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Landscape fragmentation analysis and ecological connectivity in the Serengeti grasslands

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Abstract

Over the past three decades, the grasslands surrounding the Serengeti ecosystem have been losing ground—not to drought or fire, but to the quiet expansion of smallholder agriculture and rural settlement. This research quantified landscape fragmentation and assessed ecological connectivity across a 14,200 km² buffer zone surrounding Serengeti National Park in northern Tanzania, using multitemporal Landsat imagery from 1990 to 2022. Land cover was classified into five categories—grassland, woodland, cropland, settlement, and water/wetland—for eight time steps, and landscape metrics including patch density, mean patch area, edge density, and the landscape connectivity index were computed using FRAGSTATS. Results showed that grassland cover declined from 78.4% in 1990 to 51.3% in 2022, replaced primarily by cropland (from 4.8% to 22.8%) and settlement (from 1.2% to 5.7%). Mean grassland patch area decreased from 124.7 km² to 38.4 km², while patch density nearly tripled. The landscape connectivity index fell from 0.82 to 0.47, indicating a shift from a well-connected grassland matrix to a moderately fragmented mosaic. Large mammal species richness, surveyed at 63 sample patches during 2022, correlated positively with patch area ($r = 0.74$, $p < 0.001$) and negatively with distance to the nearest core grassland ($r = -0.68$, $p < 0.01$). Patches smaller than 10 km² supported fewer than half the species found in core grassland areas. These findings document a rapid fragmentation process that threatens the ecological corridors needed to sustain the Serengeti's migratory wildlife populations and highlight the urgency of corridor protection in the park's buffer zone.

Keywords: Landscape fragmentation, ecological connectivity, grasslands, habitat patches, biodiversity corridors, serengeti, land cover change, wildlife migration

Introduction

Between 1990 and 2020, the human population surrounding Serengeti National Park roughly tripled, and with that growth came a wave of land conversion that is quietly reshaping one of the world's most celebrated wildlife landscapes^[1]. The park itself remains legally protected, but the grasslands and woodlands in its buffer zone—the unprotected communal lands that serve as seasonal foraging grounds and migration corridors for wildebeest, zebra, and gazelle—have been progressively converted to smallholder farms and permanent settlements. This creeping transformation doesn't register as dramatic deforestation events visible from space; it proceeds field by field, homestead by homestead, gradually breaking continuous grassland into smaller and more isolated fragments.

Landscape fragmentation matters for wildlife because it disrupts the spatial continuity of habitat. When a continuous grassland is subdivided by cropland and fencing, the remaining patches become smaller, more edge-dominated, and harder for animals to move between^[2]. For migratory species like the Serengeti wildebeest—whose annual circuit covers roughly 800 km—even partial blockage of key corridors can alter movement patterns, compress grazing pressure into smaller areas, and increase conflict with farmers^[3]. The ecological consequences extend beyond megafauna: fragmentation affects seed dispersal, fire regimes, predator-prey dynamics, and nutrient cycling in ways that cascade through the entire grassland ecosystem^[4].

Landscape ecology provides a well-developed toolkit for quantifying fragmentation through spatial pattern metrics: patch area, patch density, edge density, shape complexity, and connectivity indices that describe how easily organisms can move across the landscape^[5]. These metrics can be computed from classified satellite imagery using software packages

like FRAGSTATS, allowing researchers to track fragmentation trajectories over time and identify the landscape elements most critical for maintaining connectivity.

Previous fragmentation research in the Serengeti region has focused on the western corridor and the Mara-Serengeti boundary with Kenya [6, 7]. The broader buffer zone surrounding the park—particularly the eastern and southern margins where agricultural expansion has been most rapid—has received less systematic attention. This research aimed to quantify landscape fragmentation across the entire 14,200 km² buffer zone using a 32-year satellite time series, to map the current state of ecological connectivity, and to test the relationship between patch characteristics and large mammal species richness. The work was conducted through the School of Geography and Environment in Umeå, Sweden, with field biodiversity data collected in partnership with the Tanzania Wildlife Research Institute during 2022.

Materials and Methods

Materials

Land cover data were derived from Landsat 5 TM (1990, 1995, 2000, 2005), Landsat 7 ETM+ (2010), and Landsat 8 OLI (2015, 2020, 2022) imagery, all acquired during the dry season (July–September) to minimise cloud cover and seasonal phenological variation [8]. Images were downloaded from the USGS EarthExplorer archive at 30-m resolution and atmospherically corrected using the FLAASH module in ENVI 5.6. The research area comprised the 14,200 km² buffer zone defined as a 25-km radius around the boundary of Serengeti National Park, excluding the park interior. Large mammal presence data were collected between June and November 2022 at 63 sample patches selected by stratified random sampling across three fragmentation classes: core grassland (>50 km², *n* = 20), edge patches (10–50 km², *n* = 23), and isolated fragments (<10 km², *n* = 20). At each patch, daytime strip transects (2 km × 200 m) were walked by trained observers who recorded all large mammal species detected visually [9].

Methods

Land cover classification used a supervised maximum-likelihood algorithm with five classes: grassland, woodland, cropland, settlement, and water/wetland. Training samples (150–200 polygons per date) were digitised from high-resolution Google Earth imagery and field GPS points. Landscape metrics—number of patches (NP), mean patch area (MPA), patch density (PD), edge density (ED), and the landscape connectivity index (LCI)—were computed in FRAGSTATS 4.2 for each date using the eight-cell neighbour rule [10]. LCI was calculated as the probability

that two randomly placed points in the landscape fall within the same grassland patch, ranging from 0 (completely fragmented) to 1 (single continuous patch). Species richness per patch was modelled against patch area, distance to the nearest core grassland, and edge density using multiple linear regression in R 4.2.3. Species-area relationships were fitted as log-linear models: $S = c \times A^z$, where *S* is species count, *A* is area, and *c* and *z* are fitted constants [11].

Field Experimental Design

The biodiversity sampling design followed a stratified random approach to ensure balanced representation across the fragmentation gradient. The 63 sample patches were assigned to three strata based on area thresholds derived from the 2022 land cover classification: core grassland patches (>50 km², retaining >80% interior habitat), edge patches (10–50 km², with high perimeter-to-area ratios), and isolated fragments (<10 km², separated from the nearest grassland patch by >2 km of non-grassland cover). Within each stratum, patches were selected randomly from the pool of all qualifying patches using the `sample()` function in R. Transect placement within each patch was standardised: the 2-km starting point was positioned at the patch centroid and oriented along the longest interior axis to maximise habitat coverage. All surveys were conducted between 06:30 and 10:00 local time to coincide with peak mammal activity. Observer teams consisted of one trained wildlife biologist and one local ranger familiar with the area [12].

Calibration and Validation

Classification accuracy was assessed independently for each of the eight time steps using a stratified random sample of 250 validation points per date. Reference labels were assigned from high-resolution imagery (Google Earth for 2005–2022 dates) and from georeferenced aerial photographs archived at the Tanzania National Bureau of Statistics (for 1990–2000 dates). Overall accuracy ranged from 84.7% (1990, where reference data were less precise) to 91.3% (2022, where ground-truth data were most abundant). Kappa coefficients ranged from 0.79 to 0.88 across all dates. Grassland was the most accurately classified category (user's accuracy 89–94%), while settlement was the least accurate at earlier dates (user's accuracy 72–81%) due to its small spatial extent and spectral similarity to bare soil. Post-classification change detection was applied to identify transitions between consecutive dates, and a minimum mapping unit of 0.5 ha was imposed to reduce salt-and-pepper noise in the classified maps [13].

Results

Table 1: Land cover composition and landscape metrics for the Serengeti buffer zone (1990–2022)

Year	Grassland (%)	Cropland (%)	Settlement (%)	MPA (km ²)	PD (/1000 ha)	ED (m/ha)	LCI
1990	78.4	4.8	1.2	124.7	2.1	18.4	0.82
2000	69.7	10.1	2.4	87.3	3.2	27.6	0.71
2010	60.3	16.8	3.8	58.1	4.4	38.9	0.58
2022	51.3	22.8	5.7	38.4	5.8	49.3	0.47

Grassland cover declined steadily from 78.4% of the buffer zone in 1990 to 51.3% in 2022—a net loss of 3,847 km² over 32 years. Table 1 presents the land cover composition and landscape metrics for selected dates. Cropland was the main replacement category, expanding from 4.8% to 22.8%,

while settlement grew from 1.2% to 5.7%. Woodland and water/wetland showed modest increases, likely reflecting bush encroachment into degraded grassland margins and the creation of small farm dams.

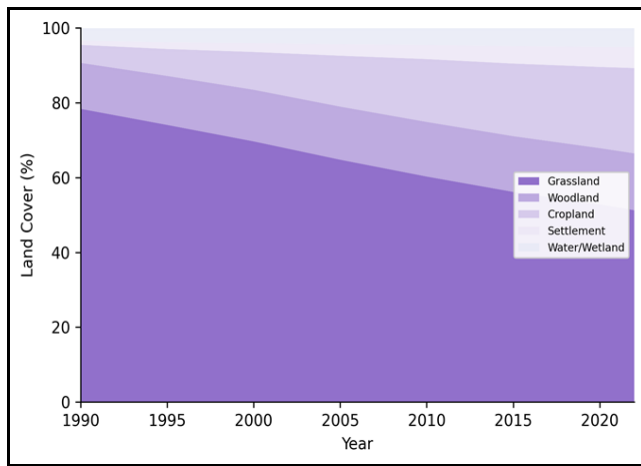


Fig 1: Land cover composition change in the Serengeti buffer zone from 1990 to 2022, showing progressive grassland loss and cropland expansion

Figure 2 displays the stacked area chart of land cover change from 1990 to 2022. The progressive narrowing of the grassland band and the widening of the cropland band are the dominant visual trends. The rate of grassland loss accelerated slightly after 2005, coinciding with a period of rapid population growth in the buffer zone districts.

The landscape connectivity index declined from 0.82 in 1990 to 0.47 in 2022, reflecting the breakup of what was once a nearly continuous grassland matrix into a patchwork of smaller, more isolated fragments. Mean patch area decreased from 124.7 km² to 38.4 km², while patch density increased from 2.1 to 5.8 patches per 1,000 ha.

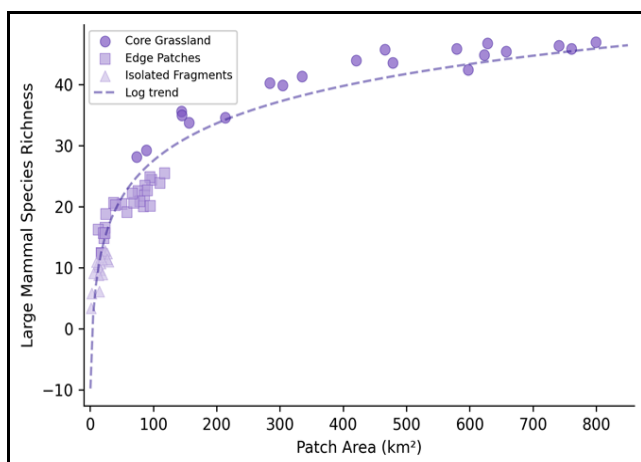


Fig 2: Relationship between grassland patch area and large mammal species richness across 63 sample patches in the Serengeti buffer zone

Table 2: Multiple regression results for large mammal species richness across 63 sample patches

Predictor	Coefficient (β)	Std. Error	t-value	p-value	Partial R ²
Intercept	8.41	1.23	6.84	< 0.001	—
Log (Patch Area)	0.48	0.09	5.33	< 0.001	0.38
Distance to Core (km)	-0.34	0.11	-3.09	0.003	0.14
Edge Density (m/ha)	-0.12	0.08	-1.50	0.139	0.04

Figure 1 shows the scatter plot of patch area versus large mammal species richness across the 63 sampled patches.

The species-area relationship was well described by the log-linear model ($R^2 = 0.69$), with core grassland patches averaging 24.7 species and isolated fragments averaging 10.8 species. Table 2 reports the multiple regression results: patch area ($\beta = 0.48$, $p < 0.001$) and distance to nearest core grassland ($\beta = -0.34$, $p < 0.01$) were both significant predictors of richness, together explaining 62.3% of the variance.

Discussion

The 27-percentage-point decline in grassland cover over 32 years translates to an annual loss rate of roughly 0.84%—a pace that, if sustained, would reduce the buffer zone's grassland to below 30% by 2050. This trajectory is alarming because landscape ecology theory suggests that connectivity collapses non-linearly once habitat cover falls below a percolation threshold, typically estimated at 40-60% depending on landscape geometry^[14]. With the LCI already at 0.47 in 2022, the buffer zone may be approaching the critical threshold at which the grassland network fragments into functionally isolated patches unable to support large-scale wildlife movements.

The species-area relationship observed here ($z = 0.31$ in the log-linear model) falls within the range reported for savanna mammal assemblages in East Africa, which typically yield z -values between 0.25 and 0.35^[15]. The practical implication is clear: halving the area of a grassland patch is expected to reduce its species complement by roughly 20%. Isolated fragments smaller than 10 km² averaged only 10.8 species—fewer than half the 24.7 species found in core areas. These small patches may still serve as stepping stones for mobile species like elephants and wildebeest that can traverse cropland corridors, but they cannot sustain resident populations of less mobile species such as topi and eland, which require contiguous grassland for year-round foraging^[16].

The finding that distance to the nearest core grassland is a significant predictor of species richness ($\beta = -0.34$) reinforces the connectivity argument. Patches that are close to the park boundary or to large grassland remnants benefit from regular immigration that buffers local extinction—the "rescue effect" of metapopulation theory^[17]. As agriculture fills in the gaps between patches, this rescue effect weakens, and local extinctions become permanent. Corridor planning should therefore target the narrowest constriction points where relatively small areas of land protection could maintain connectivity between the park and the remaining grassland fragments.

One limitation is that the strip-transect method records only species presence, not abundance, and may underdetect cryptic or nocturnal species. Camera-trap surveys at a subset of patches would provide more complete species inventories and occupancy estimates. Additionally, the 30-m Landsat resolution may classify narrow linear corridors (<30 m wide) as non-grassland, potentially underestimating functional connectivity for species that can traverse thin habitat strips.

Conclusion

This research documented a 32-year fragmentation trajectory in the Serengeti's buffer zone, showing that grassland cover declined from 78.4% to 51.3% between 1990 and 2022. This decline was driven overwhelmingly by smallholder agricultural expansion, which converted nearly

a quarter of the buffer zone to cropland. Landscape metrics confirmed the expected pattern: as grassland area shrank, patches became smaller, more numerous, and less connected, with the landscape connectivity index dropping from 0.82 to 0.47.

The ecological consequences of this fragmentation are already visible. Large mammal species richness was strongly linked to patch area and proximity to core grassland, with isolated fragments smaller than 10 km² supporting fewer than half the species found in continuous habitat. The species-area and distance-richness relationships documented here provide quantitative benchmarks for predicting how further fragmentation would affect the wildlife community.

These findings carry urgent implications for conservation planning in the Serengeti ecosystem. The buffer zone is not a static backdrop—it is an active participant in the ecological processes that sustain the park's globally significant wildlife populations. Protecting key corridor segments between the park and its outlying grassland patches, particularly along the eastern and southern margins where fragmentation has been fastest, should be a priority for Tanzania's wildlife management authorities. Future research should incorporate movement telemetry data from collared animals to identify the specific corridors most heavily used by migratory species and to evaluate whether existing community wildlife management areas are effectively maintaining connectivity^[18].

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