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Mapping and Assessment of Ecosystem Services Supply and Demand of the Kilombero Valley Floodplain, Tanzania

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abstract

Effective land use planning requires mapping and assessing ecosystem service supply and demand to inform policy and decision-makers about ecosystem service tradeoffs that are suited for long-term ecological management. This study examined the ecosystem services supply and demand of the Kilombero Valley Floodplain in Southeastern Tanzania. The supply-demand budget index was calculated using land use data from 1990, 2010, and 2016 and an expert-based matrix model examined the dynamic change of supply and demand for the 17 ecosystem services (7 regulating, 8 provisioning, and 2 cultural). The spatial analytic features of ArcGIS 10.2 were utilized to build ecosystem services evaluation matrices and regionally explicit supply, demand, and supply-demand budget maps. The study found that between 1990 and 2016, the supply of ecosystem services within the Kilombero Valley floodplain decreased substantially while the demand for ecosystem services increased spatially towards the core low-lying area of the valley. Furthermore, the average ecosystem service supply-demand budget index declined from 1.8 in 1990 to 1.6 in 2016, with few exceptions of food production, pollination, and freshwater supply, where ecosystem service supply exceeds demand. The decline is linked to deforestation, agricultural expansion, agropastoralists immigration, and encroachment to the wetland area. Thus, this study recommends that the government should create effective land use plans for each ward and village in the Kilombero District, establish afforestation programs, local irrigation schemes for smallholder farmers, and enforce environmental by-laws to ensure sustainable ecological management in the Kilombero Valley Floodplain and its ecosystems.

Introduction

Effective land use planning requires mapping and assessing ecosystem service supply and demand to inform policy and decision-makers about ecosystem service tradeoffs that are suited for long-term ecological management. Ecosystem services (ES) are the direct and indirect benefits derived from ecosystems that are indispensable to human well-being (Costanza et al., 1997; Costanza et al., 2014). ES supply refers to the capacity of an ecosystem to provide a particular bundle of products and services within a given period (Burkhard, Kandziora, Hou, & Müller, 2014). ES demand is defined as the preference or expectation level of human society or individuals for the specific characteristics of ecosystem services (Wei et al., 2017). The capacity of ecosystems to provide these benefits to human society has been altered by human activities in the environment (Burkhard & J, 2017; Tolessa, Senbeta, & Kidane, 2017). Human activities, in particular deforestation, have decreased the provision of some ecosystem services (Msofe, Lyimo, Sheng, & Li, 2020) while increasing the provision of others (Zhang, Kung, & Johnson, 2017), thereby altering the ES flow and influencing the capacity of ecosystems to meet human needs, thereby indicating ecological degradation (Kindu, Schneider, Teketay, & Knoke, 2016; Rocha, Esteves, de Souza, & dos Santos, 2018). Thus, the evaluation and delineation of ecosystem services (ES) provision and utilization play a significant role in the examination of the interplay between trade-offs (mutually influencing each other) and synergies (mutually enabling each other) among ES that support sustainable ecological management (Dhakal & Kattel, 2019).

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The valley floodplain ecosystems provide a variety of ES that enhance human well-being, including provisional, regulating, and supporting services, as well as cultural services (Johansson & Abdi, 2020; Msofe et al., 2020). Millennium Ecosystem Assessment (2005) and Costanza et al. (2014) state that sustaining the structure and functions of these ecosystems is crucial for managing and securing the flow of ES now and in the future. Consequently, quantification and assessment of ES are essential for the management of natural resources, the development and allocation of resources, the formulation of policies, and the protection of ES (Rocha et al., 2018; Wang, Xiao, Huajun, & Yutao, 2019). There are several approaches employed in the quantification and assessment of ecosystem services ranging from market-based valuing methods to spatially explicit modeling tools such as the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) models developed by the Natural Capital Project and MIMES (Multiscale Integrated Model of the Earth System' Ecological Services) approach (www.uvm.edu/giee/mimes) builds on the GUMBO model. However, accurately quantifying and mapping the supply and demand for ecosystem services with comparable measurement units remains difficult due to data source scarcity, fragmented, and not publicly available (Burkhard, Kroll, Müller, & Windhorst, 2009). Burkhard et al. (2012) and Burkhard and Maes (2017) propose the use of an expert-based matrix model to assess the response of ES supply and demand in an analogous semi-quantitative unit. This method assesses the dynamics of the supply and demand for ecosystem services in response to land use and land cover change by employing expert knowledge and corresponding indicators. It has been demonstrated that expert knowledge through the matrix approach can be just as valid for assessing ecosystem services as using empirical data or biophysical indicators (Campagne & Roche, 2018). Also, the matrix approach is cost-effective because it allows for a rapid evaluation of a large number of ES, including those that are difficult to measure, such as regulatory services and cultural services (Campagne, Roche, Gosselin, Tschanz, & Tatoni, 2017; Rozas-Va´ squez, Fu¨ rst, Geneletti, & Almendra, 2018).

On the other hand, mapping ecosystem services (ES) helps communicate complex spatial data, improves understanding of ecosystem service supply and demand, promotes environmental education about humans' dependence on a healthy natural environment, and illuminates interregional flows of ecosystem goods and services (Burkhard & J, 2017; Dhakal & Kattel, 2019). The composition, dynamics, functions, and physical characteristics of an ecological landscape determine the delivery of ecosystem services (ES), which can vary temporally and spatially due to human activities and land use and land cover changes (Hasan, Zhen, Miah, Ahamed, & Samie, 2020; Msofe et al., 2020; Rimal et al., 2019). The potential of mapping ecosystem services (ES) supply and demand is significant in evaluating the sustainability of landscapes and extracting intricate information (Burkhard, Kroll, Nedkov, & Müller, 2012; Troy & Wilson, 2007).

The Kilombero Valley Floodplain has experienced alterations in land use and cover, as a result of deforestation and the expansion of agriculture (Kirimi, Thiong'o, Gabiri, Diekkrüger, & Thonfeld, 2018; Msofe et al., 2020; Msofe, Sheng, & Lyimo, 2019; Muro et al., 2017). These changes have resulted in significant pressures and limitations on Kilombero Valley ecosystems and the services they provide (Msofe et al., 2020). So, limits its ability to meet societal demands in terms of both quantity and quality of products and services. In that case, it is essential to conduct a thorough study on this issue. Furthermore, it is essential to conduct a comprehensive assessment of the supply, demand, and supply-demand budget indicators of different regulatory, provisioning, cultural, and supporting ecosystem services (ES) (Burkhard et al., 2014; Rimal et al., 2019). This is crucial for the preservation of the ecological integrity and long-term sustainability of the Kilombero Valley ecosystem, as well as for the promotion of sustainable development. The aforementioned statement aligns with the objectives set forth by the United Nations Decade on Ecosystem Restoration (2021-2030), which highlights the significance of forests, wetlands, and other natural resources in fostering sustainable development, mitigating poverty, and promoting improved human welfare (United Nations Environment Agency, 2019).

Therefore, the key aims of this study were to determine and map the spatial patterns of the ES supply, human demands for ecosystem services, and supply-demand budget indexes of the ecosystem services of the Kilombero Valley Floodplain. Hence, the findings of this study will establish a conceptual structure for decision-making and offer direction on the policies and management approaches that ensure the sustainable ecological management of the Kilombero Valley Floodplain.

Materials and methods

Study area description

This study was carried out in the Kilombero Valley Floodplain, which lies between latitude 10°00–08°40' South and longitude 35°10' –37°10' East. The administrative unit is located in the Kilombero, Malinyi, and Ulanga districts of the Morogoro region, southeastern Tanzania (Figure 1)

Kilombero Valley floodplain is the largest freshwater wetland found in East Africa at a low altitude (<300 m above sea level) covering about 39,990 km^2 (Jätzold & Baum, 1968; Thonfeld et al., 2020). The valley floodplain is divided by the Kilombero River and surrounded by the Udzungwa escarpment in the northwest and Mahenge Highlands and Mbarika Mountains in the southeast parts. The high elevation drops from an altitude of more than 1800m above sea level to about 300m above sea level in a few kilometers. The Kilombero Valley Floodplain was recognized and designated as the Ramsar site in 2002 by the International Union for Conservation of Nature (IUCN) due to its global importance (URT, 2003).

Mapping Landscape Capacities to Supply Ecosystem Services

Landscape capacities depend on the status of land cover, hydrology, soil conditions, fauna, elevation, slope, climate, and human activities (Ji et al., 2020). Using an expert-based matrix technique assigns geographical unit values/scores based on the ES supply capacity of distinct land use/cover types (Burkhard et al., 2012). Land use and land cover (LULC) classes (agricultural, bare soil, bushland, forest, grassland, urban area, water, and wetland) were extracted from the geospatial analysis of Landsat imageries of 1990, 2010, and 2016 by Msofe et al. (2019). This study examined 17 ES from the Millennium Ecosystem Assessment (2005) categories of sustaining, regulating, provisional, and cultural services. The regulating services include local and global climate regulation, flood protection, groundwater recharge, erosion regulation, nutrients regulation, and pollination were assessed. In addition, provision services including crop cultivation, cattle, capture fisheries, wild foods, timber, wood fuel, traditional medicine, and freshwater were examined. Lastly, cultural services including the intrinsic worth of biodiversity and recreation, and aesthetic services were evaluated.

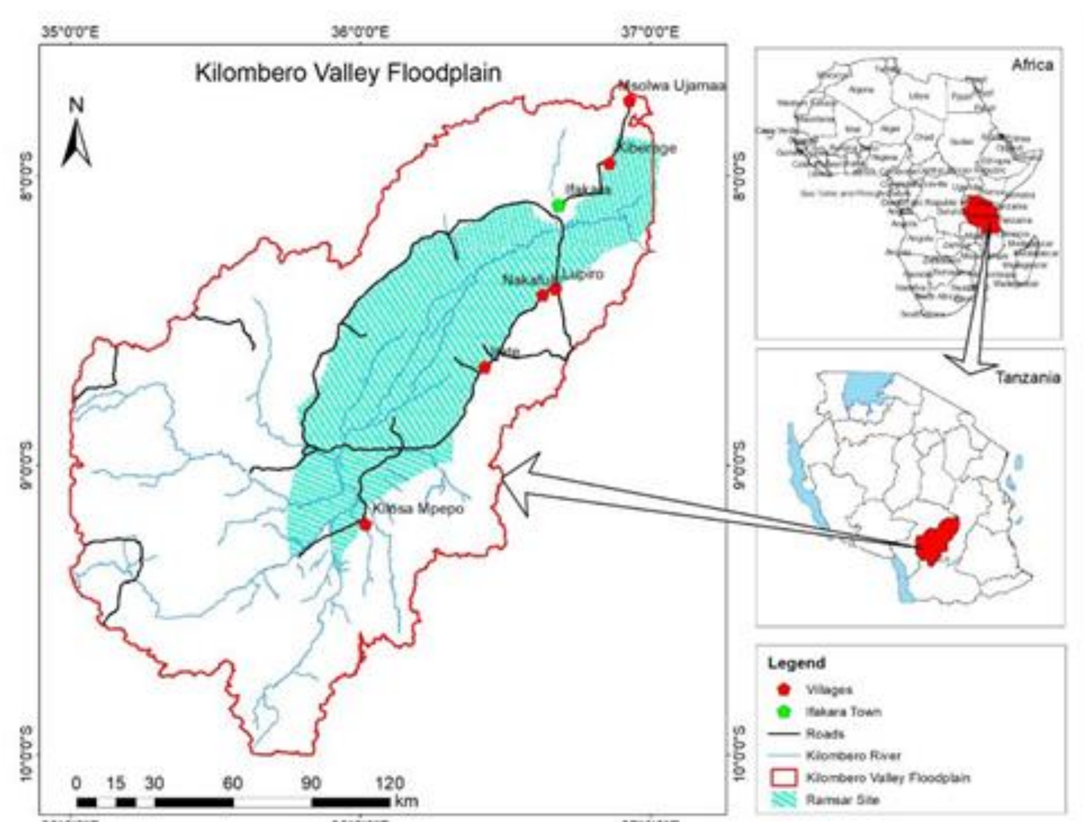

Figure 1: Location of the Kilombero Valley Floodplain showing the studied villages.

The expert scores were ranked from 0 to 5 to represent the supply capacity of ES related to each land use type based on (Burkhard et al., 2012), with 0/rosy representing no relevant capacity, 1/grey green low relevant capacity, 2/light green relevant capacity, 3/yellow green medium relevant capacity, 4/blue green high relevant capacity, and 5/dark green very high relevant capacity. During ES assessment workshops in July 2020, teams of 19 experts including District Environmental Experts, District Natural Resource Officers, District Executive Officers, Illovo Sugar Limited and Kilombero Valley Teak Company, environmental management committees, and agriculture extension officers in the study area were involved. The experts were briefed on the concept of the ES supply, its score scale for each land use type, and what each score meant to avoid confusion. Then, experts were given matrix scoring tables of ES supply and assessed each ES's supply capacities for each land use type. Based on the LULC types, SPSS version 22 calculated the mean values for each ES to statistically assess the scores (Table 1).

Moreover, the study also asked each expert to rate their confidence in their knowledge of LULC typology and ES using a confidence score from 1 to 3, whereby “1= I don’t feel confident with the score, 2 = I feel fairly confident with the score and 3 = I feel confident with the score” (Campagne et al., 2017). Then, the mean confidence scores (CS) for each ecosystem services supply and LULC type were calculated to assess their understanding of the typology (Table 1). In a participatory approach, confidence scores must be calibrated for incorporation into the ES assessment.

The spatial-explicitly maps for ES supply were constructed by mapping the 0-5 values to relevant land use and land cover polygons based on the ecosystem service supply scores for each LULC type. The attributes were extrapolated to greater spatial extensions using ArcGIS 10.2 software to generate spatial and temporal ES supply patterns in the KVFP, which were then mapped.

Mapping of human demands for ecosystem services

Assessing ecosystem service demand, statistical data, and beneficiary socio-economic monitoring is essential. This study employed an expert-based matrix approach developed by (Burkhard et al., 2012) to estimate ecosystem demand by generating expert scores on ES demand for certain LULC types. The experts' scores for demand were obtained from the same ES assessment workshops that collected the scores for the ES supply. The scores indicated that 0/rosy = no relevant demand; 1/dark rosy = low relevant demand; 2/light red = relevant demand; 3/red = medium relevant demand; 4/dark red = high relevant demand; and 5/brown, red = very high relevant demand. The expert scores were statistically examined by computing mean values for each ES and LULC type and presenting the matrix. The matrix shows relative human demand for regulating, supplying, and cultural services on the y-axis and distinct LULC kinds on the x-axis (Table 2).

Table 1: Ecosystem services (ES) supply evaluation matrix with experts’ ES capacity scores mean giving mean confidence scores (CS) of each LULC type and ES in the table margins.

Land use and land cover types	CS	Regulating services Σ	Local climate regulation	Global climate regulation	Flood protection	Groundwater recharge	Erosion regulation	Nutrient regulation	Pollination	Provisional Serives Σ	Crop production	Livestock	Capture fisheries	Wild foods	Timber	Wood fuel	Traditional medicine	Freshwater	Culture Services Σ	Recreation & aesthetic services	Intrinsic value of biodiversity
Agriculture	2.7	11	3	2	1	0	2	2	1	13	5	4	1	0	0	2	1	0	1	1	0
Bare soil	2.3	2	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0
Bushland	2.4	24	4	3	3	3	3	4	4	9	0	0	0	2	2	2	3	0	6	3	3
Forest	2.5	30	5	4	4	4	4	4	5	19	0	0	0	4	5	5	5	0	8	4	4
Grassland	2.4	18	3	2	1	4	4	4	0	9	0	4	0	1	0	2	2	0	3	3	0
Settlement	2.3	0	0	0	0	0	0	0	0	4	0	1	0	1	0	2	0	0	0	0	0
Water	2.7	13	3	3	0	4	3	0	0	14	2	2	5	0	0	0	0	5	7	5	2
Wetland	2.4	19	4	4	3	4	4	0	0	7	4	3	0	0	0	0	0	0	8	4	4
	CS		2.6	2.4	2.5	2.5	2.8	2.6	2.8		2.7	2.8	2.4	2.4	2.5	2.4	2.5	2.3		2.3	2.1

Table 2: Ecosystem services (ES) demand evaluation matrix with experts' mean ES demands scores giving mean confidence scores (CS) of each LULC type and ES in the table margins.

Land use and land cover types	CS	Regulating services Σ	Local climate regulation	Global climate regulation	Flood protection	Groundwater recharge	Erosion regulation	Nutrient regulation	Pollination	Provisional Serives Σ	Crop production	Livestock	Capture fisheries	Wild foods	Timber	Wood fuel	Traditional medicine	Freshwater	Culture Services Σ	Recreation & aesthetic services	Intrinsic value of biodiversity
Agriculture	2.3	20	4	0	4	0	4	4	4	15	4	3	0	0	0	3	0	5	5	2	3
Bare soil	2.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bushland	2.3	7	2	2	0	0	0	0	3	12	0	0	0	3	3	3	3	0	0	0	0
Forest	2.5	11	3	3	0	0	0	0	5	9	0	0	0	3	4	2	0	0	0	0	0
Grassland	2.4	2	0	0	2	0	0	0	0	6	3	3	0	0	0	0	0	0	0	0	0
Urban area	2.2	25	5	5	3	3	3	4	2	30	5	5	4	1	3	5	3	4	6	3	3
Water	2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	2
Wetland	2.5	6	1	1	4	0	0	0	0	10	5	4	0	0	0	0	0	1	3	2	1
	CS		2.3	2.3	2.4	2.3	2.5	2.3	2.3		2.5	2.4	2.3	2.3	2.4	2.5	2.4	2.4		2.3	2.1

Similar to the ecosystem services supply assessment, mean confidence ratings (CS) were generated for each ecosystem services demand and LULC type to measure their understanding of ES and LULC typology (Table 2). Based on the experts' ecosystem service demand scores, spatial-explicit maps for ES demand were constructed using classified LULC maps for the 1990-2016 period (Msofe et al., 2019) to establish spatiotemporal patterns of ES demand in the KVFP.

Mapping budgets of ecosystem services supply and demand

The ES supply and demand matrixes developed by expert judgment were further employed to calculate the budgets for ES supply demand for different LULC types. Table 3 shows the corresponding matrix of ecosystem service budgets within the different land cover classes.

Each field in the budget matrix was calculated based on the corresponding field in the supply (Table 1) and the demand matrix (Table 2). The supply-demand budget scale ranges from -5 = demand exceeds supply vastly (undersupply); 0 = neutral balance where supply is equal to demand; to 5 = supply exceeds demand vastly (oversupply). Whereas the empty fields indicate neither a relevant supply nor a relevant demand for the ecosystem service.

The study further calculated budget indexes for supply-demand using a grid-based ES supply capacity and demand intensity model (Eq. 1) developed by (Ji, Xu, & Wei, 2020)

$$E_S\,(E_D) = \frac{\sum_{k=1}^{L} E_k M_k}{M_i}$$

Eq. 1

$$E_{SD} = E_S - E_D$$

(Eq. 2)

where E_S represents the supply capacity of ES, E_D is the demand intensity for ES, E_k is the supply capacity scores or demand intensity scores of ES for land use type *k*, M_k *k* is the area of land use type *k* in the grid, M_i is the grid area, L is the number of land use types in the grid, and E_{SD} is the budget index of ES supply and demand.

The supply-demand budget index of each ecosystem service was calculated by subtracting ES supply capacity from demand. Using KVFP land use data, this study evaluated units of 0.5 km × 0.5 km. The budget index values were divided into five categories: high deficit, general deficit, supply-and-demand balance, general surplus, and high surplus (Ji et al., 2020). Then, the ecosystem service supply-demand budget indexes were linked to ArcGIS 10.2 spatial data of LULC types as a common identifier field to create spatial-explicit maps.

Results

Landscape Capacities to Supply Ecosystem Services in the Kilombero Valley Floodplain

The 26-year ecosystem services supply maps (Figure 2) demonstrate that the supply of ecosystem services within the Kilombero Valley floodplain has been spatially decreased.

The results of Table 1 revealed that forests, bushland, grassland, and wetlands have high capacities to supply multiple ecological services (scoring 4-5) in the KVFP. Bare soil and urban regions have poor scores for regulating, provisional, and cultural services (0-2). Agriculture contributes more to crop production (score 5) than wild foods, timber, freshwater, traditional medicines, and capture fisheries (scoring 0-2). Wetland could not supply several provisional services (scoring 0), except crop production and livestock (scoring 3-4). Wetlands had a high score (4) for local and global climate regulation, groundwater recharge, and flood regulation. Water areas had a better supply capability for fisheries and water supply (score 5) but less for wild foods, timber, traditional medicines, crop production, and cattle. Among all LULC types, forests, lakes, and wetlands provided the most cultural services (scoring 4-5).

Ecosystem services including erosional regulation, pollination, crop production, and livestock have high mean confidence scores (CS) (2.8), while agriculture and water have LULC-type mean confidence scores (2.7). However, biodiversity, recreation, aesthetics, and bare soil for the LULC type scored low (2.1-2.2) (Table 1).

Human Demands for Ecosystem Services in the Kilombero Valley Floodplain

The spatial-explicit ES demand maps showed that ecosystem service demand in the Kilombero Valley floodplain increased towards the core of the valley (Figure 3). The floodplain's urban areas contain low-density communities and farming along major roadways.

Table 3: Ecosystem services (ES) supply-demand budget matrix for the Kilombero Valley Floodplain.

Land use and land cover types	Regulating services Σ	Local climate regulation	Global climate regulation	Flood protection	Groundwater recharge	Erosion regulation	Nutrient regulation	Pollination	Provisional Serives Σ	Crop production	Livestock	Capture fisheries	Wild foods	Timber	Wood fuel	Traditional medicine	Freshwater	Culture Services Σ	Recreation & aesthetic services	Intrinsic value of biodiversity
Settlement		[illegible]	[illegible]	-3	-3	-3	-4	-2		[illegible]	-4	-4	0	-3	-3	-3	-4		-3	-3
Agriculture		-1	2	-3	0	-2	-2	-3		1	1	1	0	0	-1	1	[illegible]		-1	-3
Bare soil		0	0	1	1	0	0	0		0	0	0	0	0	0	0	0		2	0
Bushland		2	1	3	3	3	4	1		0	0	0	-1	-1	-1	0	0		3	3
Forest		2	1	4	4	4	4	0				0	1	1	3	5	0		4	4
Grassland		3	2	-1	4	4	4	0		-3	1	0	1	0	2	2	0		3	0
Water		3	3	0	4	3	0	0		2	2	5	0		0	0	5		4	0
Wetland		3	3	-1	4	4	0	0		-1	-1	0	0			0	-1		2	3

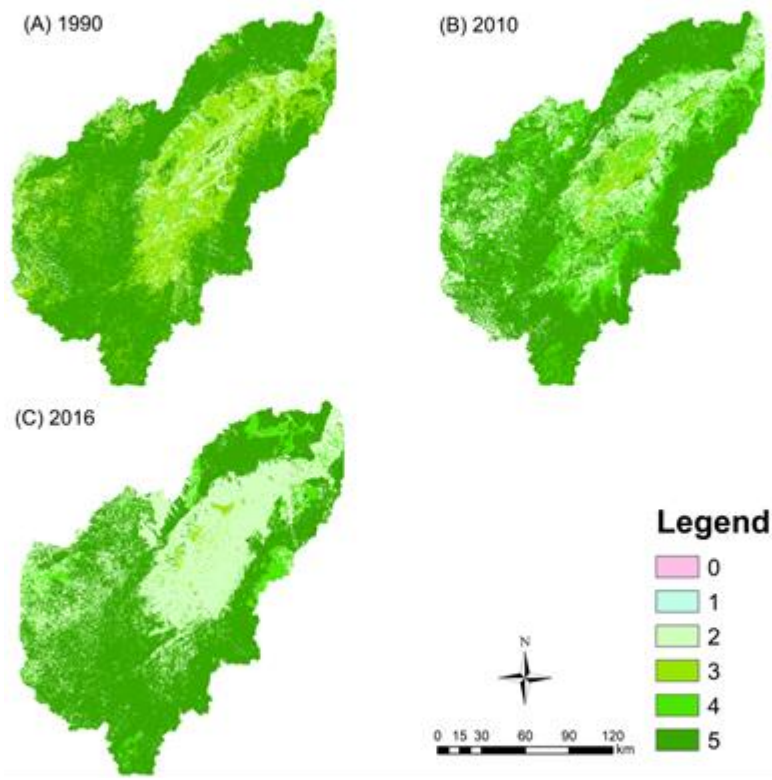

Figure 2: Map of ES supply in the Kilombero Valley Floodplain, Tanzania in (A) 1990, (B) 2010, and (C) 2016
Note: The values indicated in the legend represent the LULC types' capacities to supply ES: 0 = no relevant supply of ES; 1 = low relevant supply of ES; 2 = relevant supply of ES; 3 = medium relevant supply of ES; 4 = high relevant supply of ES; and 5 = very high relevant supply of ES

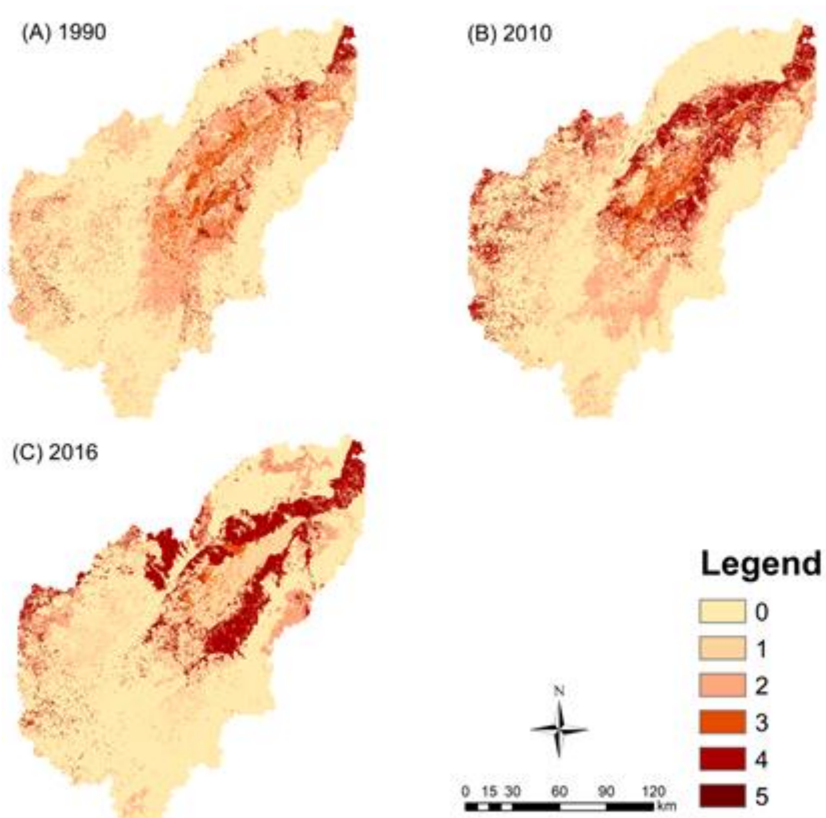

Figure 3: Map of ES demand in the Kilombero Valley Floodplain, Tanzania in (A) 1990, (B) 2010, and (C) 2016
Note: The values indicate the following demands: 0 = no relevant demand of ES; 1 = low relevant demand of ES; 2 = relevant demand of ES; 3 = medium relevant demand of ES; 4 = high relevant demand of ES; and 5 = very high relevant demand of ES.

From Table 2, urban areas have shown strong demand for local and global climate change, nutrient regulation, agricultural production, livestock, wood fuel, catch fisheries, and freshwater supplies (scoring 4-5). The agricultural area demanded highly regulating and provisional services (4-5). Rice fields have shown high demand for water supply (score 5), flood protection (score 4), erosion regulation (score 4), nutrient regulation (score 4), pollution (score 4), and local climate regulation (score 4). Whereas water bodies and bare soil had no demand for ecosystem services (score 0) except water bodies that had low demands for recreational services and intrinsic value of biodiversity (scoring 1-2). However, forest, bushland, grassland, and wetland have modest ecosystem service demands (scoring 0).

Moreover, the mean confidence scores (CS) results revealed that ecosystem services including erosional control, crop production, wood fuel; forest, and wetlands for LULC types have high mean confidence scores (2.5). Cultural services had a low confidence level, largely due to the intrinsic value of biodiversity (2.1), and settlement had a score of 2.2 (Table 2).

The Supply-Demand Budget of Ecosystem Services in the Study Area

The results revealed that the average ecosystem service supply-demand budget index in KVFP declined from 1.8 in 1990 to 1.6 in 2016 over the last 26 years. Indexes for each ES category demonstrate that KVFP ecosystem services supply surpasses demand, except for pollination, crop production, and freshwater supply, which show high deficits (Figure 4).

As shown in Figure 4, timber's supply-demand budget index ranged from 0.2 to 0.5, and wild foods from 0.5 to 0.7 from 1990 to 2016. Values below 1 indicate supply-demand balance. We also found a strong supply of groundwater recharge, flood protection, erosion regulation, and nutrient regulation with a supply-demand budget score of 3. Recreation and aesthetic value of cultural services are also abundant.

From 1990 to 2016, the spatial coverage of the supply-demand budget index (Figure 5) showed that high deficit areas were in agricultural and urban areas, while high surplus areas were mostly in ecological areas with low human activity and high natural land cover, forest, bushland, and wetland. For 26 years, agricultural growth and intensification have had a stronger impact on ecosystem services supply and demand in the Kilombero Valley Floodplain, as the high deficit area increases towards the core.

The results of the supply-demand budget of ecosystem services areas presented in Table 3 revealed that urban areas are undersupplied with ecosystem services particularly, local and global climate regulation, crop production, nutrient regulation, livestock, capture fisheries, and freshwater supply (score -5 and -4). Agriculture has also shown an undersupply of freshwater (score -5), this may be because the main crop cultivated in the KVFP is rice, which is a water-loving crop. Forest, bushland, and grassland have demonstrated high supplies of the regulating services exceeding their demands. In the case of the provisional services, the forests showed an oversupply of traditional medicines (score 5). This is similar to other studies by (Tao, Wang, Ou, & Guo, 2018) which revealed that the natural land cover types are characterized by multiple ecosystem services' supplies exceeding their demands.

Figure 4: Supply-demand budget index of regulation services, provisional services, and cultural services for the Kilombero Valley Floodplain during 1990-2016.

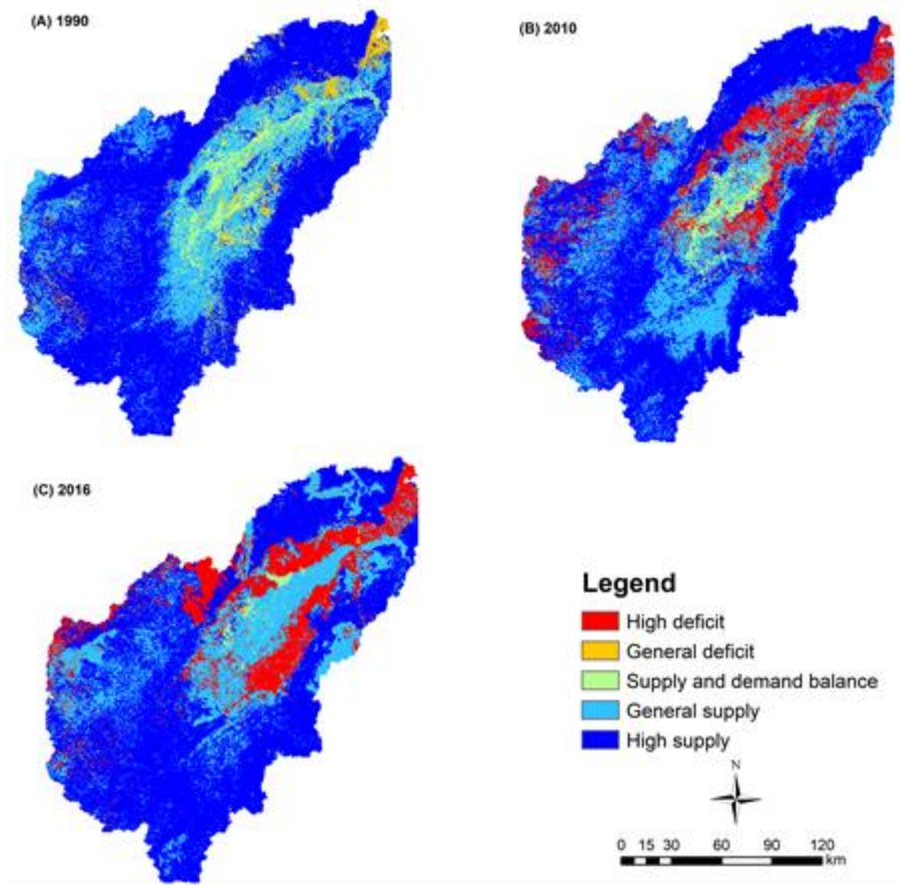

Figure 5: ES supply and demand level indexes in the Kilombero Valley Floodplain (A) 1990, (B) 2010, and (C) 2016

Wetlands supply local and global climate regulation, groundwater recharge, and erosional regulation (scoring 3-4) but have a neutral supply-demand balance for nutrient regulation and pollution (score 0). For preliminary services, the wetland has a demand/supply ratio of -1 for crop production, cattle, and water supply and 0 for catch fisheries, wild foods, and traditional medicines. Water areas in the study have oversupplied capture fisheries and freshwater. Natural land cover like forests, bushlands, waterways, and wetlands gives more regulating and cultural functions than they demand (scoring 3-4). Regulatory and cultural services for all LULC kinds have supply values above demand values (oversupply), while provisional services have the opposite (undersupply).

Discussion

Landscape Capacities to Supply Ecosystem Services

The spatial and temporal patterns of ES supply were determined, it revealed that forest, bushland, grassland, and wetland provide more ecosystem services than urban areas and bare soil in the Kilombero Valley floodplain. Similarly, Burkhard et al. (2012) and Tao et al. (2018) found that natural land cover types like forests, bushlands, grasslands, and wetlands high capacity to provide multiple ecosystem services, while human-modified land cover types like urban areas and bare land have no or very low relevant capacities to provide ecosystem services. Moreover, the higher surplus ES budgets are generally concentrated in ecological zones with minimal human activity and high natural land cover, mostly forests, bushland, and wetlands (Ji, 2020). In addition, the supply of ecosystem services within the Kilombero Valley Floodplain has been spatially decreased for the last 26 years, due to a decrease in the forest, bushland, and wetland by 10.3%, 10%, and 3.8% respectively (Msofe et al., 2019). Most of these LULC changes in the Kilombero Valley Floodplain are influenced by massive agricultural development and intensification due to climate change, and rapid population growth to assure food security and income (Johansson & Abdi, 2020; Muro et al., 2017).

Human Demands for Ecosystem Services

The spatial and temporal patterns of ES demand were determined revealing that urban and agricultural areas with human-dominated land cover have the greatest demand values in the Kilombero Valley floodplain. Moreover, the study found that forest, bushland, grassland, and wetland had low or no demand rates for ES, this is due to the fact that these are natural land cover types with lower human population, and less ecosystem service consuming activities (Burkhard et al., 2012). Spatial-explicit maps demonstrate that ecosystem service demand has increased near the core low-lying areas of the valley floodplain between 1990 and 2016. This could be due to increased agriculture and urban areas by 11.3% and 0.1%, respectively (Msofe et al., 2019). The urban area in this floodplain is characterized by low-density towns and farms along main roadways. ES supply and demand were mostly balanced in bare soil, grassland, and neighboring areas. The ES supply and demand respond to LULC change, but they are sensitive to different LULC types (Stoll et al., 2015). The main driver of sensitivity variance in the Kilombero Valley floodplain was ES capabilities across land use and cover types.

The Supply-Demand Budget of Ecosystem Services

The spatial and temporal patterns of the ES supply-demand budget determined revealed that the average supply-demand budget index for ecosystem services in KVFP declined from 1.8 in 1990 to 1.6 in 2016 over the last 26 years. The supply-demand indexes demonstrate that KVFP ecosystem services supply surpasses demand, except for crop production, pollination, and freshwater supply, which shows demand exceeds supply (high deficit). The ES budget deficits were concentrated in agricultural and urban areas, whereas surpluses were predominantly in ecological zones with little human activity and high natural land cover, such as forest, bushland, and marsh. This is due to the fact that areas with human activities such as agricultural and human settlement have a high demand for ES compared to areas dominated by natural land cover. The core low-lying area of the seasonal floodplain has a higher deficit area, showing stronger consequences of agricultural growth and intensification, especially paddy fields, for 26 years. The ES supply-demand budget indices are intimately related to land use and land cover type, which affect ecosystem structure and function (Burkhard & Maes, 2017). Furthermore, the equilibrium between the supply and demand of ecosystem services in the KVFP is affected by various factors including deforestation, and agricultural expansion, which were in turn influenced by rapid population growth, immigration of agro-pastoralists, and the establishment of large commercial agricultural enterprises focused on rice and sugarcane cultivation within the floodplain. This study analyzes the supply and demand of ecosystem services (ES), providing scientific insights for sustainable ecosystem management in the KVFP.

Ecological Management Strategies and Policy Implications

Overgrazing, agricultural development, and intensification, combined with a growing population in the Kilombero Valley floodplain, threaten the valley's ecological future. Forest, bushland, and grassland in the Kilombero Valley Floodplain provide a large excess of ES and should be protected. They are ecologically sensitive, thus human activities like cutting down trees to start new farms, logging, and cattle grazing must be strictly controlled. Moreover, different management techniques should be developed based on the spatial analysis results of the ES supply, demand, and supply-demand budgets in different periods and local experts' knowledge. The district government should create effective land use plans for each ward and village, carefully limit population agglomeration, and enforce environmental by-laws. To preserve the deforested areas, local government reforestation and afforestation projects should be established.

Moreover, ES supply and demand are borderline in areas with a general surplus dominated by wetland and paddy farms found in the floodplain ecosystem's low-lying plain. These areas can be easily affected by human activities, creating deficits. These locations should enforce the fundamental cultivated land protection line and ban crop production, especially rice, in the floodplain ecosystem. The agricultural structure should also be changed to improve ES advantages, notably in critical wetland areas along the Kilombero River. The local authorities should also protect wetland resources from fires, poaching, encroachment, fishing, grazing, and invasive species in the Kilombero River.

Finally, high deficit locations are mostly along roadways, agricultural land, and urban areas with simple ecological structures dominated by farms, settlements, and small vegetation. The study recommends the government should put more emphasis on land use planning and establish local irrigation schemes for smallholder farmers to reduce floodplain encroachment, conserve natural land cover, preserve biodiversity, and ensure sustainable ES supply in the Kilombero Valley floodplain. These study findings hold significant policy implications for the sustainable ecological management of the KVFP.

Limitations and Contributions of the Research

The assessment of ecosystem services supplies and demand in the Kilombero Valley Floodplain will guide land use policy and decision-makers on sustainable ecological management strategies. This study used an effective approach to examine dynamic ES supply and demand and inform sustainable ecological management strategies. However, this study has drawbacks. First, the ES matrix approach cannot reflect the regional variation of ES capacity within the same land use category. ES capacity may vary within the same land use category. For instance, low-density areas integrated with the countryside may provide fewer services than urban areas. Second, the ES matrix approach simply defined probable ES scores. No biophysical or consumer processes were considered. However, the ES supply-and-demand budget index created in this work still represents human demand on ecological resources carried by the ecosystem, and the ES matrix shows the carrying state of the ES in the Kilombero Valley Floodplain.

Despite its shortcomings, this study paradigm is suitable for ecological management, especially in data-scared areas. This study shows that indexes can portray ecosystem carrying capacity and zone ecological areas for optimal management. Moreover, the expert-based matrix of ES supply and demand quickly evaluates the status of ES supply and demand in the Kilombero Valley Floodplain, which helps policy-makers compare temporal dynamics and quickly identify crucial spatial points and priority areas of protection.

Conclusion

This study employed land use data from 1990, 2010, and 2016, as well as an evaluation matrix including the perspectives and experts' knowledge. The matrix based on expert knowledge, efficiently assessed the state of supply and demand for ecosystem services (ES) in the Kilombero Valley Floodplain. The objective of the study was to determine and map the changes in the supply, demand, and supply-demand budget indexes of ecosystem services (ES) in the Kilombero Valley Floodplain over a period of 26 years. The findings of the study indicate that over the course of the last 26 years, KVFP has witnessed a decline in the provision of ecosystem services, mostly attributed to land use and land cover change. Spatially explicit maps indicate that there has been a spatial increase in the demand for ecosystem services in the central low-lying flat areas of the Kilombero Valley from 1990 to 2016. The region exhibiting equilibrium between ecosystem services supply and demand was predominantly found in areas characterized by bare soil, grassland, and their surrounding environment. Over the course of the past 26 years, there has been a decline in the average supply-demand budget index, which decreased from 1.8 in 1990 to 1.6 in 2016. The supply-demand indexes indicate that the supply of ecosystem services within KVFP generally surpasses the demand, except for pollination, crop production, and freshwater supply, where the demand exceeds the supply. These changes in ES supply-demand are linked to deforestation, agricultural expansion, agropastoralists immigration, and encroachment to the wetland area. Thus, this study recommends that the government should create effective land use plans for each ward and village in the Kilombero District, establish afforestation programs, local irrigation schemes for smallholder farmers, and enforce environmental by-laws to ensure sustainable ecological management in the Kilombero Valley Floodplain and its ecosystems.

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Declaration statement

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Author contributions

Nangware Kajia Msofe conceptualized and designed the paper. **James Lyimo** acquired data, analyzed, and interpreted data together with **Nangware Kajia Msofe**. **Lianxi Sheng** assumed an advisory role. All authors reviewed and approved the final manuscript version to be submitted for publication.

Conflicts of interest

The authors declare no conflict of interest.

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Data availability

All data generated or analyzed during this study are included in this published paper.

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