 13*, 53–71.

Mawenda, J., Watanabe, T., & Avtar, R. (2020). An analysis of urban land use/land cover changes in Blantyre City,

Southern Malawi (1994–2018). *Sustainability, 12*(6), 2377. https://doi.org/10.3390/su12062377

Maxwell, J. (2013). *Qualitative research design: An interactive approach*. Sage.

MEA. (2005). *Ecosystems and human well-being: Synthesis*. Island Press.

Mekonnen, M., & Hoekstra, A. (2010). *Mitigating the water footprint of cut-flowers from Lake Naivasha Basin, Kenya.Value of water research report series no 45*. Delft, The Netherlands: UNESCO-IHE.

Mendoza-González, G., Martínez, M., Lithgow, D., Pérez-Maqueo, O., & Simonin, P. (2012). Land use change and its effects on the value of ecosystem services along the coast of the Gulf of Mexico. *Ecological Economics, 82*, 23–32.

Mkanda, F. (1999). Drought as an analog climate change scenario for prediction of potential impacts on Malawi's wildlife habitats. *Climate Research, 12*(2–3), 215–222.

Msofe, N., Sheng, L., Li, Z., & Lyimo, J. (2020). Impact of land use/cover change on ecosystem service value in the Kilombero Valley floodplain, southeastern Tanzania. *Forests, 11*, 109. https://doi.org/10.3390/f11010109

Mtui, T., Lepczyk, C., Chen, Q., Miura, T., & Cox, L. (2017). Assessing multi-decadal land-cover – land-use change in two wildlife-protected areas in Tanzania using Landsat imagery. *PLoS One, 12*(9), e0185468. https://doi.org/10.1371/journal.pone.0185468

Mucova, S., Filho, W., Azeiteiro, U., & Pereira, M. (2018). Assessment of land use and land cover changes from 1979 to2017 and biodiversity & land management approach in Quirimbas National Park, Northern Mozambique, Africa. *Global Ecology and Conservation, 16*, e00447. https://doi.org/10.1016/j.gecco.2018.e00447

Muleta, T., Kidane, M., & Bezie, A. (2020). The effect of land use/land cover change on ecosystem services values of Jibat forest landscape, Ethiopia. *GeoJournal*. https://doi.org/10.1007/s10708-020-10186-4

Munthali, K., & Murayama, Y. (2015). Modeling deforestation in Dzalanyama Forest Reserve, Lilongwe, Malawi: A multi-agent simulation approach. *GeoJournal, 80*, 743–757.

Mzembe, C. (1990). *Wetland Development and Management in Malawi: Malawi Country Paper*. Lilongwe, Malawi: Department of Irrigation, Ministry of Agriculture.

Mzuza, M., Zhang, W., Kapute, F., & Wei, X. (2019). The Impact of Land Use and Land Cover Changes on the Nkula Dam in the Middle Shire River Catchment, Malawi. In A. Pepe, & Q. Zhao, Geospatial Analyses of Earth Observation (EO) data (p. 9). Rijeka: IntechOpen

Nagoli, J., Green, E., Mulwafu, W., & Chiwona-Karltun, L. (2017). Coping with the double crisis: Lake Chilwa Recession and the Great Depression on Chisi Island in Colonial Malawi, 1930–1935. *Human Ecology, 45*, 111–117.

Nagoli, J., Mulwafu, W., Green, E., Likongwe, P., & Chiwona-Karltun, L. (2016). Conflicts over natural resource scarcity in the aquatic ecosystem of the Lake Chilwa. *Environment and Ecology Research, 4*(4), 207–216.

Ngongondo, C., Zhou, Y., & Xu, C. (2020). Multivariate framework for the assessment of key forcing to Lake Malawi level variations in non-stationary frequency analysis. *Environmental Monitoring and Assessment, 192*, 593. https://doi.org/10.1007/s10661-020-08519-4

Niquisse, S., Cabral, P., Rodrigues, A., & Augusto, G. (2017). Ecosystem services and biodiversity trends in Mozambique as a consequence of land cover change. *International Journal of Biodiversity Science, Ecosystem Services & Management, 13*(1), 297-311. https://doi.org/10.1080/21513732.2017.1349836

Njaya, F. (2007). Governance challenges for the implementation of co-management: Experiences from Malawi. *International Journal of the Commons, 1*, 137–153.

NSO. (2005). *Integrated Household Survey 2004–2005*. Zomba, Malawi: National Statistical Office.

NSO. (2012). *Population Household Census*. Zomba: National Statistics Office.

Ogutu-Ohwayo, R., Hecky, R., Cohen, A., & Kaufman, L. (1997). Human impacts on the African Great Lakes. *Environmental Biology of Fishes, 50*, 117–131. https://doi.org/10.1023/A:1007320932349

Palamuleni, L., Annegarn, H., & Landmann, T. (2010). Land cover mapping in the Upper Shire River catchment in Malawi using Landsat satellite data. *Geocarto International, 25*(7), 503–523. https://doi.org/10.1080/10106049.2010.49060

Patton, M. (1990). *Qualitative evaluation and research methods* (2nd ed.). Washington DC: Sage Publications, Inc.

Pettorelli, N., Vik, J., Mysterud, A., Gaillard, J., Tucker, C., & Stenseth, N. (2005). Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology and Evolution, 20*(9), 503–510. https://doi.org/10.1016/j.tree.2005.05.011

Phiri, D., Morgenroth, J., & Xu, C. (2019). Long-term land cover change in Zambia: An assessment of driving factors. *Science of the Total Environment, 697*, 134206. https://doi.org/10.1016/j.scitotenv.2019.134206

Powers, B., Ausseil, A., & Perry, G. (2020). Ecosystem service management and spatial prioritization in a multifunctional landscape in the Bay of Plenty, New Zealand. *Australasian Journal of Environmental Management, 27*(3), 275–293. https://doi.org/10.1080/14486563.2020.1768165

Pullanikkatil, D., Palamuleni, L., & Ruhiiga, T. (2016). Assessment of land-use change in Likangala River catchment, Malawi: A remote sensing and DPSIR approach. *Applied Geography, 71*, 9–23.

Pullanikkatil, D., Palamuleni, L., & Ruhiiga, T. (2015). Impact of land use on water quality in the Likangala catchment, southern Malawi. *African Journal of Aquatic Science, 40*(3), 277–286. https://doi.org/10.2989/16085914.2015.1077777

Qureshi, A., Gill, M., & Sarwar, A. (2008). Sustainable groundwater management in Pakistan: Challenges and opportunities. *Irrigation and Drainage, 59*(2), 107–116. https://doi.org/10.1002/ird.455

Ritse, V., Basumatary, H., Kulnu, A., Dutta, G., Phukan, M., & Hazarika, N. (2020). Monitoring land use land cover changes in the Eastern Himalayan landscape of Nagaland, Northeast India. *Environmental Monitoring and Assessment, 192*, 711. https://doi.org/10.1007/s10661-020-08674-8

Robertson, G., & Swinton, S. (2005). Reconciling agricultural productivity and environmental integrity: A grand

challenge for agriculture. *Frontiers in Ecology and the Environment, 3*, 38–46.

Salas,, S., Bjørkan, M., Bobadilla, F., & Cabrera, M. (2010). Addressing vulnerability: Coping strategies of fishing communities in Yucatan, Mexico. In S. Jentoft, & A. Eide, *Poverty Mosaics: Realities and Prospects in Small-Scale Fisheries,* (pp. 195–220). Springer.

Sanchez, P. (2002). Soil fertility and hunger in Africa. *Science, 295*(5562). https://doi.org/10.1126/science.1065256

Sanmuganathan, K. (2000). *Thematic review options assessment IV: Assessment of irrigation options.* World Commission on Dams.

Shiferaw, H., Bewket, W., Alamirew, T., Zeleke, G., Teketay, D., Bekele, K., ... & Eckert, S. (2019). Implications of land use/land cover dynamics and Prosopis invasion on ecosystem service values in Afar Region, Ethiopia. *Science of the Total Environment, 675*, 354–366.

Solomon, N., Segnon, A., & Birhane, E. (2019). Ecosystem Service Values Changes in Response toLand-Use/Land-Cover Dynamics in Dry Afromontane Forest in Northern Ethiopia. *International Journal of Environmental Research and Public Health, 16*, 4653. https://doi.org/10.3390/ijerph16234653

Song, W., & Deng, X. (2017). Land-use/land-cover change and ecosystem service provision in China. *Science of The Total Environment, 576*(2017), 705–719. https://doi.org/10.1016/j.scitotenv.2016.07.078

Stringer, L., Fraser, E., Harris, D., Lyon, C., Pereira, L., Ward, C., & Simelton, E. (2020). Adaptation and development pathways for different types of farmers. *Environmental Science and Policy, 104*, 174–189. https://doi.org/10.1016/j.envsci.2019.10.007

Sutton, P., Anderson, S., Costanza, R., & Kubiszewski, I. (2016). The ecological economics of land degradation: Impacts on ecosystem service values. *Ecological Economics, 129*, 182–192.

Tendaupenyu, P., Magadza, C., & Murwira, A. (2017). Pamela Tendaupenyu, Christopher Hilary Dennis Magadza & Amon Murwira (2017) Changes in land use/landcover patterns and human population growth in the Lake Chivero catchment Zimbabwe. *Geocarto International, 32*(7), 797–811. https://doi.org/10.1080/10106049.2016.11788

Teucher, M., Schmit, C., Wiese, A., Apfelbeck, B., Maghenda, M., Pellikka, P., & Habel, J. (2020). Behind the fog: Forest degradation despite logging bans in an East Africa cloud forest. *Global Ecology and Conservation, 22*, e01024.

Tolessa, T., Senbeta, F., & Kidaneb, M. (2017). The impact of land use/land cover change on ecosystem services in the central highlands of Ethiopia. *Ecosystem Services, 23*, 47–54.

Wang, Z., Zhang, B., Zhang, S., Li, X., Liu, D., Song, K., & Duan, H. (2006). Changes of Land Use and Ecosystem Service Values in Sanjiang Plain, Northeast China. *Environmental Monitoring and Assessment, 112*, 69–91. https://doi.org/10.1007/s10661-006-0312-5

Wangai, P., Burkhard, B., & Muller, F. (2016). A review of studies on ecosystem services in Africa. *International Journal of Sustainable Built Environment, 5*, 225–245.

Weyl, O., Ribbink, A., & Tweddle, D. (2010). Lake Malawi: Fish, fisheries, biodiversity, health, and habitat. *Freshwater Fishes and Fisheries of Africa, 13*(3), 241–254. https://doi.org/10.1080/14634988.2010.504695

Wong, C., Jiang, B., Kinzig, A., Lee, K., & Ouyang, Z. (2015). Linking ecosystem characteristics to final ecosystem services for public policy. *Ecology Letters, 18*(1), 108-118. https://doi.org/10.1111/ele.12389

Woodruff, D. (2010). Biogeography and conservation in Southeast Asia: How 2.7 million years of repeated environmental fluctuations affect today's patterns and the future of the remaining refugial-phase biodiversity. *Biodiversity and Conservation, 19*, 919–941.

Zhang, S., Wu, C., & Na, X. (2011). Impact of urbanization on natural ecosystem service values: A comparative study. *Environmental Monitoring and Assessment, 179*, 575–588. https://doi.org/10.1007/s10661-010-1764-1

Zuze, S. (2013). *Measuring the Economic value of wetland ecosystem services in Malawi: A case study of Lake Chiuta wetland.* University of Zimbabwe.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.