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Research article

Characterizing landscape fragmentation of Koitobos river sub-basin-Trans-Nzoia, Kenya

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ABSTRACT

The changes of landscape structure and functioning due to unprecedented human interference is hastening across the globe and it is thus a compelling necessity to preserve and restore our ecosystems. This study aimed to characterize levels of landscape fragmentation, habitat structure, driving forces and perceptions of the residents on most preferred reconfiguration approaches. The land use/ land cover (LULC) change was first determined by interpreting the 1973, 1986, 1995, 2002, 2014 and 2022 Landsat images using the QGIS 3.26 while the selected landscape fragmentation metrics were analyzed using FRAGSTATS 4.2. Forests, shrubs, grasslands showed a declining trend, except agriculture, water and built-up areas, which depicted high increases for the study periods (1973 to 2022). The landscape of the study area is characterized as progressively fragmenting as signified by high escalated values of patch number (374 %), edge density (7828 %) between 1986 and 2002, contagion (10.3%), and a declined value of Shannon Diversity Index (SHDI) (-17.42%), Shannon evenness index (SHEI) (-25.8 %) and connectiveness (-43.3%). Considering these results, high losses of forests and grasslands coupled with expansive farmlands and built_up areas have led to unprecedented landscape fragmentation From field surveys and oral interviews, this has not only left streams vulnerable to massive sediment loads but has also triggered annual floods which occur during wet months even though change in onset of rainfall seasons was also reported. The findings call for restoration an integrated and sustainable restoration efforts especially for the forests, grasslands, riparian corridors. along sustainable urban planning and community-based sensitization on watershed management

1. Introduction

Globally, most landscapes are now heavily disturbed and transformed (Steffen et al., 2009) and in particular, between 1960 and 2019, 32% of the land area has been altered (Winkler et al. 2021). Key interests areas include biodiversity hotspots comprising higher species diversity and which have experienced more than 70% loss of their pristine native vegetation (Laurance, 2010). Various studies have confirmed that anthropogenic landscape fragmentation results into habitat loss and ecosystem services offered by different habitats such as forests, shrubs, grasslands, wetlands, water bodies across landscapes on spatio-temporal scales (Cuke & Srivastava, 2016; Ramirez et al., 2019; Muhammed & Elias, 2021). Disturbance and alteration of natural habitats of any magnitude affects physical attributes of ecosystem processes and the environment's, a scenario which ultimately results to ecological degradation (VEAC, 2011). Further, studies have revealed that landscape fragmentation leads to changes in temperature (Mendes & Prevedello, 2020) within watersheds while also affecting the hydrological processes (Ziegler et al., 2007 ;Thomas et al., 2020, ; Guo et al., 2021 ;, Liu et al., 2022).

Impacts of landscape fragmentation are influenced by intensive land-use practices, which affects qualitative and quantitative components of land-covers ((Baste & Watson, 2022; Liu & Yang, 2018**)** . The rapidly increasing human population, which have triggered an ever-growing demand for food, wood products and energy, are some of the primary drivers of land-use, land-cover (LULC) changes and thus landscape fragmentation and habitat loss. Further, the rate and extent of land cover conversion and unprecedented human modification of environments beyond recovery levels have triggered changes in Ecosystem functioning (Abhilash et al., 2021 ; Butler, 2021).

The rate of anthropogenic landscape degradation is increasing worldwide, especially in African region where rapid human population is being experienced (Malcolm et al., 2006; Fischer et al., 2021). Further, ecosystems in the East African region are frequently restructuring due to complex societal and biophysical factors (Were et al., 2013). For example, Bullock et al., **(**2021**)** revealed that fragmentation in East Africa is reflected by the increase in croplands by 34.8 % for the period 1998-2017 while 20 million hectares woodlands had been convereted to less woody classes due to fragmentation. LULC due to rocketing human population, fragmented watershed governance, livestock keeping, is a crucial and usual occurrence in heterogeneous watershed areas of Kenya (Akali et al., 2015 ;Kogo et al., 2020).

Various studies have been carried out to assess the rate and degree of LULC change in Kenyan ecosystems and water towers (Githui, 2008; World Bank, 2013 ;Omwenga, 2019; Murunga, 2021; Masayi et al., 2021). Results from these studies have revealed that, most watersheds are marked by a decline of habitats such as forests, shrublands, grasslands, wetlands and water bodies but with a significant spatial-temporal expansion of farmlands, grazing and barren lands.

Increasing human population, intensive livestock keeping, inappropriate land-use practices, land tenure laws, fragmented watershed governance, and in Kenyan watersheds have led to land degradation (World Bank, 2020). Democratization, politics and regime change and particular the political power has contributed to illegal destruction of

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protected forests, wetlands and grasslands by illegal loggers, pastoralists and farmers (Klopp, 2012). Moreover maps of protected ecosystems are influenced by political power which in-turn leads to destruction of major ecosystems (Klopp & Sang, 2011). Koitobos River Sub-basin (KRSB) is one of the biophysical and ecological hotspot where landscape fragmentation and land cover modification have steadily occurred over the past years (World Bank, 2017; World Bank, 2020). Even after devolution of landscape related protection functions to counties, protection of key ecosystems is challenged by limits of institutional fix and veto players (Boone et al., 2019). KRSB represents part of Mt. Elgon National Game Park which is home to various small, large bird species, mammals with a complex floristic composition (Wasonga & Opiyo, 2018). KRSB is unique with reference to its vegetative landscapes structures which are strongly dictated by altitude (Hamilton et al., 2011; Wesche, 2002). The sub-basin is characterized by large-scale African Development Corporation (ADC) Panocal African Development Corporation and Kenya Seed Farms (Justus & Yu, 2014) and major urban centres; Kitale town, Endebess and Kwanza centres which are Trans-Nzoia headquarters and Sub-county centres respectively (CGT, 2018). KRSB is crucial as it forms part of the upper drainage system that drains into Nzoia river which then flows to transboundary Lake Victoria. However, it is impacted rapid population growth, excessive settlements and encroachment to protected areas of Mt. Elgon National Park, illegal logging, livestock rearing, a myriad of institutional failure, and watershed governance issues. As a result, previously large habitats are heavily fragmented while small sized habitats are lost.

Many studies on landscape fragmentation in watersheds have been conducted at small spatial scales with individual ecosystems or fragments being considered as units of study. However, to draw inferences and conclusions about the consequences of landscape fragmentation, it is key to compare how the whole landscape have differed in their structure and patterns of fragmentation at various spatio-temporal scales (McGarigal et al., 2015). Landscape fragmentation particularly structural characteristics of LULC at classes, patches and landscape levels within the Kenyan landscapes have not to a significant level received appropriate research attention. Many studies have focused on LULC changes while those focused on landscape structure coupled with LULC changes in heterogeneous watersheds comprising of protected areas, highly intensive agricultural lands, human settlements and livestock are scarce. Hence, the main objective of this research was to investigate spatio-temporal landscape fragmentation structural changes from 1973 to 2022 by selecting Koitobos river sub-basin as a case study watershed. Specific objectives included (1) To determine spatio-temporal landscape fragmentation metrics and structure; and (2) to explore the driving factors of landscape structure changes in KRSB.

Therefore, outputs of this study seek to identify trends of fragmentation, and to suggest implementation of important conservation measures in KRSB that will serve as a foundation for sensitization of communities on sustainable land-use policies, implementing existing watershed protection regulations and preparing future integrated watershed management plan and landscape planning strategy.

2. Materials and methods

2.1. Study area

KRSB is the principal river which drains an area of approximately 825 km^2 from Mt Elgon and discharges to Nzoia River, a few kilometers from Kitale town. It falls within Mt Elgon watersheds which forms a segment of the Upper Nzoia River Basin and lies within the jurisdiction of Lake Victoria North Basin Service Board (LVNBSB). The location of the study area is presented in Figure 1. KRSB encompasses a wider and rich range of habitats ranging between an altitude of 1792 m and 4221 m. It is recharged by tributaries such as Muberi, Kaibei which originate from Easterly slopes of Mt. Elgon (Namwamba, 2012). In the middle and lower reaches, it is joined by other ephemeral tributaries which drain wetland areas during the wet; Chemususu and Sikubu wetland areas.

KRSB experiences the first and wettest rainfall season in March through May (MAM). This is followed by short rainfall period (July-September) while December-March is a dry period (World Bank, 2020). The rains in this sub-basin are influenced by hydrological dynamics in Mt. Elgon in the West and Cheranganyi hills in North-East (Namwamba, 2012). The foot-hill of Mt. Elgon experiences more rainfall than Kitale area and the lowland areas due to differences in attitude. Foot hill areas experience an average rainfall amount of 1270 mm especially in the Elgon Sawmill areas and a minimum of 1016 mm. However, a maximum of 1549 mm has ever been recorded (Namwamba, 2012). Wet season is characterized with night temperatures of 19 ^{0} C rising to about 25.6 ^{0} C during hottest portion of the day. However, the range is higher during the dry season, in which low temperatures of 15.8 ^{0} C and high temperatures of 27.9 ^{0} C have been recorded (Namwamba, 2012).

Soils in Upper parts of KRSB are Ferralsols, which are weathered soils characterized with low nutrient levels. The Ferralsols are interspersed with deep and red Nitisols soils containing some good percentage of organic matter (Jones et al., 2013). The basin has several urban centres though most of the population resides in rural areas. Most farms are in KRSB are privately owned and the sizes have been decreasing to smaller sizes due to land tenure rights that have driven subdivision of land amongst family. Large corporations that own large scale farms; Agricultural Development Corporation (ADC), Kenya Seed Company, Kenya Seed driers, Western seed and Kenya Cooperative Creameries and Panacol Flower International Limited. Urban centres in this watershed include; Endebess and Kitale town. The sub-basin also hosts part of Mt. Elgon Game Park and Mt. Elgon National Reserve.

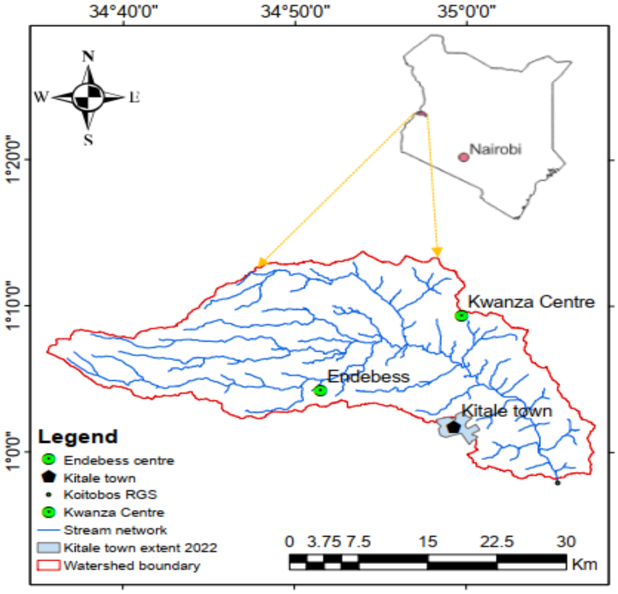

Figure 1: location of the study area

2.2. Data source, image processing and classification

The sources of data were from satellite-based remote sensors, field-surveys, field observation and ancillary data. Preprocessed Landsat imagery for the years 1973, 1984, 1994, 2002, 2014, 2018, 2022 were used to generate time-series of the LULC. Landsat satellite imagery are proposed as it provides a continuous coverage area with same resolution apart from Landsat 1-5 MSS for 1973 which has a spatial resolution of 60 m.

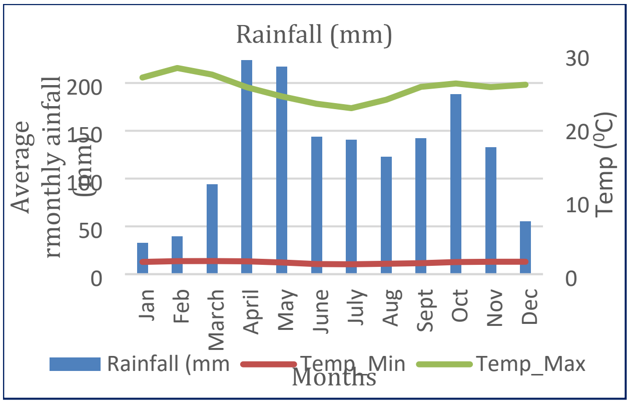

Figure 2: Mean monthly rainfall and temperature of Trans_Nzoia, where KRSB is located.

Imagery used in this study and their properties are summarized in Table 1. Cloud free images of similar periods and seasons were selected to reduce phonological and atmospheric effects. In QGIS-SCP plugin, atmospheric correction was addressed using procedures outlined by (Hollingsworth et al., 1996). Subsequently, the imagery was orthorectified using the spectral bands of Red (630-685 nm), Blue (440-510 nm) and Near Infrared (760-850 nm). LULC change and landscape fragmentation analysis followed satellite imagery standard pre-processing and post-processing procedures (Figure 2).

Landsat bands were extracted and the six bands excluding the thermal bands were stacked in QGIS –SCP plugin according to (Congedo, 2016) to form multiband imagery. Image masking, band setting, colour compositing, and sub-setting was accomplished consecutively in QGIS- SCP plugin. The multi-band images outputs were then orthorectified to Universal Transverse Mercator (UTM) datum of EPSG: 32636 37N (https://epsg.io/) using the Nearest Neighbour technique. Supervised classification using the maximum likelihood algorithm according to (Congedo, 2016 ;Enderle & Jr, 2005) was be used for classification. Accuracy assessment will be accomplished using field based ground truthing points collected using Garmin Etrex 32x GPS tool according to (Gbodjo et al., 2020) and the high resolution Google Earth imagery (Murunga, 2021).

Accuracy assessment was carried out to measure accuracy of classified maps against the reference points obtained from the field (30 points for each LULC category). Pixels classified under different various LULC polygons were compared with ground truthing points using the error matrix (Congalton, 2005). Error matrices were determined inform of user accuracy, producer accuracy and overall accuracy (Olofsson et al., 2014) and Kappa statistics (Congalton, 2005). Accuracy should be over 60% for producer and user accuracies (Shao & Wu, 2008). However in principle overall accuracy should meet the minimum of 85% (Anderson et al., 1976). Further, Kappa coefficient of 1 implies perfect agreement between classified map and reference map. A value between 0.7 and 1 is considered good while a value < 0.20 signifies poor agreement. The percentage of change rates and extent (Equations 1 and 2) was based on the procedures outlined by (Mezgebu & Workineh, 2017).

Table 1: Landsat satellite series used for landscape change.

Satellite and sensor	Path and row	Date of acquisition	Resolution
Landsat 1-5 MSS	182/59	20 May 1973	60 m
Landsat 5 TM	170/59	22 June 1986	30 m
Landsat 5 TM	170/59	02 April 95	30 m
Landsat 7 ETM on	170/59	15 May 2002	30 m
Landsat 8 OLI	170/59	05 March 2004	30 m
Landsat 9 OLI	170/59	04 April 2022	30 m

$$\%\ change\ extent = \frac{Area\ of\ final\ year - Area\ of\ initial\ year}{Area\ of\ initial\ year} \times 100 \qquad (1)$$

$$\%\ change\ rate = \frac{Area\ of\ final\ year - Area\ of\ initial\ year}{Time} \times 100 \qquad X \qquad (2)$$

The data about the major drivers of LULC change in the study area Major diving causes of landscape fragmentation in the area were collected through key informant interviews using structure questionnaires and field observations. Random sampling followed procedures outlined by Taherdoost, (2016) while validation and validation followed guidelines by Taherdoost, (2017) and Deniz & Alsaffar (2013). 10 questionnaires were used to test for reliability and validity while 40 questionnaires were administered and 32 collected (80%). Further, oral interviews with selected locals were conducted to triangulate information from other interviewees and to establish some of the causes of landscape fragmentation. Key informants were selected based on age and experience on LULC distribution in the area (such as old farmers), responsibilities (foresters, community elders, natural resources experts) and spatial distribution/cultural representation (by altitude and resources). This exercise followed procedures outlined by (Jamshed, 2014).

2.3. *Quantification of landscape fragmentation*

Landscape metrics under three main categories (landscape configuration and composition metrics) were extracted using procedures outlined by (McGarigal, 2012; Muhammed & Elias, 2021). In the first category, class metrics of patch number (PN), patch density (PD), Edge density (ED), interspersion and juxtaposition (IJI), connectiveness, PAFRAC, and core area were considered. In the second category, patch metrics of patch area, Euclidean Nearest Neighbour (ENN), FRAC and contagion were considered. Average and small metrics under this category were not considered as it was determined that the smallest were limited by the spatial resolution of the satellite while the average were affected the compromised smallest metrics. Lastly, the third category of landscape metrics included Edge density (ED), Contagion (Contag), Connectiveness, Euclidean Nearest Neighbour Distance (ENN), Interspersion & Juxtaposition Index (IJI), Shannon Diversity Index (SHDI) and Shannon Evenness Index (SHI) were considered. Landscape Ecology Statistical tool (LECOS) a plugin in QGIS alongside FRAGSTATS tool version 4.2.1 were used for landscape pattern analysis (McGarigal & Marks, 1994). To achieve this, an 8-cell neighborhood rule was used to define the patches (Posada,2012). Selected metrics are described in Table 3.

Table 2: Description of selected LULC classes

LULC Classes	Description
Forest	Includes native forests, bamboo trees, mixed forests and forest plantations established in Mt. Elgon in 1990s
Shrubs	Includes bushlands consisting with small to medium woodlands
Grasslands	Includes grazing lands and areas under permanent grass cover
Agriculture	It includes crops, irrigated land, plantations, heterogeneous agricultural areas and agro-forestry areas.
Water	Includes wetlands, swamp areas, established water storage infrastructures etc
Built-up	It includes urban centers, roads, greenhouses etc

Table 3: Description of selected landscape metrics

Metrics	Formula	Description	Scale	Units
Patch Number	PN = $\sum_{i=1}^{n} Pi$, where $Pi = patch\ type\ i$	- Total number of patches within a class - Degree of sub-division	Class/landscape	No
Patch Density	PD = N $_i$/A where A = Area of each landscape type in m^2 and i = number of patches	- Degree of landscape heterogeneity and fragmentation	Class/Landscape	No per 100 ha
PAFRAC	PAFRAC = $\frac{2}{\beta}$ 100 where β = slope of area against perimeter regression	- Degree of patch complexity	Class	none
FRAC	FRAC = $\frac{2 * ln * \ (0.25 * pij)}{lnaij}$ 100 where A = Area of each landscape type in m^2.	- Levels of patch complexity, scale dependent. Based on patch area and perimeter	Patch	none
Core area	$COA = \sum_{j=1}^{n} aij$, aij −c, c = buffer size usually 50 m	- Area of interior habitat	Class/Landscape	Hectare
Edge Density	ED = $\frac{E}{A}$ where A =total area, E = Total edge	- Perimeter-Area ratio	Class/Landscape	Metre/ha
Contagion	CONTAG = $\frac{\sum_{q=1}^{na} \ Pq \ln(Pq) -}{2\ln{(t)}}$ P$_q$ = adjacency table for all LULC classes divided by total sum of the table and t = total number of classes in a given landscape. Classes ≥2	- Irregularity of patches	Patch	%
Connectiveness	CONNECT= $\frac{\sum_{j=k}^{n} \ cijk,}{\frac{ni(ni-1)}{2}}$ 100 cijk = The joining between the patch j and patch k (where 0 = unjoined, 1=joined) of the patch I (corresponding patch) based on threshold distance defined by the user	- Functional joinings between total patches of the corresponding patch within the specified distance	Class/landscape	%
Euclidean Nearest Neighbour Distance	ENN = h$_{ij}$ Where h$_{ij}$ = Distance to the nearest patch of the same LULC class neighbour in m	- Edge-edge distance between neighboring patches of same category	Patch	m
Interspersion & Juxtaposition Index	IJI = $\frac{\sum_{i=1}^{m} \sum_{i=1}^{m} [(\frac{eik}{E} * \ln\frac{eik}{E}}{\ln(0.5[m(m-1)]}$ 100, e$_{ik}$ = total length of edge (m) determined between i classes and k. m = number of total classes present in a landscape and E = total edge lengths of a denominated class within a landscape	- Measure of patch adjacencies evenness. 100 represents 100 even and 0 for unevenness	Class/Landscape	%
Shannon diversity index	$SDI = \sum_{i=1}^{n} (Pi - lnPi)$, where Pi = proportion (%) of landscape occupied by patch types of class i	- Degree of landscape heterogeneity and diversity	Landscape	None (ratio)
Shannon evenness index	SHEI = SDI/ln (m) = $\frac{\sum_{i=1}^{n} (Pi - lnPi),}{\ln{(m)}}$	- Landscape composition and richness	Landscape	None (ratio)

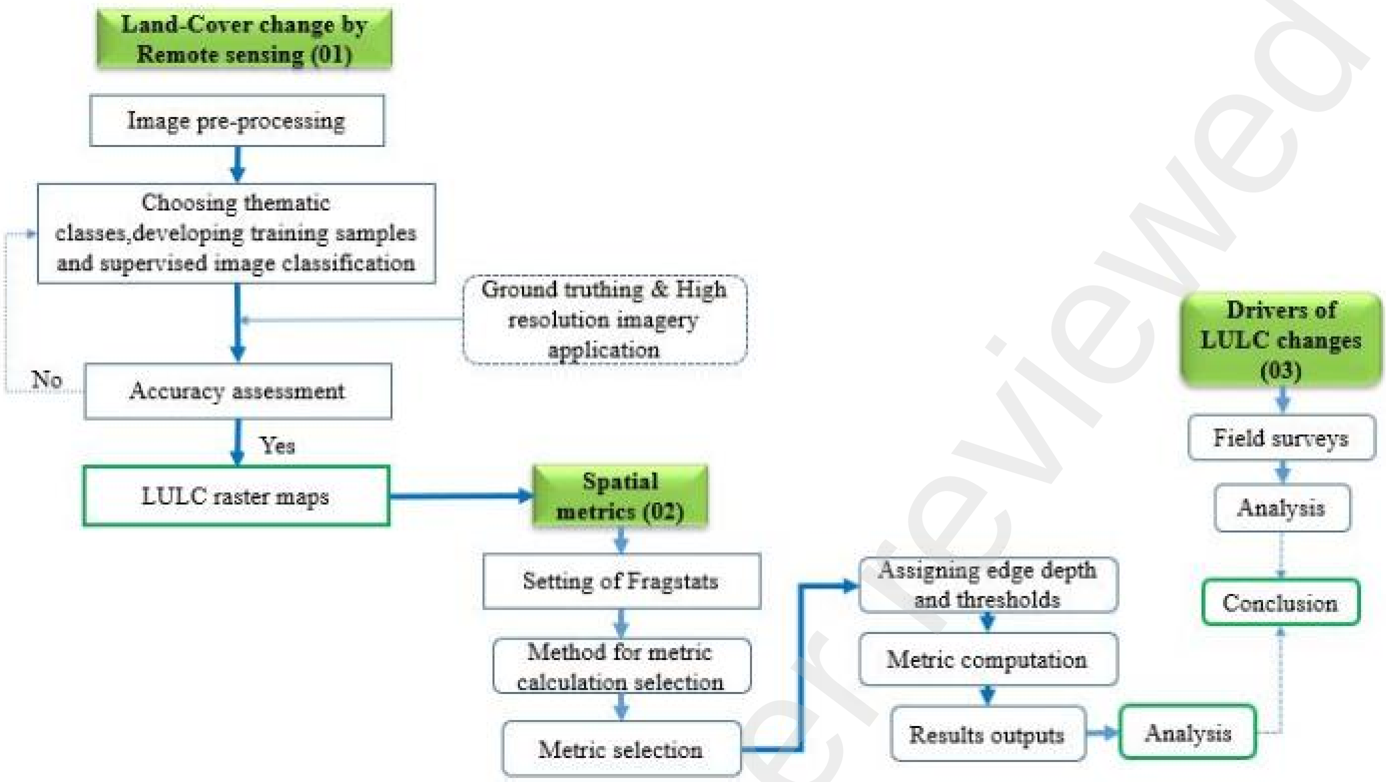

Figure 3: Flowchart showing steps and procedures to produce LULC maps and analysis of landscape fragmentation

3. Results and discussion

3.1. Land use/land cover changes

The analysis of LULC changes in the KRSB were made from 1973 to 2022 for 49 years. Forests and shrubs and wetlands depicted an overall decreasing trend in area and extent, except the farmlands and built-up areas which show an increasing trend. (Figure 5). Forested lands, shrubs and grasslands were dominant for the 1973 to 1986 period while farmlands and water occupied the least area. However, since 2002, farmlands and built-up areas were dominant with more isolated forests remaining in along the riparian corridors, near Kitale town and Mt. Elgon Nationa park. These were, a decreasing trend for forests, shrubs and grasslands and an increasing trend for built-up areas and farmlands respectively. Farmlands increased by 56186.19 at an annual rate of 1146.7 ha, water for 11.25 ha (0.22 ha per annum), for the study period while built-up areas increased by 567 .27 ha from 12.42 ha at annual rate of 56.3 ha for the period 2002-2022. This is at the expense of forests, shrubs and grasslands which reduced over the study period at a rate of -118.8 ha, -104.1 ha and 935.8 ha. However, water extent shows an increasing extent for the period 1973 to 1995 and a decreasing trend between 1995 to 2022. This indicates an ongoing conversion of natural to human dominated ecosystems. A rapidly increasing human population, demand for wood products triggered by urbanization, increasing demand for food and intensified agricultural activities with perception of making maximum profits are the main factors influencing LULC changes. These findings echoes similar results reported in Upper Nzoia by Kogo et al., (2020), Mt. Elgon ecosystems by Masayi et al., (2021)and Maasai Mara by (Murunga, 2021). Human population growth in Trans Nzoia County in which most of the watershed lies is depicted in Figure 4. Overall accuracies for 1973, 1986, 1995, 2002, 2014 and 2022 classified images were 89.8 %, 95.2 %, 90.2 %, 91.5%, 90.8 and 91.8 % with kappa coefficients of 0.816, 0.916, 0.817, 0.835, 0.807 and 0.815 respectively. Accuracies indicate reliability of LULC change detection maps produced. LULC maps analyzed for landscape fragmentation are presented in Figure 5.

The increase in agricultural land, built-up area aligns with increase in human population within the watershed. Human population growth in Trans Nzoia County in which most of the watershed lies is depicted in Figure 4. Population in Trans-Nzoia increased at a rate of 5.1% (1979-1989), 4.6% (1989- 1999), 4.2 % (1999-2009) and 2.09% (2009-2019) (Figure 4). Higher populations increase was observed for the period 1979-2009.

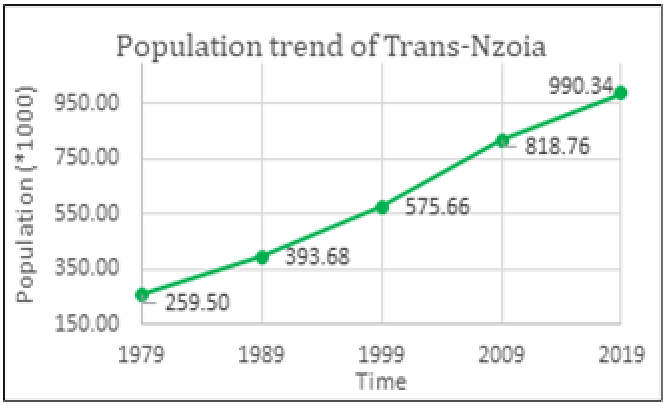

Figure 4: Population dynamics in Trans Nzoia where KRSB is located

Modified from https://www.citypopulation.de/en/kenya/admin/rift_valley/26trans_nzoia/

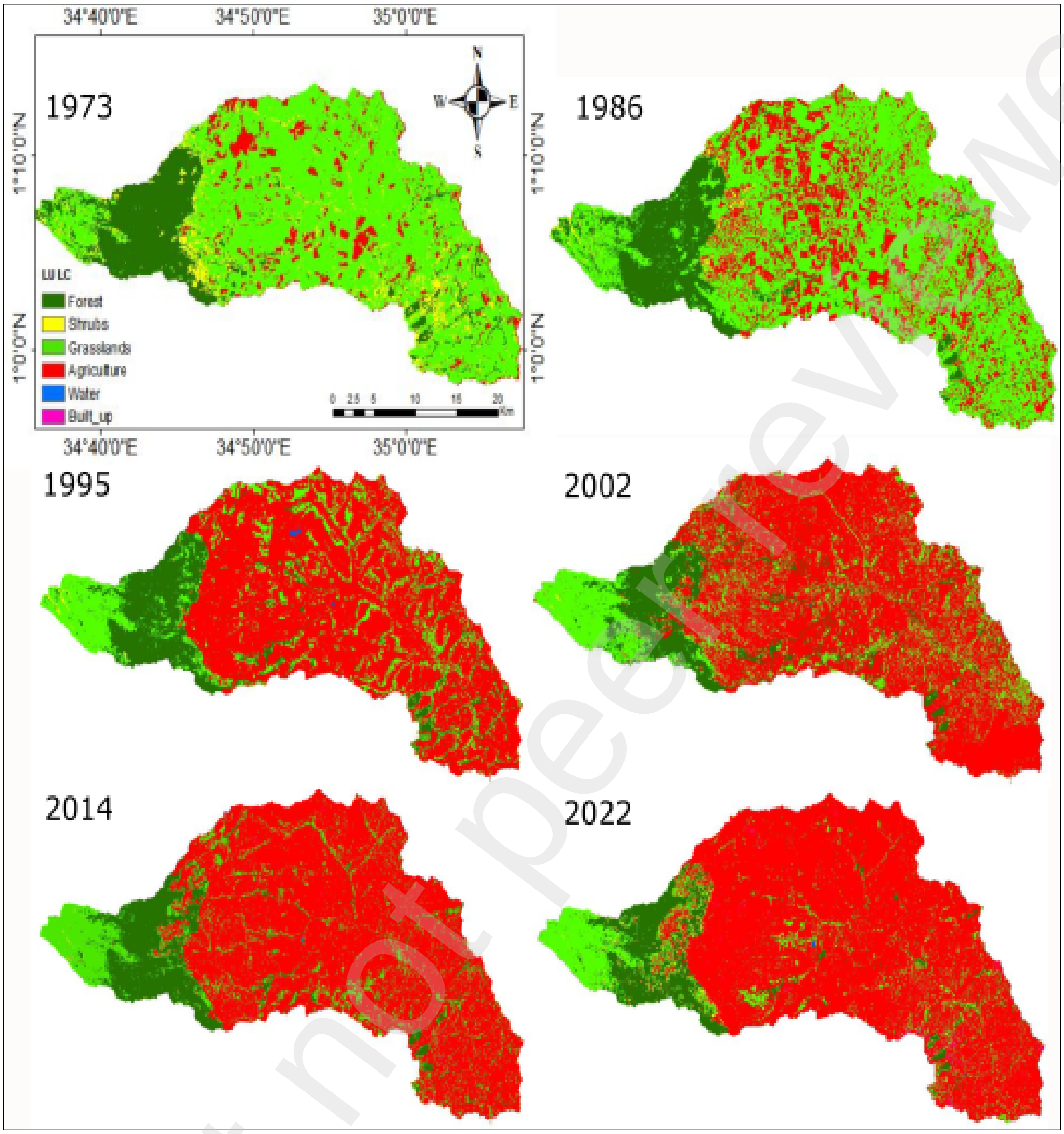

Figure 5: LULC maps for landscape structure fragmentation analysis.

As depicted in Table 4 , LULC analysis show a decreasing trend for forests, shrubs and grasslands and an increasing trend for agriculture, urban and water covers. Different LULC experienced higher decreasing and increasing trends. Forest decrease rates were experienced during the period 1995-2002 period (-2.09 %), shrubs for the period 2014-2022 (+313.97), grasslands between 1986-1995 (-6.15%), agriculture (+17.44%) for the period 1986-1995, water (+91.6%) between 1986-1995 and built_up (+142.63%) for the period 2002-2014. Lowest rates for forests were experienced between 2002-2014 (-0.28%), shrubs at -0.52% for the period (2002-2014), grasslands (-0.80%) between 1986-1995, agriculture (+0.11%) between 1995-2002, water (-0.509%) between 2014-2022 and built_up (+12.42%) between 1995 and 2002. Grasslands are the most vulnerable as they can easily be converted to Agriculture while most forest were degraded to shrubs. Built-up areas show a continuous trend especially since the County governments were established and more satellite urban centres established to serve as administrative zones and economic hubs for the increasing population. Agriculture is not only increasing but also getting intensified due to population increase and high growth rates (Figure 4). This poses a danger of diffusive pollution to water resources especially from sediments, insecticides, pesticides and fertilizers. Built_up areas due to urban sprawl and human settlements is on an increase and this means accelerated runoff is expected. Forests and grasslands reduction leaves many areas bare and susceptible to erosion and more runoff generation that could lead to flooding and soil fertility losses. Results echo the findings by Kogo et al., (2020) in upper Nzoia and Masayi et al., (2021) in Mt. Elgon ecosystem.

Table 4: Land cover proportion (km^2)

	Area proportion (km^2)					
LULC classes	**1973**	**1986**	**1995**	**2002**	**2014**	**2022**
Forest	144.0	123.7	118.9	100.1	96.7	85.7
Shrubs	58.8	13.1	1.3	0.3	0.3	7.8
Grasslands	560.3	502.4	253.2	175.9	130.2	101.8
Agriculture	62.1	186.1	451.8	548.2	595.7	624.0
Water	0.036	0.086	0.164	0.099	0.155	0.149
Urban				0.124	2.250	5.8

3.2. The extent of landscape fragmentation at the class level

3.2.1. Patch number and patch density

Landscape metrics analysis in this study area revealed that KRSB is characterized by increases in patch numbers (PN) and patch density for forests, grasslands and water for the period 1973-2002 and decrease for almost LULC classes apart from built_up areas between 2002 and 2022 (Figures 6). These occurrences ultimately led to attrition (complete disappearance of patches) in some areas and replacements in others, particularly forest lands, shrubs and grasslands. From 1973 to 2002, forests and grasslands show an increase in PN by +738 %, +4818.4 % respectively while water show a similar trend of +1267.7% between 1973 and 1995. Similarly, built_up areas show an increment of +3867% since its detection in 2002 and 2024. Overall, a decline in PN is observed between 2002 and 2014 apart from built_up areas. Especially, forests, grasslands and agriculture PN values decreased by -72.3%, -35.6%, -65.5 over the same period respectively. However, a new trend of further PN increases was observed between 2014 and 2022. Oertli et al., (2002) outlined that high number of patches of a habitat was directly proportional to the levels of fragmentation.

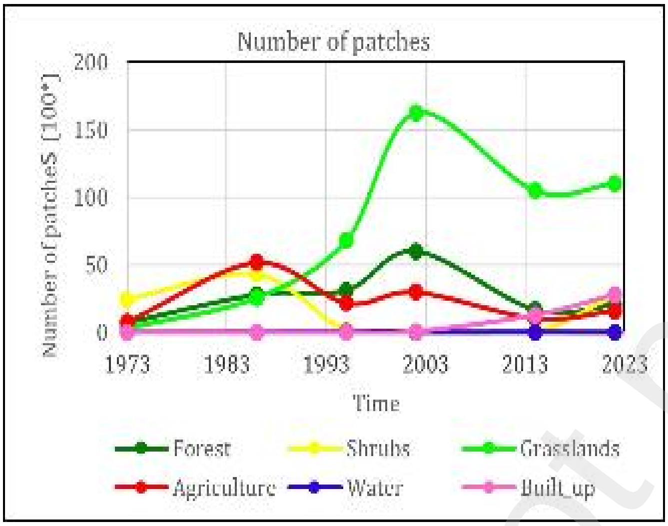

Figure 6: Number of patches

Despite there being some urbanization from 1973, this class could not be detected due to coarse spatial resolution of the Landsat sensors that existed by then and due to the mixed spectral signatures between rooftops (grass thatched and tiles) and the neighboring shrubs covers.

Proportionately, grassland was the most vulnerable and threatened habitat. The increment in its PN is comparatively higher compared to forests as most grassland patches areas were directly converted to farmlands unlike forests which at some instances were first converted into shrubs before being converted to farmlands or grasslands. This key finding is in agreement with result reported by (Masayi et al., 2021).

Even though agriculture show a low PN values, land has been heavily divided among family under the land tenure laws and it is only that the satellite sensors could not distinguish one parcel of land belonging to one family from the other due to spatial resolution limitation. Thus, the sensor considers most parcels as one large parcel.

Table 5: Patch density (PN/ha)

Year	Forest	Shrub	Grassland	Agric	Water	Built_up
1973	0.87	2.98	0.401	0.93	0.0036	0
1986	0.06	0.09	0.054	0.11	0.0006	0
1995	3.78	0.18	8.280	2.63	0.0497	0
2002	7.32	0.07	19.763	3.63	0.0109	0.0862
2014	2.02	0.08	12.736	1.25	0.0194	1.585
2022	2.46	3.40	13.390	1.94	0.0085	3.41

Considering the PN, grasslands constituted the highest net increment of 10720 patches for the entire study period but still it represented the highest patch density PD of 13 when compared with other land cover classes. The PD values increased when the PN was also increased.

3.2.2. Edge density

Edge density across all land covers was inconsistent (Figure 7). ED decreased in both forests, grasslands, shrubs, agriculture and water especially for the period 1973 to 1986 before increasing again from 1986 to peak in 2002.

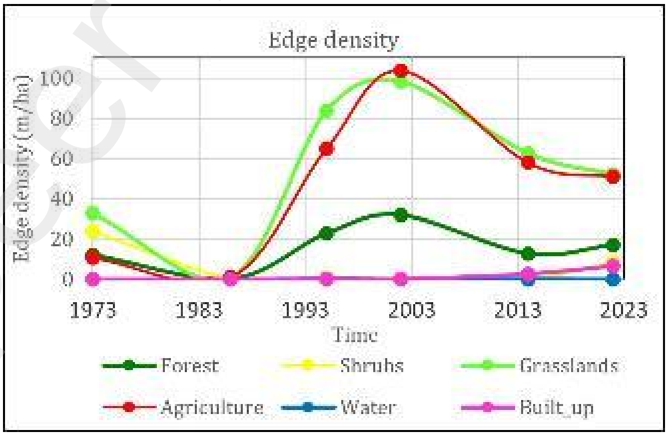

Figure 7: Edge density

Higher values of 98.2 and 103.8 were respectively observed for grasslands and agriculture in 2002. For the period 1986 to 2002, the value of ED increased by +10086% for agriculture, +7240 % % for grasslands, +1.63 % for shrubs +8668.8 % for forests and +9933.3% for water. A continuous decline of ED is observed between 2002 and 2022 for agriculture by - 51% and grasslands by - 46.08%. Forests however show a slight increase between 2014 and 2022 as more patches got fragmented. However, the built_up area show a continuous increase of +4372.2% for the same time period (2002-2022). An increase in ED values is even expected close to protected forests in Mt. Elgon as more settlements continue to build up close to these key protected biomes. Similarly, higher edges of grasslands over time show a similar trend as agriculture as more grasslands got converted to agriculture. As emphasized by McGarigal, (2012), variations of ED indicate a major change and reduction of spatial heterogeneity scale of the landscape. This was true in the grassland class. Likewise, the higher value of ED indicated by the forests shows no or little central tendency of the ecosystem as a result of some invasions and disturbances as outlined by (Daye & Healey, 2015).

3.2.3. Interspersion and Juxtaposition Index (IJI)

IJI varies inconsistently over time across all the LULC classes (Figure 8). The high variation is an indication of high, random and unpredictable level of landscape fragmentation. Built_up area class show an increasing IJI which shows its growth in terms of evenness and dispersion. Built_up area has increased IJI values of +1227% from 2002 to 2022. Agriculture also shows a continuous growth of IJI as more farmland patches get interconnected.

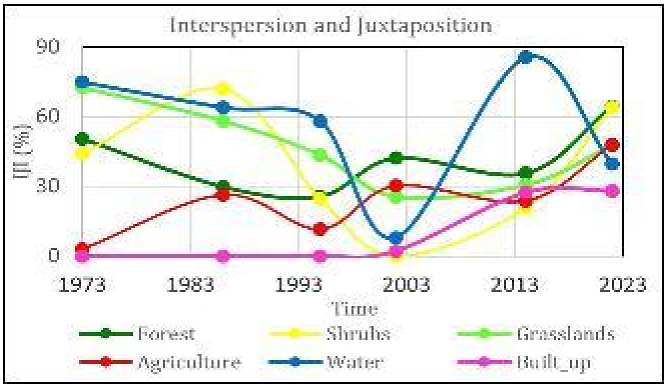

Figure 8: Interspersion and Juxtaposition

For example, IJI for agriculture increased by +1522 % for the study period 1973-2022 while IJI values for grasslands declined by - 34.3% over the same study period. However, forests, shrubs and water show an inconsistent pattern as most deforestation occur differently across the landscape and whereas some forests are first reduced to shrubs, some are directly converted to bare lands or agricultural lands. However, a decline in grasslands occurs at the expense of increasing evenness of agriculture as it is easily convertible.

3.2.4. Connectiveness and PAFRAC

Connectiveness measures total patches in a class and the Euclidean Nearest Neighbour (ENN) distance (Keeley et al., 2021). All classes show an increase in connectiveness between 1973 and 2002 and built_up areas from 2002 (Figure 9 and 10). Water and shrubs show connectiveness change of +13.88, +5.014 respectively for the period 1973 to2002 and urban for +0.966 for the period 1995-2002. The same classes show a decline between 2002 and 2022 possible as number of their patches and the ENN distances between them widened.

Low values of connectiveness of forests, agricultural lands and grasslands indicates that even though there was fragmentation, the ENN distances between patches of these classes are not much isolated compared to shrubs and water.

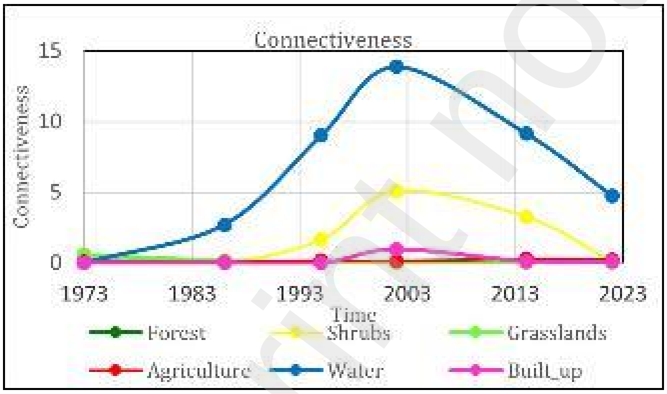

Figure 9: Connectiveness

PAFRAC values (Figure 13) show an increasing trend from 1973 to 1995 followed by an increase between 1995 and 2002. From 2002 to 2014,

PAFRAC values show a decline. Water shows an irregular trend because of how PAFRAC is calculated in FRAGSTAT tool. PAFRAC value changes when the patch sizes of different classes change with form. This means that the value won't change if the form remains constant. The value returns N/A particularly when patches of any specified class is less than 10. Values is 1 when shapes of patches are simpler and approaches 2 when shapes are highly irregular (McGarigal et al., 2015).

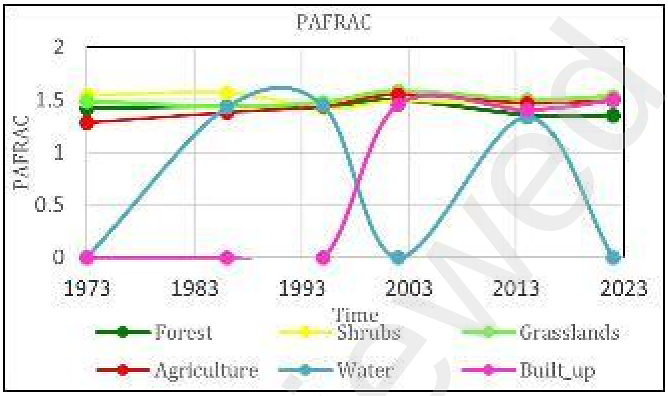

Figure 10: PAFRAC

As shown in Figure 10, all patches of different classes have changed in form an indication of continuous human disturbances that has led to attritions or replacements of some patches with patches of different classes.

3.2.5. Core area

McGarigal et al., (2015) defines core area as area of a land cover class further from a defined edge distance. In this study, 100 m was defined. Core area of agriculture, built_up area and water shows an increase over the study period while grasslands, forests and shrubs show a decline over the same period (Figure 11). For the entire period, the core area of grasslands, forest, shrubs show a decline of 81.83%, 40.4% and 86.73% respectively for the entire study period.

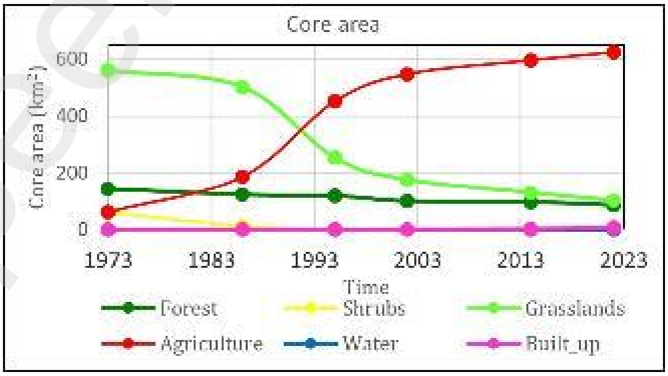

Figure 11: Core area

However, agriculture and urban growth show an increase by +9042% and +4567% for the period 1973-2022 and 2002-2022 respectively. A reduction of grasslands corresponds with an increasing cora area for agriculture. It is critical that forests and grasslands which serve the function of promoting infiltration in watersheds is on a continuous decline.

3.3. The extent of landscape fragmentation at the patch level

3.3.1. Maximum patch area

The maximum patch area (Figure 12) depicts a growing patch of a land cover in a landscape. The general trend for the study period 1973-2022 shows an increasing trend for agriculture, built_up areas and water and a decreasing maximum patch area for grasslands and shrubs. Agriculture has expanded by 605.26 km^2 (9634.86%) for the period 1973-2022 and built_up area by 0.0963 km^2 (535%) for the period 2002-2022 while water increased by 0.0738 km^2 (256%) with the highest being experienced between 1995 and 2002 by 0.0513 km^2 (196.6%). Forests have reduced by 42.91 km^2 (60.86%) for the period 1973-2022 while shrubs reduced by 2.57 km^2 (98.1%) for the period 1973 to 2014 before it increased slightly between 2014 and 2022 by 0.121 km^2 (243%) between 2014 and 2022.

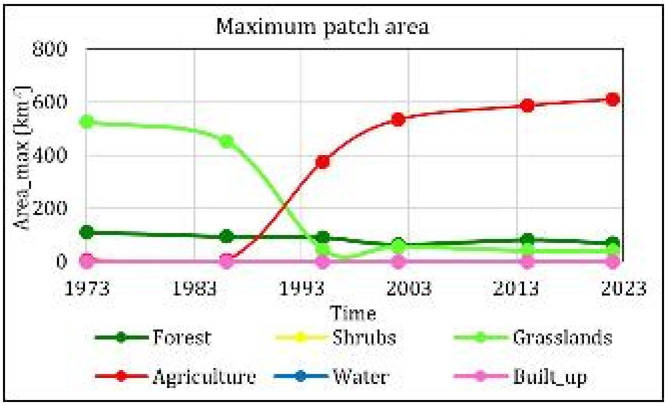

Figure 12: Maximum patch area

The agriculture patch is larger as more divided lands under cultivation by different farmers become indistinguishable by satellites due to the limited 30 m spatial resolution. Water shows a variation due to the seasonal changes and the extent to which the existing wetlands were exposed y continuous encroachment human activities. Results of an expansive large patch area coincides with the findings by Murunga, (2021) in Mara basin.

3.3.2. Maximum patch ENN

The ENN (Figure 13) depicts the distance between patches of same LULC class. The higher the distance, the higher the separation. For KRSB, patch for all LULC classes show a non-uniform separation distance.

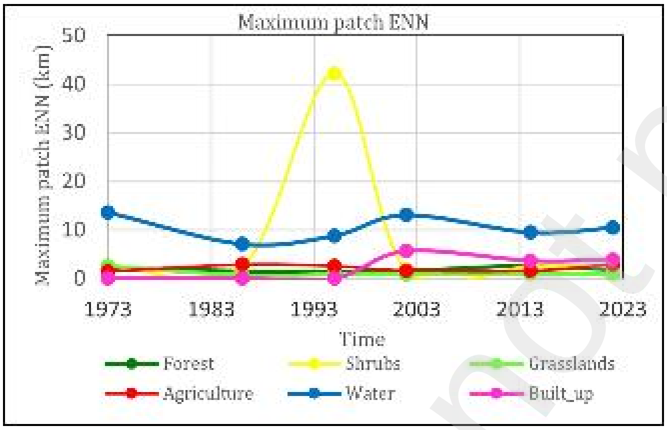

Figure 13: Maximum patch ENN

For example, shrubs had the highest separation observed for the period 1996-1995 (39.8 km). This is the period when most shrubs were fragmented and separated. Water is characterized with a huge variation with major ENN variation between 1973 and1986 (-6.464 km) and a general decline of 4.11 km for the study period 1973-2022. Agriculture patches show an almost constant value as the farms owned by different agencies and residents are interconnected. Similarly, max forest patches was high in 1973 (2.13km) and 2.6 km in 2014. The maximum forest patch ENN in 2014 indicates the element of forest decline and elimination of some of the existing patches. The built_up area maximum patch ENN was in 2002 when it was first detected (5.66km) and 3.86 km in 2022. This reduction is associated with the decreasing distance triggered by the continuous extension of built_up areas due to urban sprawl and human settlements.

3.3.3. Maximum patch FRAC

FRAC explains the patch complexity of different land covers over time and relates perimeter of a patch to a patch area. This indicates that change in size of a patch without changing the form of a patch does not change the index and the value varies between 1 and 2. For KRSB (Figure 14), it was observed that all land cover changed the form a sign that all land covers are fragmented.

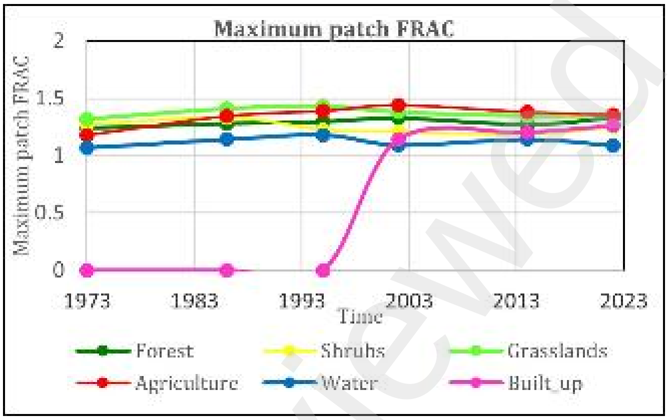

Figure 14: Maximum patch FRAC

Grasslands show the highest FRAC between 1973 and 1995 (-0.1113) overtaken by agriculture between 2002 and 2022 (0.0831). This interchange coincides with the LULC change where most of the grasslands were converted to agriculture because of its vulnerability and easy of conversion. Forests show a moderate change in FRAC and change in form due to the remaining forest large patch in the protected area and is characterized with an increase of FRAC of 0.0909 (+7.3%) between 1973 and 2002 followed by a decrease between 2002 and 2014 (-4.3%) before it increased again between 2014 and 2022 by +4.85%. water show the lowest FRAC as its area coverage is the lowest in KRSB and its low susceptibility to change in form. McGarigal et al., (2015) indicates that high FRAC values indicate high fragmentation levels in terms of form and size and this leaves the KRSB vulnerable to environmental issues that could affect the watershed health and ecosystem functioning.

3.3.4. Maximum patch contagion

Overall, maximum contagion in KRSB (Figure 15) varies across all LULC classes with the forest being the highest between 1973 and 1995 and built_up area being the lowest since its detection between 2002 and 2022.

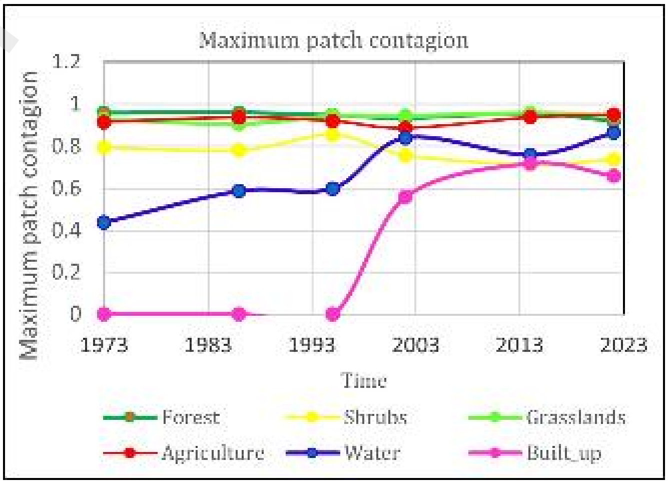

Figure 15: Maximum patch contagion

Low contagion values indicate high dispersion and this is observed for water whose detection is spatially distributed across the watershed. The built_up area are also spatially distributed in the watershed and thus low contagion values even though this rose between 2002 and 2014 by +28.4 %. This is reflected by Mcgarigal, (2015) who highlights that high contagion indicates low dispersion because patches are close to each other. Even though the value for grass seems high it only indicates that the remaining patches are adjacent to each other and confined in key areas such as the riparian corridors.

3.4. The extent of landscape fragmentation at the landscape level

3.4.1. Edge density

As shown in Figure 16, Edge density for KRSB shows a general decrease between 1973 and 1986, a rise for the period 1986-2002 and a decline between 2002 and 2022.

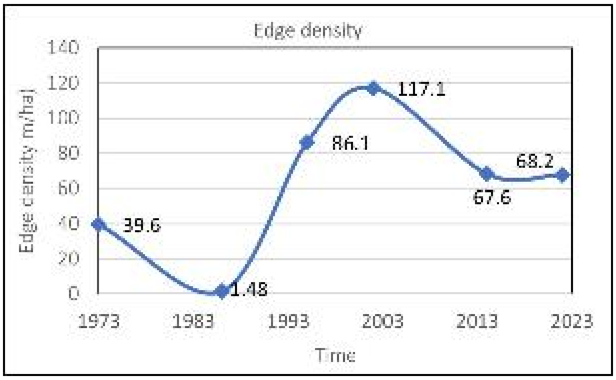

Figure 16: Edge density

The ED of KRSB landscape show a decreasing trend from 1973 to 1986 and rose between 1986 and 2002 by +115.63 when more forests, shrubs and grasslands reduced at the expense of increasing agricultural land and built_up area. This signifies the period when more edges were generated due to a surge in human settlements and encroachment of the protected areas.

A decrease between 2002 and 2014 (-49.49) as remaining patches were eliminated or totally replaced by farmlands and built_up area. According to Mcgarigal, (2015), edge density refers to the number of total edges in relation to the total landscape area and the higher the number of edges, the higher the level of landscape structural fragmentation.

3.4.2. Contagion

Contagion (Figure 17) is a key metric applied to measure dispersion and includes interspersion between patches. The general trend shows a continuous increasing contagion for the period 1973-2022 (+10.30) which shows a continuous dispersion of patches especially for forests, shrubs, grasslands and water, a scenario which indicates an integrated ecosystem fabric of the landscape has been fragmenting leaving the watershed vulnerable to erosion and flooding due to accelerated runoff caused by increases of loose, bare and paved surfaces.

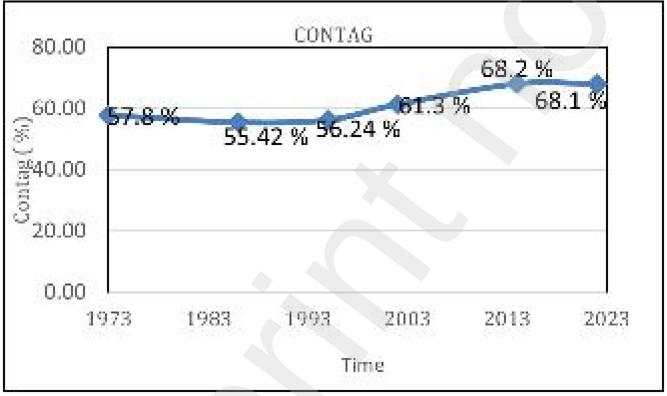

Figure 17: Contagion

3.4.3. Connectiveness

Connectivity in KRSB has been reducing over time from 1973 to 2014 (-0.0454) and a slight increase between 2014 and 2022 (+0.0496). The increase (Figure 18) is associated with reforestation efforts by individual farmers but as observed from the field, reforested patches serve short term functionalities as they are harvested for commercial purposes. Further the increase of built_up areas trail has a significant effect on the increases on connectiveness of patches of different land classes even though the general trend is a decrease leading to ecoscapes which minimizes biological diversities, structural functionalities necessary to improve hydrological performances of the watersheds.

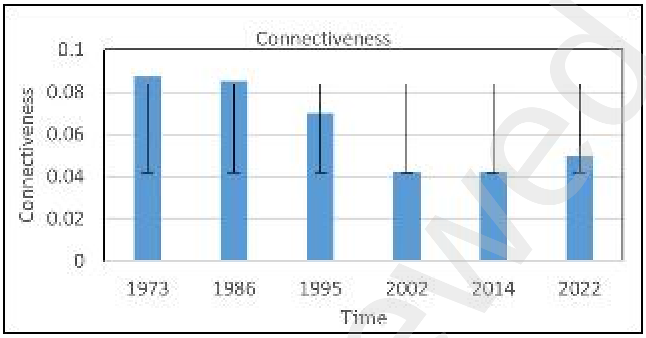

Figure 18: Connectiveness

According to Keeley et al., (2021) and McGarigal et al., (2015), any changes in connectiveness leads to a reduction in landscape structural functioning, habitat loss and biodiversity loss necessary to promote climate change resilience of not only wildlife, vulnerable plant species but also ecosystem functioning of the landscape within the natural limits.

3.4.4. Interspersion and Juxtaposition Index (IJI)

IJI for KRSB (Figure IJI) show a decrease between 1973 and 2014 by -27.2 % and an increase of +23.4% between 2014 and 2022. The decrease shows closeness of fragmented patches of different land cover classes while the between 2014 and 2022 exhibit an increase in dispersion of different land covers (Figure 19).

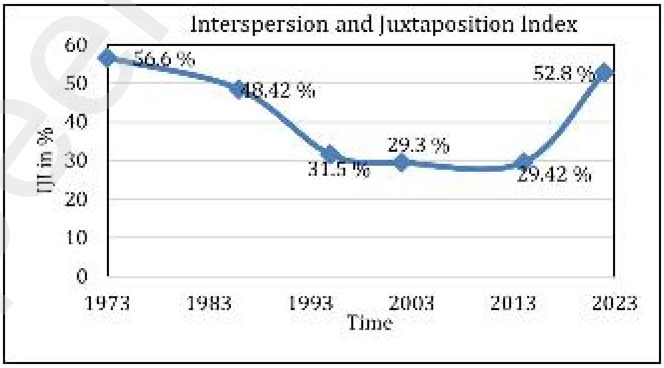

Figure 19: Interspersion and Juxtaposition Index

This is due to emergence of built_up areas and extended agricultural lands which has dispersed other classes even more. Muhammed & Elias, (2021) found similar results where they indicated that an increase in IJI vales indicates a high magnitude fragmentation and hence the landscape experienced the worst interspersion between 2014 and 2022 a trend which needs to be considered for urban planning and human settlements.

3.4.5. Shannon Diversity Index and Shannon Evenness Index

Both SHDI and SHEI show a general declining trend over the study period. The rates stand at -17.42% and -25.8% and respectively and this indicates a continuous habitat loss and replacement of total elimination of patches of different classes in the landscape (Figures 20).

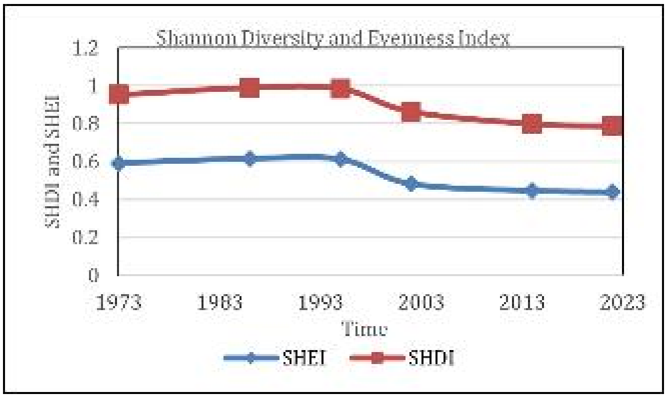

Figure 20: Shannon diversity and evenness index

The decrease in SHDI shows a decrease in the intermixing of patches of different classes in the entire KRSB landscape which corresponds with a decrease in evenness of species of different classes. This is an indication of high fragmentation in terms of richness of land cover species and adjacencies. A decrease of both SHDI and SHE signifies a degraded landscape whose ecosystem functionality is compromised. This leaves most areas vulnerable to unprecedented environmental changes such as increased runoff, soil losses and compromised biomes. Relationship between SHDI and SHEI and flood peaks have been applied by Liu et al., (2022) and has found that there was a positive correlation even though this needs to be established in different landscapes.

3.4.6. Spatial distribution of SHDI and SHEI

Spatial SHDI and SHEI derived from spatial maps indicated that these values vary across the landscape in both time and space (Table 6). Low SHDI and SHEI were found to be in areas with only a few or one species and high values were confined close to the riparian corridors or built _areas characterized with some forests and tree plantations.

Table 6: Spatial distribution of SHDI and SHEI

YEAR	SHDI		SHEI	
	Min	Max	Min	Max
1973	0.500	1.332	0.722	0.971
1986	0.300	1.472	0.278	0.999
1995	0.300	1.30	0.596	0.999
2002	0.298	1.355	0.272	0.677-1
2014	0.251	1.461	0.497	0.999
2022	0.251	1.571	0.393	0.999

The findings coincide with those by Redowan (2015) who found that SHDI values were above 1 and that low and high values for each should be indicated to inform temporal variation of landscape fragmentation.

3.5. Driving forces of landscape fragmentation

Landscape change in KRSB is driven by several factors. Based on the feedback received from 32 survey questionnaires, and oral interviews, hotspot areas vulnerable to landscape degradation were first analyzed followed by nature of prevalent LULC conversion and the main drivers of landscape fragmentation. Results are discussed in section 3.5.1 and 3.5.2.

3.5.1. Identified hotspot areas vulnerable to landscape fragmentation

Vulnerable areas of the watershed and nature of land cover conversion, were assessed using survey questionnaires and oral interviews. Results are as presented in Figures 21 and 22 respectively.

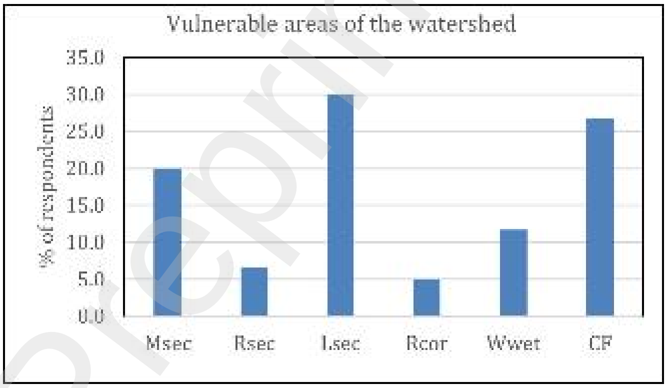

Figure 21: Vulnerable areas of the watershed

M_{sec} = Middle section (Endebess, Kaisagat & Zea areas), R_{sec} = Recharge sections (Mt. Elgon), L_{sec} = Low recharge areas (Kitale town, sibanga, Kibomet), R_{cor} = Riparian corridors, W_{wet} = Wetlands and C_F = Commercial farms.

From responses, it is observed that all sections are vulnerable even though lower sections were highlighted as being vulnerable. This is due to frequent flooding and high sediment load that has become a common menace in the downstream areas. Further, most of the wetlands have been encroached or totally depleted.

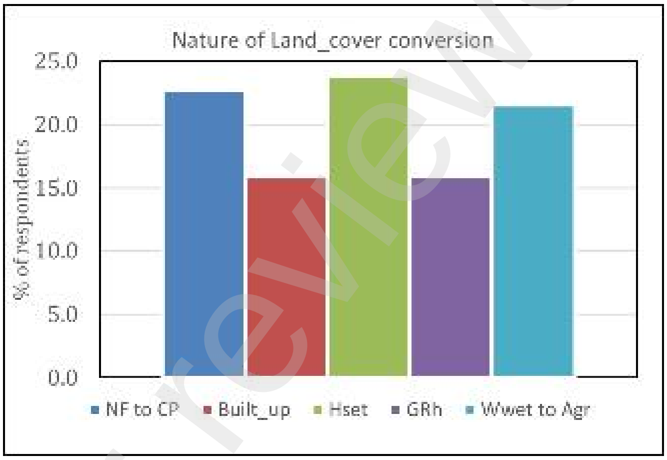

Figure 22: Nature of land_cover conversion

NF = Native forests, CP = Croplands, H_{set} = Human settlements, G_{Rh} = Greenhouses and W_{wet} = Wetlands

The watershed is dominated by conversion of various classes such as shrubs, grasslands and forests to human settlements, conversion of wetlands to agricultural land (maize and sugarcane) and to built_up areas (mostly urban settlements and infrastructure). A new trend was also observed from the feedback where the number of greenhouses is increasing and this may trigger direct transformation of rainfall to runoff.

3.5.2. Driving forces of landscape fragmentation in KRSB

Choosing unsustainable economic model by farmers was identified as one of the driving forces and it was established that farmers over cultivated farmlands with perceptions of making maximum economic gains. This was true among farmers in the lower, middle and upper parts of the watershed. This practice has left soils loose and more vulnerable to erosion which leaves most lands unable to support vegetative regeneration.

Ineffective land-use management laws were also highlighted. Even though laws exist to protect the riparian corridors, it was established that most river sections along Koitobos river including its distributaries were encroached with little or no forest patches remaining. Most riparian zones are replaced with farmlands.

Oral interviews revealed that there is a reputation of farmers bribing people who disguise as officers to clear edges of forests and expand or create farmlands was a major issue. This was established majorly along the protected forest boundaries encompassing Mt. Elgon National Park. To some extent, some small size farms were concealed as patches within the main forest ecosystem. Major crops cultivated in encroached areas included Irish potatoes, sorghum, maize and millet.

Politics and power on a 5-year cycle was also highlighted as a major driver. Data from survey and oral interviews revealed that politics and power were some of the key drivers of landscape fragmentation in KRSB. Every five years during campaigns, politicians promise communities close to forests of flexibility of farming once they resume offices. To a great extent these promises gave an avenue to periodic encroachment to forest ecosystems. Moreover, this has fueled a debate as to where the forest borders exist.

Further, it was noted from the feedback that there is rapid population growth in the watershed with development of new satellite urban centers. This has been triggered by devolution which has led to creation of sub_county headquarters such as Endebess, Kwanza sub_county headquarters and Kitale, the County headquarters. Population surge has led to more demand for food which in turn had triggered intensive agricultural practices and competition for space along the riparian corridors during the dry months. The case is the same in rural areas where population has also surged.

Increased demand for wood product triggered by rapid urbanization has also led to more logging especially in few remaining forest patches including illegal logging in the protected Mt. Elgon ecosystem.

Secret risks were also uniquely identified as a major driving force. One of the forests near Kitale town (famously referred to as Mt. Elgon academy forest) has been cleared due to security risks. Oral interviews with County officials revealed that the forest has been a crime scene where murder has been occurring including dumping of human bodies. Due to this reason, the forest has to an extent been cleared to curb insecurity and during field work, it was established that most areas have been converted to farmlands. Crops currently being grown include beans, vegetables and Irish potatoes.

Human-wildlife conflict especially near formerly wetlands was a key direct driver of landscape change. Wetlands such as Sikubu dam, Chemususu and Kitalale wetlands were encroached and cleared by citizens as a result of repeated attacks from wildlife to their livestock. Wildlife attacks mentioned by interviewees included resulted mostly from pythons. However, these cases are nowadays low as most wetlands have been completely destroyed.

3.5.3. Implication for landscape conservation and restoration

Over the last 49 years, rates of landscape fragmentation in KRSB have been augmented. Forests, grasslands and shrubs show high fragmentation rates based on high increment of PN, ED, FRAC and a decline in SHDI, SHEI, and IJI and this threat will possibly lead to habitat loss, and changes in hydrological processes as habitat fragmentation is a precondition of habitat loss and ecosystem dysfunction. According to Haddad et al., (2015) and Fischer & Lindenmayer, (2006), habitat fragmentation, ecosystem dysfunction and habitat loss go hand in hand and outcomes leads to a compromised landscape whose processes are beyond the normal range.

These shifts indicate a deteriorating landscape matrix characterized with decreasing connectivity and richness of habitats especially as farmland and built-up areas expands. Likewise, analysis showed a decreasing AREA_MN and COA which signifies that core dependent ecospecies are likely to experience extinction or more survival pressure unless some sustainable watershed conservation measures are put in place.

Fragmented forest patches the watershed are natural ecosystems that provide inhabiting communities with timber, food, medicinal products, fuel and wild fruits.

Role of communities proximal to the protected Mt. Elgon National Park is critical in protecting forests and vulnerable ecosystems in the park. This part of the watershed is fundamentally important in providing ecosystem services such as climate regulation, nourishment of the flow regime of Koitobos river, air and purification, soil fertility loss control and soil erosion control.

It is also critical that increases in built-up areas will lead to demand for more wood products and food supplies. This will put pressure on farmers to intensify agricultural activities which may also mean total access to the already degraded riparian zones. To curb this, government institutions should do follow-up to ensure riparian zones are regenerated, conserved and protected. This should go hand in hand will civic education to residents in KRSB with emphasis on the importance of citizen participation in watershed management.

Further, it is important to clearly demarcate where Mt. Elgon National Park boundaries start or end in order to avoid cases of free-range encroachments. In addition, overlapping of roles and responsibilities as to who is in charge of protecting vital ecosystems should be reevaluated including reevaluation of institutional fragmentation. Of great importance is also rehabilitation of degraded wetlands which have been cited as great sources of ecosystem services by interviewees. Lastly, despite there being some efforts of reforestation by individuals, it is empirical that planted forest patches on individual farms only last for some time before they are harvested for timber. An option would be to promote a payment for ecosystem services, an idea which was deemed feasible during the interviews.

4. Conclusion

The LULC change, landscape structural and pattern analyses were combined to measure the extent to which the study area has fragmented. Evidence derived from the study revealed the change in the spatial landscape transformations and structure of land covers for four decades from 1973 to 2022. The landscape structure of KRSB was analytically and spatial characterized as highly fragmented as it is signified by high value changes between 1973 and 2022 for PN (4284-20312), Connectiveness (0.0875-0.0496), and SHDI (0.9509-0.7852). It was observed in this study that both the class, patch and landscape level fragmentation has increased over time and thus an urgent ecological restoration, integrated watershed management restoration and conservation effort is required to minimize its potential impacts on hydrological health of the watershed such as increased sediment loads, short circuited or prolonged hydrological processes, uncertainties of runoff regime and the wildlife population. This is due to the unprecedented adverse impacts of human settlement and urbanization which has resulted to landscape structure changes. Even though forest plantations were observed, they were deemed not feasible as they are harvested for commercial use before they offer any viable ecological services. The high and increasing levels of resource exploitation in KRSB are projected to lead to increased runoffs, sediment loads, shifts in weather patterns and threaten many of nature-based ecosystem services. Thus, sustainable and comprehensive environmental restoration and management approaches should be accurately developed and executed to improve agricultural productivity and watershed performance within the natural limits. Moreover, traditional beliefs and indigenous knowledge must be recognized to protect and conserve natural resources in KRSB. Alternatively, policies focus on sustainable land-use practices and natural resource management must be well articulated and enforced to reflect an agri-business model that seeks to achieve socio-economic and ecological well-being in the study area. Outputs of this study forms a good base for watershed managements, policy makers with geospatial knowledge and extended knowledge of interlinkages between LULC changes and landscape structure interrelations necessary for a health watershed. Future research should focus on assessing the impacts of landscape structure changes on ecosystem services and to formulate a spatial framework of landscape restoration.

Declarations

Author contribution statement

Kennedy Wekesa Murunga: Conceptualization, methodology, data curation, analysis, writing of the original and final draft, review and editing. **Maurice Nyadawa, Sang Joseph and Charles Cheruiyot:** Conceptualizing the research, project administration, supervision, review and editing.

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Data availability statement

Data included in the article

Declaration of interests statement

Authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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