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Thirty-three years of land cover change analysis on Idjwi Island (DRC) using remote sensing and landscape metrics

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ABSTRACT
Idjwi Island, in Lake Kivu, DRC, faces increased vulnerability to human activities due to its isolation. A 33-year study (1990–2023) analysed land cover changes using remote sensing, landscape metrics, and the Random Forest algorithm. Landsat images were georeferenced, corrected, and classified to assess these changes. Results showed dramatic deforestation, with forest cover dropping from 57.16 km^2 (20.61%) in 1990 to 3.25 km^2 (1.17%) in 2023, with rates of change between −27.59% and −63.98%. As forests shrank, patch distances increased from 91.73 m to 172.54 m, indicating fragmentation. Savanna and agricultural areas expanded, peaking at 153.75 km^2 in 2015 before decreasing to 131.78 km^2 in 2023. The landscape disturbance index rose 21-fold, from 84.02 to 3.85. These shifts, driven by agriculture and urbanisation, underline the need for sustainable management, such as reforestation and balanced land use policies, to prevent further environmental degradation.

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Land cover mapping; landscape ecology; anthropization; remote sensing/GIS; biodiversity; sustainable management; Idjwi Island

Introduction

Forest ecosystems are crucial for environmental health, providing essential services such as climate regulation, biodiversity conservation, and supporting local livelihoods (Ahmad et al., 2023). They act as carbon sinks, reducing greenhouse gas emissions, and offer habitats for many species, including those that are endemic and threatened (Chirwa et al., 2020; FAO, 2020; Haseeb et al., 2024). Sustainable forest management is essential not only for maintaining ecological functions but also for ensuring the survival of species and crops reliant on them (Keenan et al., 2015). In isolated areas like islands, forest management becomes even more critical due to their vulnerability to deforestation, invasive species, and climate change (Fernandes et al., 2015; Fernández-Palacios et al., 2021).

Effective forest management involves protecting endemic species, restoring habitats, and integrating local knowledge into conservation efforts (Barlow et al., 2018). These actions are

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vital to maintaining the resilience of island ecosystems while enhancing the livelihoods of local communities (Fernandes et al., 2015). Africa's forests, especially in the Congo Basin, are vital to global conservation efforts. The Democratic Republic of the Congo (DRC) holds over 60% of this area, approximately 152 million hectares (Eba'a Atyi et al., 2021; Vancutsem et al., 2020). However, African forests face significant challenges from deforestation and degradation, driven by shifting agriculture, logging, and infrastructure development (Kadoya et al., 2022; Tyukavina et al., 2018). These pressures lead to biodiversity loss, reduced carbon storage, and heightened climate change impacts (Curtis et al., 2018).

In the Great Lakes region, especially in the Democratic Republic of the Congo (DRC), rapid population growth intensifies pressure on forest ecosystems. This leads to agricultural expansion, deforestation for firewood, and land conversion for housing (Khoji et al., 2022; Mpanda et al., 2022; Potapov et al., 2012; Useni et al., 2017). On islands, these pressures contribute to forest degradation, threatening endemic species and reducing biodiversity (Bridgewater & Kim, 2021; Whittaker et al., 2023). While political instability in the region and global crises such as COVID-19 have influenced land-use changes, this study focuses primarily on their direct impact on landscape transformations.

Idjwi Island, located in Lake Kivu, is an ideal case study for understanding land-use changes in isolated environments. The island's geographical isolation, coupled with increasing human pressures, makes it particularly vulnerable to landscape transformation. This study focuses specifically on Idjwi Island to understand how socio-ecological dynamics influence land-use change over time. Due to its isolation and fragile ecosystems, Idjwi offers a unique opportunity to examine how human activities have shaped the environment. The period from 1990 to 2023 is particularly significant for examining demographic shifts, land management practices, and socio-economic crises such as conflict and the COVID-19 pandemic, all of which contribute to current and future land-use trends (Lousada et al., 2022).

Although African islands are often overlooked in studies of land-use change, they are undergoing significant transformations driven by population growth, tourism, and economic pressures (Crossland & Kremer, 2005; Rêgo et al., 2018). These processes, including deforestation, lead to irreversible biodiversity loss and disrupt ecosystem services such as water regulation (Fernández-Palacios et al., 2021). Despite their ecological significance, research on land-use change on African islands remains limited, particularly in terms of long-term monitoring. This study addresses this gap by providing a comprehensive analysis of land-use transformations on Idjwi Island over three decades, a period marked by significant socio-economic and environmental changes.

Remote sensing offers an effective tool for monitoring land-use change, particularly in island settings where fieldwork is constrained by accessibility (Cohen & Goward, 2004; Lin et al., 2024). Satellite imagery allows large-scale, continuous monitoring of land-use changes and can be used to map degraded areas and evaluate environmental impacts. When combined with landscape metrics, remote sensing provides valuable insights into landscape structure and changes over time (Bogaert et al., 2004; Bogaert & André, 2013; Bogaert & Mahamane, 2005; Lemenkova, 2024). Given the geographical constraints of Idjwi Island, these methods are particularly well-suited to studying land-use changes and ecosystem dynamics in this isolated region.

This study aims to address the following questions:

1. What are the main changes in land use observed on Idjwi Island between 1990 and 2023?
2. How have deforestation and landscape fragmentation evolved over this period?
3. What are the key factors influencing these changes?

We hypothesise that Idjwi Island has experienced significant land-use changes between 1990 and 2023, driven primarily by agricultural expansion, deforestation, and socio-economic pressures.

These changes are expected to increase forest fragmentation and alter natural habitats. The resulting fragmentation could reduce the landscape's resilience to climate change, disrupt biodiversity, and increase vulnerability to invasive species and diseases. This study aims to fill the knowledge gap regarding land-use change on African islands, a topic that has been under-researched. By focusing on Idjwi Island, we aim to advance scientific understanding of how human-driven land-use changes impact isolated ecosystems, especially in the context of ecological fragmentation and long-term environmental sustainability. This research will provide insights into the challenges and opportunities for effective conservation strategies in isolated island ecosystems, contributing to the broader discourse on landscape ecology and ecosystem management.

Materials and methods

Study area

Idjwi Island, located in Lake Kivu in the DRC at 1°56′ to 2°8′ S latitude and 28°56′ to 29°5′ E longitude, is the second-largest lake island in Africa, covering 280 km^2 (Dusabe et al., 2024; Jimenez-Redal et al., 2021) (Figure 1). It falls within South Kivu province and became an autonomous territory in 1974. Accessible only by boat, Idjwi is positioned between Goma and Bukavu, near Rwanda (Thomson et al., 2012). The island is divided into two chiefdoms: Rubenga in the north and Ntambuka in the south (Hoffmann et al., 2022). Idjwi has a mountainous landscape, with elevations reaching 2300 m at Mount Nyamusisi, and varying temperatures from 20 °C near Lake Kivu to 15 °C at higher altitudes (Ngabo, 2020). The island's soils vary, with sandy terrain in the north and clayey soils in the south, supporting agriculture. It is known for producing

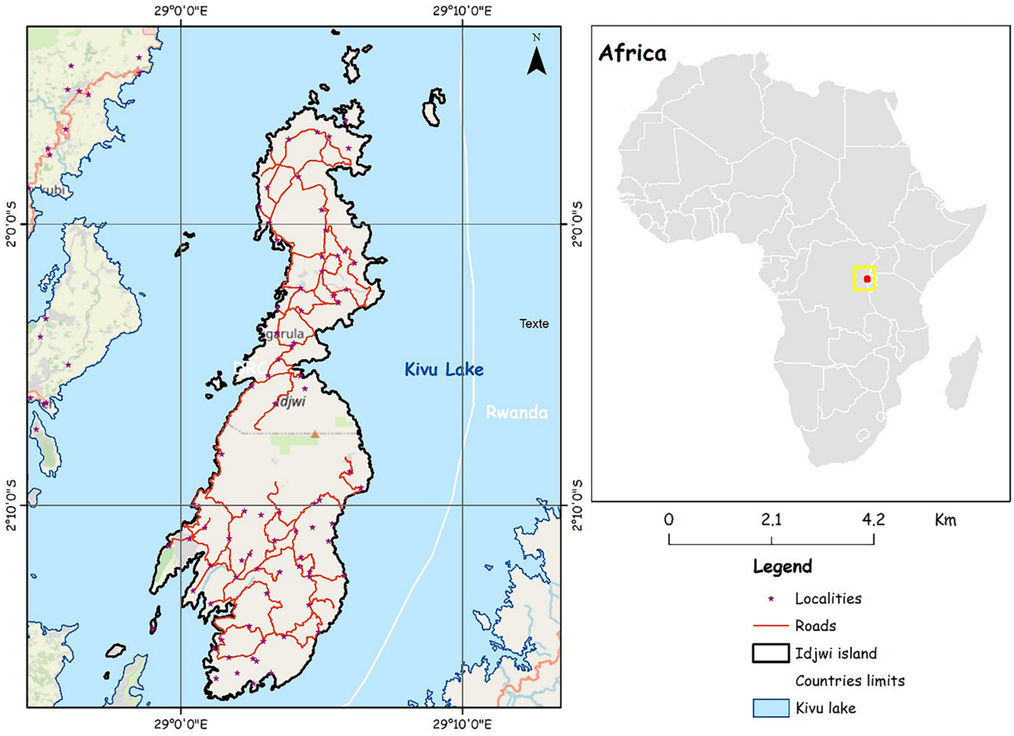

Figure 1. Map of the geographical situation of Idjwi Island in the east of the DRC, produced using GIS software (ArcGIS version 10.8.1).

large, sweet pineapples, along with crops like maize, cassava, and beans (Iragi Mukotanyi, 2022). Fishing is another important economic activity (Nyakabeji et al., 2023). The population, estimated at 245 267 in 2013, primarily consists of Bahavus, with Pygmy and Rwandan minorities. Idjwi has faced a fragile political situation, recovering from conflicts that began in the 1990s (World Bank, 2015a). Over 80% of its residents work in the informal sector, relying on agriculture, fishing, and farming (UNDP, 2019). Despite threats from human expansion, Idjwi's vegetation, including secondary forests, savannas, and shrublands, remains a critical part of its natural heritage (Macumu et al., 2015).

Data

The DRC, including Idjwi Island, lacks systematic land cover records, with no official statistics or detailed historical data available. Existing planning documents and maps often miss essential quantitative information. To address this knowledge gap, we used Landsat imagery from 1990, 2000, 2008, 2015, and 2023 to analyse land cover dynamics on Idjwi Island. These years were selected to capture significant changes, such as those before and after development initiatives, periods of socio-political instability, and major land use shifts. The imagery selection prioritised high quality and minimal cloud cover, focusing on images acquired during the dry season to avoid high cloudiness commonly found in the rainy season (Useni, Mpanda, Malaisse, et al., 2023; Cabala et al., 2022). This approach ensures a comprehensive overview of land cover changes, aiding the analysis of long-term dynamics impacting Idjwi Island (Khoji et al., 2023; 2024).

Landsat image classification

In this study, Landsat satellite images from 1990, 2000, 2008, 2015, and 2023 were pre-processed to ensure high quality for land cover analysis. Preprocessing steps included atmospheric correction and radiometric calibration using the Sensor-Invariant Atmospheric Correction (SIAC) module on Google Earth Engine (GEE) (Gorelick et al., 2017; Zhu & Woodcock, 2012). False-color composites, integrating near-infrared, red, and green bands, enhanced vegetation visibility and tracked land cover changes over time (Wulder et al., 2016). The land cover classification encompassed forests, savannas, agriculture, Built-up Areas & Bare Soil, and water bodies (Table 1), based on 300 regions of interest (ROIs) established in November 2023 to ensure consistency. Each ROI represented specific land cover types, reducing errors in transitional zones (Useni, Mpanda, Malaisse, et al., 2023; Useni, Mpanda, Khoji, et al., 2023).

The Random Forest (RF) algorithm was chosen for land cover classification due to its robustness in handling high-dimensional data and suitability for remote sensing. It is an ensemble method based on decision trees, with key parameters including the number of trees (50), maximum tree depth, and minimum samples per leaf (1) to ensure fine-grained distinctions and avoid overfitting (Breiman, 2001). A bagging fraction of 0.5 was used to enhance generalisation. RF performs well with large, complex datasets, handling noisy or missing values

Table 1. Land cover categories and their descriptions.

Land cover category	Description
Forests	Miombo woodland includes patches of dry, dense forest and gallery forest. It is characterised by a sparse herbaceous layer beneath forest stands that reach heights of 10–20 m. In these areas, tree cover predominates, with a minimum patch size ranging from 0.05 to 1.0 hectares.
Savannas	Characterised by low tree density and predominance of herbaceous cover.
Agriculture	Includes harvested, abandoned, or areas occupied by annual and off-season crops.
Built-up Areas and Bare Soil	Includes bare lands and residential areas with minimal vegetation.
Water bodies	Refer to natural or artificial accumulations of water, including rivers, reservoirs, and wetlands.

effectively, and outperforms other methods like SVM and k-NN in terms of accuracy and robustness (Pal, 2013). An error matrix was constructed in QGIS by comparing the classified data with 300 regions of interest (ROIs), and key classification accuracy metrics (OA, PA, UA) were calculated (Olofsson et al., 2014). PA measures the classifier's detection of land cover types, and UA assesses the reliability of classifications. These metrics were compared with regional studies (Useni, Mpanda, Malaisse, et al., 2023; Useni, Mpanda, Khoji, et al., 2023). The Cochran method (Cochran, 1977) was used to determine sample sizes, with 1200 points distributed proportionally across land cover classes.

Landscape dynamics assessment

To assess the impact of human activities on landscape dynamics on Idjwi Island, this study utilised a range of landscape metrics developed by McGarigal, Amherst, MA (USA). These metrics include class area (CA), patch number (PN), largest patch index (LPI), edge density (ED), fractal dimension (FD), and nearest neighbour distance (NND). These metrics were applied to various land cover types, such as forest, savanna, agriculture, and built-up/bare soil, to provide valuable insights into landscape fragmentation and structural changes over time (Table 2). They are crucial for understanding the spatial dynamics of the landscape and the effects of human activities on fragmentation, connectivity, and habitat quality. The selected metrics were chosen for their established ability to reflect changes in landscape structure and their relevance to the ecological and socio-economic context of Idjwi Island. Additionally, the disturbance index (U) was calculated at the landscape level by determining the ratio of the cumulative area occupied by anthropogenic land cover types to the cumulative area of forest on the island (O'Neill et al., 1988). While this index offers valuable insights into human-induced pressures on the landscape, it has certain limitations. It may not capture all forms of disturbance, such as subtle land use changes that do not result in visible land cover alterations. Furthermore, some land use types, like small-scale agroforestry, may not be fully recognised as anthropogenic, despite their potential contribution to fragmentation and ecological shifts.

Spatial transformation processes affecting land cover were identified using a decision tree algorithm (Bogaert et al., 2004). This method analyzes changes in patch number, class area, and perimeter over time (Figure 2). Attrition occurs when both patch number and area decrease, indicating land cover loss. Aggregation happens when the area increases without changes in patch number, suggesting smaller patches merged. Enlargement is when patch number stays constant but area increases, reflecting patch expansion. Creation occurs when both patch number and area increase, indicating new land cover types. Dissection happens with decreased area, increased patch number, and minimal loss, indicating fragmentation into smaller patches. Fragmentation involves an increase in patch number and significant area loss. A ratio above 0.75 indicates dissection, while a ratio below or equal to 0.75 indicates fragmentation (de Haulleville et al., 2018). Changes in perimeter help distinguish perforation (area decrease, perimeter increase), patch shrinkage (both decrease), shift (constant patch number/area, perimeter change), and deformation (perimeter change, no changes in number/area). These transformations clarify land cover evolution and landscape dynamics.

Results

Classification validation and mapping

The overall accuracy (OA) of the supervised classifications of Landsat images using the Random Forest classifier was consistently above 90% for all analysed periods, demonstrating a high level of reliability in distinguishing between land use categories (Table 3). Both the user's accuracy (UA)

Table 2. Landscape metrics and their ecological significance.

Index	Definition	Formula	Range of variation	Ecological Significance
Class Area (CA)	Quantifies the total extent of each land cover type, revealing spatial distribution changes (Wang et al., 2022).	$CA = \Sigma A_i$ (where A_i is the area of each patch of a given class)	CA > 0, expressed in square kilometre	Indicates spatial evolution and the relative dominance of land cover classes.
Patch Number (PN)	Quantifies the number of distinct patches for each land cover type, reflecting the degree of landscape fragmentation (Fahrig, 2019).	PN = n (total number of patches for a given class)	PN ≥ 1	A high number suggests strong fragmentation, while a low number indicates greater landscape continuity.
Largest Patch Index (LPI)	Measures the proportion of the land cover class occupied by the largest patch, highlighting the dominance of large patches over smaller, fragmented ones (Haddad et al., 2015).	$LPI = (A_{max}/A_{total}) \times 100$	0–100 %	A high LPI indicates increased dominance of a single patch, while a low LPI reflects a more fragmented landscape.
Edge Density (ED)	Assesses the total edge length per unit area, indicating the degree of fragmentation and the exposure of patches to external influences (McGarigal et al., 2012).	$ED = \Sigma E/A_{total}$ (where E is the total edge length and A_{total} is the total area)	ED ≥ 0	A high ED reflects greater fragmentation and increased exposure to environmental pressures.
Fractal Dimension (FD)	Evaluates the complexity of patch shapes, reflecting irregularity and fragmentation at fine spatial scales (McGarigal et al., 2012).	$FD = (2 \ln(P))/(\ln(A))$ (where P is the perimeter and A is the patch area)	1–2	The closer the value is to 2, the more complex and fragmented the patch shapes are.
Nearest Neighbour Distance (NND)	Measures the distance between patches of the same type, providing insight into habitat connectivity and isolation (McGarigal et al., 2012).	$NND = \Sigma d_i/n$ (where d_i is the distance to the nearest neighbour for each patch and n is the total number of patches)	NND ≥ 0	A low value indicates better connectivity between patches, while a high value reflects increased isolation.

and producer's accuracy (PA), which range between 90% and 100%, further confirm the quality of these classifications, with minimal classification errors. Additionally, a visual analysis of the land use maps (Figure 3) highlights a significant decline in forest ecosystems on Idjwi Island.

Landscape composition dynamics

The analysis of land cover change on Idjwi Island from 1990 to 2023 highlights significant alterations due to both natural processes and human activities (Figure 4). Forest cover declined drastically from 57.16 km^2 in 1990 to 3.25 km^2 in 2023, a nearly 95% loss, driven by agricultural expansion, logging, and urbanisation, especially between 2000 and 2008. This has severe implications for biodiversity, climate regulation, and local water cycles. Savanna areas fluctuated, expanding from 142.13 km^2 in 1990 to 150.13 km^2 in 2000, but then contracting to 100.94 km^2 by 2015 before recovering to 121.60 km^2 in 2023. This reflects the influence of both human and environmental factors, such as changes in agricultural practices, reduced grazing pressure, and

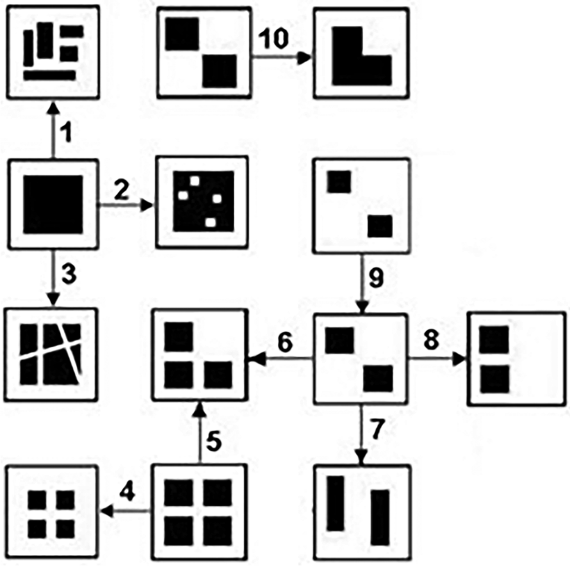

Figure 2. A diagram illustrating ten spatial transformation processes based on thirteen common spatial configurations or geometries in a binary landscape: (1) Fragmentation: conversion of a continuous landscape into five disconnected patches of varying sizes and shapes; (2) Perforation: transformation involving the creation of four holes; (3) Dissection: subdivision of a continuous area by narrow, evenly spaced lines; (4) Shrinkage: reduction in patch size; (5) Attrition: elimination of one patch from the original landscape; (6) Creation: formation of a new patch, increasing the number of patches from two to three; (7) Deformation: change in the shape of two patches into rectangles without altering their area; (8) Shift: movement of one patch; (9) Enlargement: increase in the size of both patches; (10) Aggregation: merging of patches. Modified from Bogaert et al. (2004).

favourable climatic conditions. Agricultural land increased from 75.98 km^2 in 1990 to 153.75 km^2 in 2015, with a slight reduction to 131.78 km^2 by 2023, indicating agrarian saturation and further pressure on forests and savannas. Built-up and bare land grew from 1.94 km^2 in 1990 to 19.70 km^2 in 2023, highlighting rapid urbanisation and infrastructure development, contributing to habitat fragmentation and increasing pressures on biodiversity and conservation efforts.

Between 1990 and 2000, forest cover decreased by 27.59% annually at −2.8%, while savanna and agricultural areas saw slight increases. Built-up and bare land areas, however, surged by 223.20%, reflecting rapid urbanisation or intensive deforestation, with an annual rate of 22.3%. From 2000 to 2008, forest cover declined more sharply by 63.98% at an annual rate of -8.0%, while savanna decreased by 18.04% (−2.3% annually). During this time, agricultural land grew by 59.45% (annual rate of 7.4%), and built-up areas expanded significantly (Table 3). Between 2008 and 2015, deforestation continued at a high rate (−62.78%, annual rate of −9.0%), though the expansion of agriculture and urban areas slowed, suggesting a potential saturation in agricultural land. The most recent period, from 2015 to 2023, showed a reduction in forest loss (−39.64%, annual rate of −5.7%) and a recovery of savanna areas (+20.45%, annual rate of 2.9%). Agricultural land decreased by 14.29% (−2.0% annually), likely due to land conversion or abandonment of agricultural practices, while built-up and bare soil areas continued to expand, but more moderately (Table 4).

Landscape spatial pattern dynamics

The class area (CA) of forests decreased from 1990 to 2023, accompanied a decrease in the number of patches (PN) (Table 4). This decline in both CA and PN is indicative a process of attrition, whereby forest areas are progressively reduced and remaining patches become more consolidated or lost. In contrast, the savanna exhibited a different trajectory (Table 5). From 1990 to 2000 and 2015 to 2023, the CA of savanna increased despite a decrease in PN,

Table 3. Evaluation of the accuracy of land cover change maps of Idjwi territory from 1990 to 2023, based on the supervised classification of Landsat images using the Random Forest classifier.

1990_2000	Forest	Savanna	Agriculture	Built-up	Forest loss	Savanna loss	Agr gain	Built-up gain
Accuracy measure								
Prod. acc.	99.67%	100.00%	99.27%	100.00%	83.46%	100.00%	94.69%	95.85%
User acc.	100.00%	97.22%	100.00%	100.00%	99.78%	95.09%	100.00%	100.00%
Overall acc.	98.59%							
Stratified estimators of area ± CI [% of total map area]								
Area	14.93%	47.34%	27.40%	0.70%	6.54%	0.97%	0.23%	1.63%
95% CI	0.00%	0.01%	0.00%	0.00%	0.01%	0.00%	0.00%	0.00%
2000_2008	Forest	Savanna	Agriculture	Built-up	Forest loss	Savanna gain	Agri loss	Built-up loss
Accuracy measure								
Prod. acc.	99.45%	99.86%	99.93%	99.29%	99.78%	98.62%	91.20%	100.00%
User acc.	99.75%	99.17%	99.60%	100.00%	99.52%	99.75%	99.42%	100.00%
Overall acc.	95.76%							
Stratified estimators of area ± CI [% of total map area]								
Area	5.37%	32.24%	20.53%	1.78%	5.94%	5.73%	2.31%	0.48%
95% CI	0.05%	0.25%	0.12%	0.02%	0.05%	0.12%	0.21%	0.00%
2008_2015	Forest	Savanna	Agriculture	Built-up	Forest loss	Savanna loss	Agr gain	Built-up gain
Accuracy measure								
Prod. acc.	100.00%	99.77%	99.55%	100.00%	100.00%	100.00%	96.49%	98.54%
User acc.	100.00%	99.49%	99.83%	100.00%	100.00%	99.20%	100.00%	99.17%
Overall acc.	99.63%							
Stratified estimators of area ± CI [% of total map area]								
Area	2.01%	34.37%	45.19%	4.12%	2.63%	8.80%	0.69%	2.17%
95% CI	0.00%	0.28%	0.29%	0.00%	0.00%	0.08%	0.05%	0.05%
2015_2023	Forest	Savanna	Agriculture	Built-up	Forest loss	Savanna gain	Agr gain	Built-up gain
Accuracy measure								
Prod. acc.	100.00%	100.00%	100.00%	99.60%	100.00%	100.00%	100.00%	100.00%
User acc.	100.00%	100.00%	100.00%	100.00%	100.00%	99.71%	100.00%	100.00%
Overall acc.	99.93%							
Stratified estimators of area ± CI [% of total map area]								
Area	1.17%	35.11%	47.22%	6.22%	0.52%	8.50%	0.26%	1.26%
95% CI	0.00%	0.00%	0.00%	0.05%	0.00%	0.05%	0.00%	0.00%

FR: Forest; SV: Savanna; AG: Agriculture; BBS: Built-up & Bare Soil; UA: User's Accuracy; PA: Producer's Accuracy. CI: confidence interval.

suggesting aggregation as spatial transformation process. However, between 2000 and 2015, the CA of the savanna decreased while PN increased, reflecting dissection of patches. For agriculture, the CA and PN increased from 1990 to 2000, suggesting the creation of new agricultural areas. Between 2000 and 2015, CA continued to increase while PN decreased, indicating aggregation of existing agricultural areas. However, from 2015 to 2023, the CA decreased while PN increased through the spatial process of patches dissection. The BBS class showed a continuous expansion throughout the study period (Table 5). The CA and PN of BBS increased from 1990 to 2023, reflecting the creation of new built-up and bare soil areas.

In 1990, forests had a Landscape Pattern Index (LPI) of 10.83%, indicating large, continuous areas of forest cover. By 2023, this dropped to 0.18%, signalling a significant loss of unbroken forest areas. Savanna LPI decreased from 24.00% in 1990 to 16.77% in 2023, showing a shift towards a more fragmented landscape. Agricultural areas saw an increase in LPI, peaking at 18.89% in 2015 before stabilising at 11.10% in 2023 (Table 6). For forest areas, Edge Density (ED) decreased from 58.53 m/ha in 1990 to 8.59 m/ha in 2023, while savanna ED peaked at 183.05 m/ha in 2008, then slightly declined to 160.13 m/ha by 2023. Agricultural ED rose significantly from 101.52 m/ha in 1990 to 177.52 m/ha in 2023, with built-up areas also showing

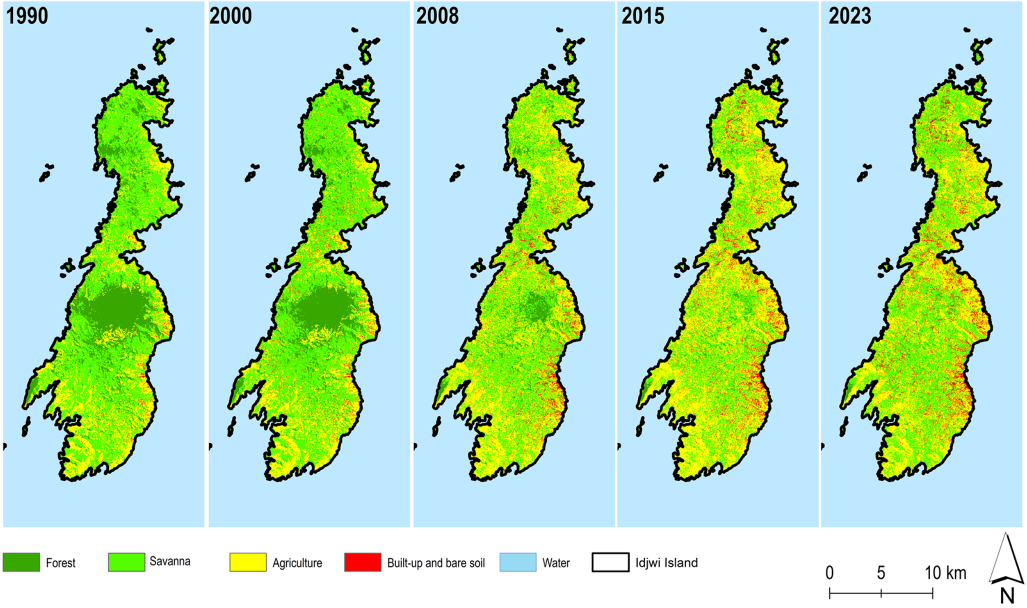

Figure 3. Spatial mapping of land cover dynamics in the Idjwi Island from 1990 to 2023, utilising supervised classification of Landsat images with the Random Forest classifier.

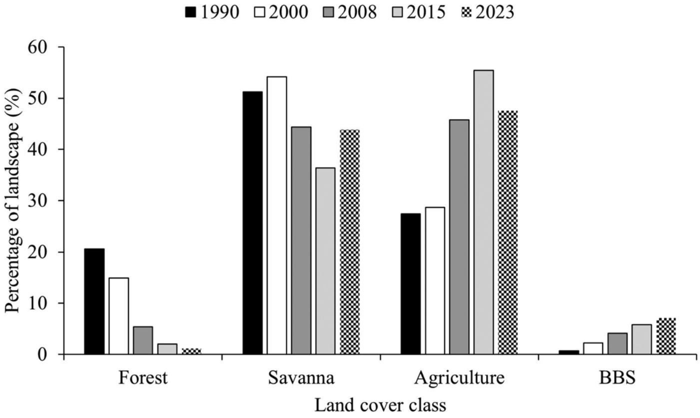

Figure 4. Composition of land cover in 1990, 2000, 2008, 2015 and 2023 in Idjwi Island. Total area of the landscape = 280 km^2. The total landscape proportion for each year does not sum to 100% as water land cover classes were excluded from the analyses due to their relatively stable nature. BBS: Built-up and bare soil.

Table 4. Rate of change in land cover over the period 1990–2000, 2000–2008, 2008–2015 and 2015–2023 Idjwi island. Values in bracket refer to annual rate of change.

	Land cover class			
Year	Forest	Savanna	Agriculture	BBS
1990–2000	−27.59 (−2.8)	5.62 (0.6)	4.51 (0.5)	223.20 (22.3)
2000–2008	−63.98 (−8.0)	−18.04 (−2.3)	59.45 (7.4)	82.23 (10.3)
2008–2015	−62.78 (−9.0)	−17.96 (2.6)	21.12 (3.0)	40.77 (5.8)
2015–2023	−39.64 (5.7)	20.45 (2.9)	−14.29 (−2.0)	22.44 (3.2)

BBS: Built-up and bare soil.

Table 5. Identification of the Spatial Transformation Processes (STP) of land cover within Idjwi Island using decision tree Algorithm of Bogaert et al. (2004).

	Land cover class			
Year	Forest	Savanna	Agriculture	BBS
CA1990	57.16	142.13	75.98	1.94
PN1990	3167	1962	3986	852
STP 1990–2000	Attrition	Aggregation	Creation	Creation
CA2000	41.39	150.13	79.41	6.27
PN2000	2537	1822	4055	3407
STP 2000–2008	Attrition	Dissection	Aggregation	Creation
CA2008	14.91	123.04	126.94	11.43
PN2008	2181	3507	3974	4284
STP 2008–2015	Attrition	Dissection	Aggregation	Creation
CA2015	5.55	100.94	153.75	16.09
PN2015	1460	4100	2356	5248
STP 2015–2023	Attrition	Aggregation	Dissection	Creation
CA2023	3.25	121.60	131.78	19.70
PN2023	987	3123	3777	6253

BBS: Built-up and bare soil.

a rise in ED from 6.65 m/ha in 1990 to 60.57 m/ha in 2023 (Table 6). The Fractal Dimension, indicating patch shape complexity, remained stable across all land types, ranging from 1.03 to 1.05 (Table 6). The Nearest Neighbour Distance metric, showing patch connectivity, increased for forests from 91.73 m in 1990 to 172.54 m in 2023, indicating growing forest patch isolation. Savanna patches showed stable distances between 73.31 m and 77.80 m, while built-up areas saw a decrease in nearest neighbour distance from 169.97 m in 1990 to 92.15 m in 2023, reflecting increased urban clustering (Table 6).

In 1990, the disturbance index for Idjwi was 3.85 (Figure 5). By 2000, the index had risen to 5.70, indicating a significant increase in human activities and their impact on the forest. The significant jump to 17.5 in 2008 indicates a period of accelerated disturbance. This trend continued with the index reaching 84.02 in 2023, reflecting an alarming rate of forest loss and an intensification of anthropogenic land-use pressures.

Discussion

The decline of forest cover on Idjwi Island is driven by increased sand and mineral extraction. Sand mining, fuelled by urban demand in Goma and Bukavu, has led to vegetation loss and land disturbances along coastlines and riverbeds. Similarly, gold and coltan extraction, especially since the early 2000s, has contributed to deforestation, fragmenting habitats and reducing ecological continuity (McGarigal et al., 2012). Satellite imagery from 1990 to 2023 reveals a significant increase in bare soil and built-up areas, linked to extraction sites, reflecting vegetation removal and infrastructure development. This urban expansion reduces landscape heterogeneity, increases impervious surfaces, and disrupts ecological flows. Socio-political conflicts have exacerbated environmental pressures on Idjwi Island. The 1994 Rwandan genocide and subsequent conflicts in Eastern DRC caused significant population displacement, with many refugees settling on the island. This influx intensified pressure on local resources, leading to land conversion for shelter, farmland, and fuel, which accelerated deforestation and degradation. Following the 2006 elections, demographic growth in Goma and Bukavu increased food and energy demands, driving further agricultural expansion and resource exploitation. Charcoal production, a major energy source, has contributed to extensive wood harvesting, leading to forest depletion, as seen in Nigeria (Nkem et al., 2010). The harvesting of non-timber forest products, such as medicinal plants and fruits, has further degraded habitats and reduced forest density, similar to trends in the Congo Basin. Additionally, timber demand for local construction and urban centres has exacerbated forest loss. Over time, deforestation intensity on Idjwi Island has fluctuated due to economic

Table 6. Synthesis of the spatial pattern indices in the Idjwi island in 1990, 2000, 2008, 2015 and 2023.

1990	Forest	Savanna	Agriculture	BBS
LPI (%)	10.83	24.00	4.22	0.02
ED (m/ha)	58.53	134.29	101.52	6.65
Fractal dimension	1.05	1.04	1.05	1.03
Nearest neighbour distance (m)	91.73	77.47	84.55	169.97
2000	Forest	Savanna	Agriculture	BBS
LPI (%)	8.43	46.90	8.49	0.02
ED (m/ha)	41.32	133.74	104.01	23.22
Fractal dimension	1.04	1.04	1.05	1.02
Nearest neighbour distance (m)	104.74	77.80	83.63	117.44
2008	Forest	Savanna	Agriculture	BBS
LPI (%)	1.51	25.61	14.51	0.09
ED (m/ha)	28.13	183.05	173.60	36.37
Fractal dimension	1.04	1.05	1.05	1.03
Nearest neighbour distance (m)	120.14	70.64	68.90	106.15
2015	Forest	Savanna	Agriculture	BBS
LPI (%)	0.21	13.47	18.89	0.11
ED (m/ha)	14.17	161.32	180.04	49.32
Fractal dimension	1.03	1.05	1.05	1.03
Nearest neighbour distance (m)	152.37	73.16	67.86	96.73
2023	Forest	Savanna	Agriculture	Built-up
LPI (%)	0.18	16.77	11.10	0.11
ED (m/ha)	8.59	160.13	177.52	60.57
Fractal dimension	1.03	1.05	1.05	1.03
Nearest neighbour distance (m)	172.54	73.31	68.32	92.15

LPI: Largest patch index; ED: Edge density; MPS: Mean patch size. BBS: Built-up and bare soil.

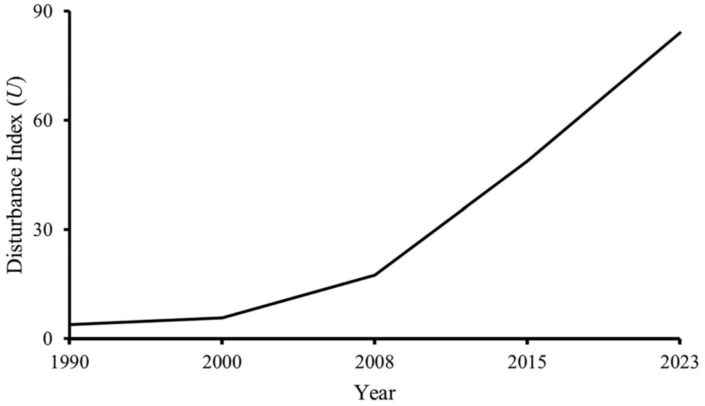

Figure 5. Evolution of the level of disturbance index in the Idjwi Island area in 1990, 2000, 2008, 2015 and 2023. This index is defined as the ratio of the cumulative area occupied by anthropogenic land cover classes to the cumulative area of forest within the landscape of Idjwi Island.

conditions, population growth, and changing demands for forest resources. Periods of economic growth, such as in 2000 and 2008, saw increased forest exploitation, while downturns in 2015 and 2023 temporarily reduced pressures, but did not halt deforestation. These patterns mirror global trends, like in the Amazon, where economic incentives and policy shifts drive deforestation rates (Fearnside, 2005). Agricultural expansion has been a major driver of forest loss, with agricultural land increasing from 75.98 km^2 in 1990 to 153.75 km^2 in 2015. By 2023, agricultural land decreased to 131.78 km^2, reflecting saturation and more intensive farming. This aligns with global land competition trends, where urban and agricultural growth limit available land (d'Amour et al., 2017). As land-use saturation occurs, economic challenges such as diminishing returns, higher production costs, and tensions over land ownership, along with ecological issues like soil depletion and biodiversity loss, emerge, similar to trends observed in the Galápagos Islands (Watson et al., 2010).

Savanna cover on Idjwi Island has fluctuated due to deforestation, agriculture, and fire management. It expanded from 142.13 km^2 in 1990 to 150.13 km^2 in 2000, likely due to forest clearings promoting heliophytic species. However, it declined to 100.94 km^2 by 2015, driven by agricultural conversion, charcoal production, and logging, leading to increased fragmentation. A partial recovery to 121.60 km^2 in 2023 is attributed to secondary succession, shifting fire regimes, and climate factors. This mirrors trends in the Brazilian cerrado, where deforestation has led to biodiversity loss and altered ecosystem functions. Continued fragmentation on Idjwi may threaten savanna stability and its ecological services, such as carbon storage and biodiversity support. The expansion of built-up and bare soil areas on Idjwi, from 1.94 km^2 in 1990 to 19.70 km^2 in 2023, reflects significant urbanisation and infrastructure growth. Similar trends in the Philippines have led to reduced agricultural and forest cover (Pulhin et al., 2007). While urban growth boosts local economies, it often results in habitat destruction and biodiversity loss, as observed in rapidly growing cities like Nairobi (UN-Habitat, 2013). Forest fragmentation on Idjwi affects biodiversity and ecosystem function, isolating species populations, exposing forest patches to edge effects, and accelerating degradation (Haddad et al., 2015). To mitigate these impacts, establishing ecological corridors and sustainable land management practices is crucial to enhance connectivity and facilitate ecosystem resilience. Overall, landscape metrics offer a robust framework for interpreting the drivers and consequences of land cover change on Idjwi Island. The observed increase in fragmentation, loss of core habitat, and rise in edge effects confirm the profound impact of human activities on the island's ecological integrity. These findings underscore the urgent need for sustainable land-use policies that balance development with conservation efforts to ensure long-term environmental stability. The analysis of spatial transformations corroborates our findings on Idjwi's forest dynamics and human impact. The decrease in forest area (CA) and patches (PN) (1990–2023) indicates attrition, with forests becoming increasingly fragmented. Savanna aggregation (1990–2000, 2015–2023) supports deforestation-driven expansion, while its dissection (2000–2015) confirms increased fragmentation due to agriculture and logging. Agricultural land creation (1990–2000) and aggregation (2000–2015) reflect demographic pressure, while dissection (2015–2023) signals land saturation. The continuous expansion of built-up areas reflects urban growth and infrastructure development. These spatial processes confirm deforestation, fragmentation, and the critical need for sustainable land policies.

Conclusion

This study examines land cover changes over a thirty-three-year period (1990–2023) on Idjwi Island, located in Lake Kivu, Democratic Republic of the Congo (DRC). Using classified Landsat imagery from 1990 to 2023, spatial evolution was mapped and quantified through landscape metrics. The results reveal an alarming shift in land dynamics, particularly the drastic deforestation and increased fragmentation of forest patches on the island. Once dominating 57.16 km^2 in 1990, forest cover shrank dramatically to just 3.25 km^2 in 2023, representing a loss of over 94%. This decline was accompanied by significant ecological fragmentation, with a marked increase in the average distance between forest patches, leading to the disruption of natural habitats. In parallel, the expansion of savannahs, agricultural lands, and urbanised areas has fundamentally altered the island's landscape structure. Agricultural land peaked in 2015, followed by a slight regression by 2023, suggesting an agricultural saturation point. These findings have profound implications for land management and public policy. It is crucial to implement reforestation strategies and ecological restoration efforts to counter biodiversity loss and ensure the resilience of the island's ecosystems. To address these challenges, public policy should prioritise sustainable agricultural practices while controlling unplanned urban expansion. Furthermore, the active participation of local communities in natural resource management is crucial for ensuring the long-term success of these conservation efforts. Future research should explore the ecological consequences of landscape fragmentation through comprehensive field surveys of the island's flora and fauna. The integration of advanced technologies, such as LiDAR and drone imagery, could also provide more detailed insights into land cover and ecosystem structure. Lastly, examining the socio-economic factors driving land use change would offer a more holistic perspective on the interplay between human activity and environmental degradation.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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