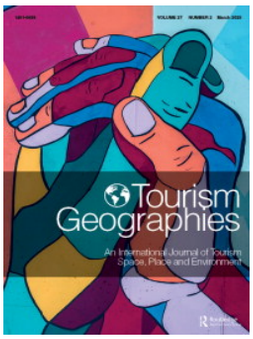

Routledge
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Tourism Geographies

An International Journal of Tourism Space, Place and Environment

ISSN: 1461-6688 (Print) 1470-1340 (Online) Journal homepage: www.tandfonline.com/journals/rtxg20

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To cite this article: Alfayo Koskei & Kyriaki Glyptou (29 May 2025): The multiple land use dilemmas of the Ngorongoro Biosphere Reserve, Tourism Geographies, DOI: 10.1080/14616688.2025.2500965

To link to this article: https://doi.org/10.1080/14616688.2025.2500965

Published online: 29 May 2025.

TOURISM GEOGRAPHIES
https://doi.org/10.1080/14616688.2025.2500965

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RESEARCH ARTICLE

The multiple land use dilemmas of the Ngorongoro Biosphere Reserve

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ABSTRACT

Ngorongoro Conservation Area (NCA), in Northern Tanzania, was among the first areas established as Multiple Land Use Model (MLUM) to foster coexistence between wildlife and the semi-nomadic Maasai community. Over time, growing tourism interest in the Maasai and the gradual transition towards a service economy contributed to nomadic sedentarisation and population growth straining NCA's resilience as a Socio-Ecological System (SES). This paper builds on Political Ecology and Systems Theory to assess the MLUM's effectiveness amidst expanding tourism development and a growing local population within UNESCO-designated Biosphere Reserves. A two-decade analysis of Land Use and Land Cover (LULC) changes in the NCA uncovers the long-term impacts of sixty years of policy interventions and the associated dynamic interactions and feedback-loops between ecosystem services, tourism-driven human activity, market pressures and evolving socio-cultural values. By integrating these theoretical lenses, the study offers a nuanced exploration of the complexity surrounding Biosphere SES transitions and resilience amidst tourism development. The findings emphasize the enduring tensions among conservation goals, tourism expansion, and the evolving socio-economic needs of indigenous communities, challenging the adaptability of MLUM to balance development in Biosphere Reserves while upholding cultural and environmental integrity overtime.

ARTICLE HISTORY
Received 30 August 2024
Accepted 22 April 2025

HANDLING EDITOR
Kelly L. Cerialo,
Paul Smith's College &
Marina Novelli,
Nottingham University
Business School

KEYWORDS
UNESCO Reserves;
Multiple Land Use Model
(MLUM); land uses;
tourism development;
systems thinking;
Ngorongoro
Conservation Area

1. Introduction

The Ngorongoro Conservation Area (hereafter mentioned as NCA) in Northern Tanzania was established in 1959 as a Multiple Land Use Model (hereafter mentioned as MLUM) area where wildlife was to co-exist with semi-nomadic Maasai community. Recognized for its ecological and cultural values, NCA was inscribed as a UNESCO World Heritage Site in 1979 and as a Man and Biosphere Reserve in 1981. NCA was established in the aftermath of the enactment of the Fauna Conservation Ordinance No.17 of 1951

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that reinstated the Serengeti National Park (SENAPA) in 1951 leading to significant tensions within the Maasai community and involving acts of sabotage and wildlife vandalism (killing of rhinos and setting wildfires). The British Administration responded by carving out the eastern portion of the park to establish the current Ngorongoro Conservation Area, which was designated as a multi-use protected area allowing wildlife conservation, pastoralism, and tourism. Consequently, two distinct management bodies were formed: Tanganyika National Parks (TANAPA) and the NCA, governed by the TANAPA Ordinance (Cap. 412) and NCA Ordinance (Cap. 413) of 1959 respectively. Under Ordinance No. 14 of 1959, the NCA was officially designated as a multi-use area, a pioneer model where wildlife coexisted with the semi-nomadic Maasai community who were resettled from the Serengeti National Park (SENAPA) (Estes et al., 2006). Today, NCA serves as a key component of the greater Serengeti-Mara-Ngorongoro biosphere, which supports the greatest animal migration on earth involving approximately 1.4 million wildebeest, 300,000 Thomson's and Grant's gazelle and 200,000 zebras (NCAA, 2024).

The NCA has maintained three major different UNESCO designations namely the World Heritage, Man and Biosphere Reserve and Mixed Natural and Cultural Heritage (UNESCO/ICOMOS/IUCN., 2012; World Heritage Committee, 2010). In 1979, the property was inscribed under natural criteria (vii), (viii), (ix) and (x) and in 2010 under cultural criterion (iv) as mixed natural and cultural heritage site. In 1981, the NCA was incorporated into the Serengeti-Ngorongoro Biosphere Reserve under UNESCO's Man and the Biosphere Program (MAB) together with other four sites namely Lake Manyara, Gombe-Masito-Ugalla, Jozani Chwaka Bay, and East Usambara (World Heritage Committee, 2019). NCA Biosphere Reserve encompasses much of the Crater Highlands and surrounding areas between the Serengeti plains and the Gregory Rift Valley (State Party of Tanzania, 2016). In April 2018, NCA was nominated as a Global Geo-Park further highlighting its geological significance. These developments underscore the ongoing efforts to safeguard the exceptional resources and ecosystem values of the NCA, preserving their value and integrity as a Biosphere Reserve.

Wildlife and humans coexisted within the NCA up until the past two decades when population density, climate change, geopolitics and the surge of tourism infrastructure put the delicate equlibrium of NCA as a SES under threat (World Heritage Committee, 2019). Galvin et al. (2008) discussed early in detail the impact of human population and activities in the disintegration of wildlife migratory corridors to and from the Ngorongoro Crater. Initially, the NCA accommodated approximately 8,000 people, 4,000 of which relocated from the Serengeti and another 4,000 who inhabited the Ngorongoro Highlands (State Party of Tanzania, 2016). However, as the population burgeoned, the SES equilibrium was disrupted prompting a revision of the Ordinance of 1975 which led to the establishment of the Ngorongoro Conservation Area Authority (NCAA) unit under the Ministry of Natural Resources and Tourism to oversee the management of the NCA. Initially, NCAA's objectives were focused on conserving natural resources, promoting tourism, and safeguarding the interests of the Maasai (NCAA., 2006). Yet, the growth in population of pastoral community and their sedentary transformations have necessitated a shift in these objectives over the years (NCAA, 2020).

On the social sphere, the living conditions of resident pastoralists have also deteriorated, highlighting the urgent need to review the MLUM's effectiveness to address the issues surrounding sustainability of livelihoods, the conservation of natural

resources, and tourism activities (Scheyvens & Laeis, 2021; UNESCO/IUCN/ICOMOS, 2019). Despite the government ordinance that affirmed the legal rights of the Maasai community within the NCA, pressures from conservation and tourism development have resulted in recent relocations of pastoralists out of the NCA (NCAA, 2020; UNESCO/ICOMOS/IUCN, 2019). The state party under the Government Voluntary Relocation Plan has continued to facilitate the voluntary relocation of residents from the NCA. By January 2023, 551 households, 3,010 people and 15,321 livestock had voluntarily relocated to Msomera village (UNESCO, 2023).

Building on data of the last two decades, this paper aims to explore the effectiveness and adaptability of the MLUM in the context of increasing tourism development and local population in the NCA UNESCO Biosphere Reserve. It adopts a systems thinking approach within the political ecology paradigm to simultaneously consider the complex adaptive systemic resilience dynamics of NCA as protected MLU Socio-Ecological System (SES). The application of systems thinking moves beyond the fragmented consideration of land use changes but rather treats them as evidence of both intended and unintended long-term consequences of the multi-dimensional policy interventions over the years. The contribution of this research is bifold. On a theoretical perspective it explores the effectiveness of the MLUM to safeguard NCA's SES services and to safeguard the systemic NCA resilience amidst ongoing land use competition, socio-cultural transitions and changing policy priorities. In this way, it contributes to the theoretical exploration of the systemic boundaries of the adaptive and transformative ability of UNESCO Biosphere Reserves as MLU Socio-Ecological Systems (SES). Its managerial implications lay in the promotion of transparent multi-stakeholder collaborations that promote adaptive and inclusive policies catering to the long-term systemic resilience of Biosphere Reserves.

2. Systems thinking in the context of Mixed Land Use Models (MLUM)

Mixed Land Use Models (MLUMs) emerged as effective planning strategies to overcome the segregated land use challenges and conflicts for land in multi-use areas such as Biosphere Reserves (Turner, 2014). MLUMs as lawful deliberate plans of intended mixture of complementary land use types were the optimal ground to foster the interrelations and interconnectedness of multiple uses by multiple stakeholders. In the context of NCA, the MLUM established in 1959 allowed local ethnic groups to continue to live within a protected area, in what has been described as 'one of Africa's longest experiments' (Thompson, 1997). Interestingly though, the boundaries of roles, interests, and responsibilities of local communities around decision making were not clarified (United Republic of Tanzania, 2019). Political ecology examines how and why economic structures and power relations drive environmental change in an increasingly interconnected world (Roberts, 2020). At its core it involves the study of interactions among different groups in a specific environment, examining power relations at various scales. Douglas (2014) asserts that political ecology has powerful implications for understanding the intricancies of tourism development particularly within developing nations since it emphasises the role of power, inequality, and historical context in shaping environmental outcomes, highlighting how political and economic structures influence access to and control over natural resources.

Moreover, it is useful in unveiling stakeholders' perspectives and their levels of influence concerning multiple aspects of the development of multi-use resources particularly in the context of Socio-Ecological Systems (Turner, 2014).

Systems thinking in the context of a SES enables the dialectical framework for analysing these relationship between environment and society, acknowledging their interconnections, mutual influences, feedback loops, complex dynamic relationships and transforming dynamics. Systems thinking critically integrates the in-between and across system dynamics (context and connections), perspectives (stakeholder interests), and boundaries (scope and scale) to support sustainable transitions through informed policy interventions. Systems thinking value in policy and decision-making has only recently been more widely recognised (OECD, 2020; UK GOV, 2021), yet effective considerations of multi-dimensionality and conflicts of interests remain a real challenge. In essence, systems thinking overcomes the traditional management theories that address policy concerns in isolation and in fragmentation aiming at immediate outcomes, by recognising the underlying complexity and interconnectedness of socio-ecological, economic and political systems and their elements (Baggio, 2008). As such, the System Thinking approach captures the dynamic adaptation (complex adaptive thinking) and re-organisation of the system over time considering time delays between policy actions and their intended and unintended systemic consequences (Glyptou, 2024).

The application of systems thinking in the context of MLUMs is grounded on the recognition of the interdependencies between the social and ecological values and services of the Biosphere system. It builds on the principle of connectivity where changes in one property (here land use of the system) will result in multi-dimensional dynamic interactions that affect the properties of the SES in the short or medium-long term through feedback loops. Systems thinking equips MLUM's with the necessary flexibility to capture population, environmental resources and economic activities' change over time and foster systemic adaptability in the face of transitions. Turner (2014) provides further insights into the value of understanding power dynamics and conflicts of interests in the context Socio-Ecological Systems and calls for collaborative, multi-stakeholder decision making. The integration of systems thinking within political ecology offers a holistic approach in the study of MLUMs. Political ecology reveals critical insights into who benefits or suffers from land policy interventions, while systems thinking enables the mapping of the broader structural patterns and emergent properties of the outcome interactions. Together, they enable a deeper understanding of how environmental governance, pressures for natural resources, policy, socio-cultural change and local agency co-create outcomes in complex and contested landscapes such as the Biosphere Reserves.

3. Land zoning and SES uses in NCA

In Tanzania, land is a public property whose management is vested under the President as trustee on behalf of all citizens (Nnkya,1999). Generally, land is classified into three categories namely: village land, general land, and reserved land. NCA being part of Serengeti-Mara Ecosystem (SME) falls under both a village and a reserve land. Moreover, NCA being a multiple land use area adopted the MLUM in attempt to strike a balance

between the interests of indigenous people, conservation, and tourism development (Mwabumba et al., 2022). In its early year of inception, this model was successful (ICOMOS/IUCN., 2017). However, the increasing challenges emanating from increasing human population and tourism activities forced the State Party, World Heritage Centre, and the Advisory Bodies to review the model in 2023. It proved unsustainable, given the needs to balance between conservation and socio-economic needs of communities (Scheyvens & Laeis, 2021; UNESCO., 2023).

In response to these increasing challenges in MLUM, NCAA have implemented a zonation system with four major classifications albeit with overlaps; (i) Crater zone, dedicated to conservation and tourism; (ii) development zone for commercial use such as tourism accommodations and facilities (iii) catchment zone and (iv) buffer zone (external use zone) as interface areas between protected areas and community occupied realm (NCAA, 2018a). The diverse climate, landforms, and altitudes in crater has overlapping ecosystems with abundant and unique biodiversity. These include short grass plains, highland catchment forests, savanna woodlands, montane long grass plains, and high open moorlands (Niboye, 2010). Despite the zonation, there have been significant shifts in land use and land cover changes (LULCC) in the last decades (Näschen et al., 2019). Notwithstanding the changes in different zones, the number of important keystone species such as Black Rhino (*Dicerous birconis michaeli*) has increased since UNESCO inscribed the area as world heritage site from 12 individuals in 1980s to 60 rhinos in 2018 (Gadiye et al., 2016; NCAA, 2011).

The human population in NCA have grown exponentially from initial 8000 people in 1959 to over 93,136 people in 2017. This was against the initial plan of 20,000 people (about 5,000 households). However, the Tropical Livestock Units per person (TLUs), which represent the common unit of livestock numbers, have greatly declined from 11.6 in 1959 to 2.3 in 2017 indicating a shift in societal behaviour (United Republic of Tanzania, 2019). At the same time, tourism accounted for about 92% of the total economy of the area already a decade ago (Melita & Mendlinger, 2013). In the last four decades tourists' volume has increased in NCA, from about 54,935 tourists in 1984 to over 644,000 in 2022 (NCAA, 2020). The pressure from this burgeoning tourism development may eventually surpass NCA 's carrying capacity or the integrity of its natural resources, leading to irreversible environmental consequences. Additionally, certain levels of tourism development can be socially detrimental to culture and lifestyles of the host community (Masao, Makoba, & Sosovele, 2015; Rimisho & Matei, 2024). Within NCA, tourists often overcrowd in the Ngorongoro Crater leaving other attractions relatively unexplored. As a result, sites like Ngorongoro Crater and Olduvai Gorge are bustling with tourism flows while others remain neglected and underdeveloped (see Figure 1) (NCAA, 2020).

The restrictions on land use and the population explosion have seen the collapse in pastoral economy—indigenous residents' socio-economic conditions have deteriorated due to food insecurity, water scarcity, poverty, increasing human-wildlife conflicts, unfavourable laws, poor health, and illiteracy level (Botha et al., 2021). Moreover, the subsequent modernisation of their lifestyle and introduction to a cash-based economy, and increased sedentarisation has jeopardize the balance and resilience of the socio-ecological system (NCAA, 2020; Slootweg, 2017).

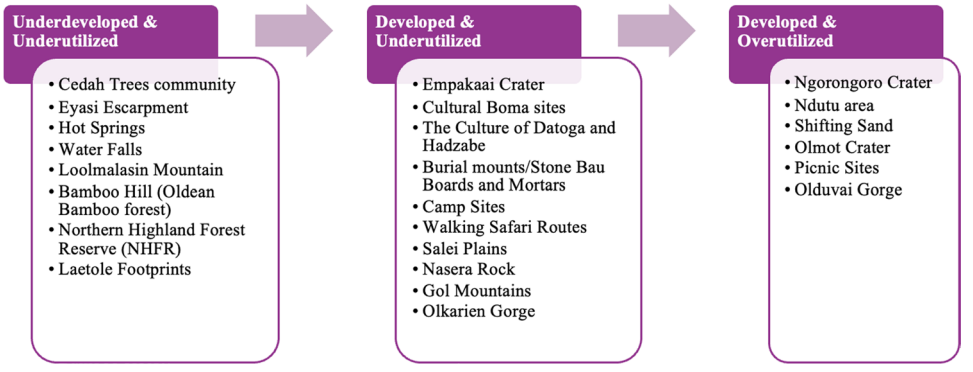

Figure 1. Status of tourists' attractions in NCA.

In the last decade over 139 invasive plant species have been recorded in NCA including crater floor (Table 1) and some are highly toxic to humans and animals (Ngondya & Munishi, 2021). The influx of these invasive species is attributed to tourism activities and changes in the grazing pressure that have adjusted the competitive balance between forbs and grasses (State Party of Tanzania, 2020). The study employed remote sensing and GIS methodologies to examine the transitions in land use and land cover (LULC) within the NCA, with particular focus on the influences of human population growth, tourism development, and associated infrastructure. Additionally, it considered the effects of various management paradigms, such as UNESCO World Heritage site designations, including mixed natural and cultural sites, and biosphere reserves. The primary objective of this research was to assess how tourism development and human population dynamics have impacted LULC changes in the NCA.

4. Methods

The study was conducted in NCA and neighboring areas covering 9,661km2 (966,120hac). It lies within longitude between 34.0°–36.0°E and latitudes 2.5°–3.6°S (Figure 2). This ecosystem has five major eco-zones namely the Crater Highlands, Kakesio/Eyasi Mountain, Salei Plains, Serengeti Plains, and Gol Mountains (Masao et al., 2015).

The data for this study was collected from both secondary and primary sources. Secondary data comprised Landsat imagery, data on human population, settlement density, and tourism infrastructure obtained from open sources ([1,2]). Primary data consisted of tourism arrival figures to the NCA and GPS coordinates used for ground truthing, which were collected at the NCAA head offices and during fieldwork. All Landsat images were inspected for low cloud cover of less than 10% with resolution of 30 by 30 pixels, as outlined in Table 2.

4.1. Land cover types

The major LULC classes used for classification were forest, woodland, scrubland, grassland, highland grassland, water, wetland, riverine vegetation and cultivated area (Table 3).

Table 1. Major invasive and threatened species in NCA.

Threaten species			Invasive species		
Common name	Bionomial name	Status	Common name	Binomial name	Family
Black Rhino	*Diceros bicornis michaeli*	CR	Erlangea	*Gutenbergia cordifolia*	*Asteraceae*
Cheetah	*Acinonyx jubatus*	VU	Marigold	*Tagetes minuta*	*Asteraceae*
Lion	*Panthera leo*	VU	Bidens spp	*Bidens schimperi*	*Asteraceae*
African Wild Dog	*Lycaon pictus*	EN	Fever tree	*Lippia Javanica*	*Verbenaceae*
African Elephant	*Loxodonta africana*	VU	Red water fern	*Azolla filiculoides*	*Salviniaceae*
Sandalwood	*Santalum album)*	VU	Black wattle	*Acacia mearnsii*	*Fabaceae*
Mountain reedbuck	*Redunca fulvorufula*	EN	Eringa	*Melia azedarach*	*Meliaceae*
Hippopotamus	*Hippopotamus amphibius*	VU	Lantana	*Lantana camara*	*Verbenaceae*
Eastern black-and–white colobus	*Colobus guereza caudatus*	VU	Mysore thorn	*Caesalpinia decapetala*	*Fabaceae*
Lesser flamingos	*Phoenicopterus minor*	NT	Jimsonweed	*Datura stramonium*	*Solanaceae*
Patas monkey	*Erythrocebus patas*	CR	Thorn apple	*Solanum incanum*	*Solanaceae*
African buffalo	*Syncerus caffer*	NT	Prosopis	*Prosopis juliflora*	*Fabaceae*
Ground pangolin	*Smutsia temminckii*	VU	Devil weed	*Chromolaena odorata*	*Asteraceae*
African Clawless Otter	*Aonyx capensis*	NT	Tree marigold	*Tithonia diversifolia*	*Asteraceae*
Spotted-necked Otter	*Hydrictis maculicollis*	NT	Prickly pear	*Opuntia stricta*	*Cactaceae*
African golden cat	*Profelis aurata*	VU	Vervain	*Verbena officinalis*	*Verbenaceae*
African rock python	*Python sebae*	NT	Goose grass	*Eleusine jaegeri*	*Poaceae*
Madagascar pond heron	*Ardeola idae*	EN	Mexican Poppy	*Argemone mexicana*	*Papaveraceae*
African fish-eagle	*Haliaeetus vocifer*	CR		*Indigofera spinosa*	*Fabaceae*
Tawny eagle	*Aquila rapax*	VU	Canadian thistle	*Cirsium arvense*	*Asteraceae*
Pallid harrier	*Circus macrourus*	NT	Water Willow	*Justicia exigua*	*Acanthaceae*
Secretary bird	*Sagittarius serpentarius*	EN	Thumba	*Leucas aspera*	*Lamiaceae*
Grey-crowned crane	*Balearica regulorum*	EN	Famine weed	*Parthenium hysterophorus*	*Asteraceae*
Kori bustard	*Ardiotis kor*	NT	Ashwagandha	*Withania somnifera*	*Solanaceae*
Great snipe	*Gallinago media*	NT	Lion's ear	*Leonotis nepetifolia*	*Lamiaceae*
Blackwinged pratincole	*Glareola nordmanni*	NT	Button Mangrove	*Conocarpus erectus*	*Combretaceae*
Fischer's lovebird	*Agapornis fischeri*	NT		*Plantago afra*	*Plantagineae*
Southern ground hornbill	*Bucorvus cafer*	VU	Indian Turnsole	*Heliotropium indicum*	*Boraginaceae*
Grey-crested helmet shrike	*Prionops poliolophus*	NT	Pigweed	*Amaranthus spinosus*	*Amaranthaceae*
Karamoja apalis	*Apalis karamojae*	VU	*Restharrow*	*Ononis spinosa*	*Fabaceae*

4.2. Data processing and analysis

The analysis pathway followed is summarised in Figure 3. The spatial analysis was done in GIS environment involving data pre-processing, image classification, and assessment of user and producer accuracy. LULCC was detected using multi-temporal image methods using hybrid classification method (Mwabumba et al., 2022 Strzelecka et al., 2017). Unsupervised classification initially yielded 20 classes, which were subsequently reclassified into eight classes using the reclassify tool. The resulting mosaic raster comprised six bands, incorporating all infrared and visible bands except for the thermal infrared. The raster data was then transformed to the right projection coordinate system[3]. The maps were interpreted using the Normalized Difference Vegetation Index (NDVI) calculations and colour Density Slicing. LULC classifications were analyzed by calculating the area of each land use type using the field calculator in a GIS environment and percentage proportion of each type using Excel. To quantify the extent of land cover changes, the study developed a change detection matrix

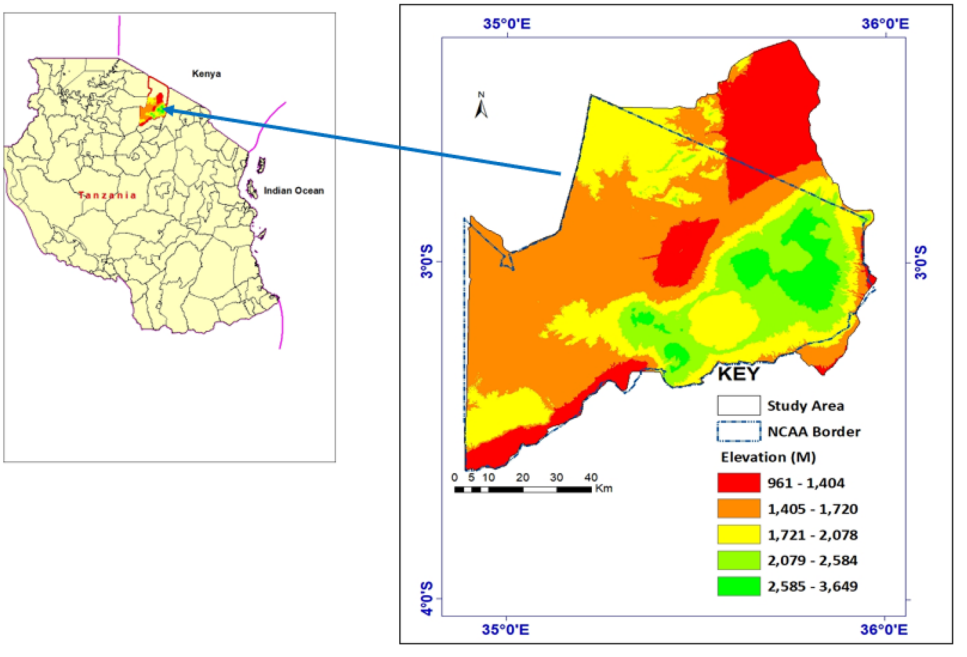

Figure 2. Map of the study area.

Table 2. Properties of landsat images used.

Year	Satellite	Sensor	Resolution	Path/row	Date of acquisition	% cloud cover
2003	Landsat 7	ETM	30	169/062	2003/02/04	0
2013	Landsat 8	OLI_TIRS	30	169/062	2013/09/03	8.08
2023	Landsat 8	OLI_TIRS	30	169/062	2023/03/07	0.02

Table 3. Description of land use land cover (LULC) types.

Land cover type/class	Description
Forest	This represents a continuous stand of trees, most of which grow to height of > 50 m, and it includes both planted forest and natural forest.
Grassland	It consists of an open area covered by tall and short grass.
Water	Includes lakes, rivers, streams, seasonal reservoirs, and ponds with NDVI < 0
Highland Grassland	Represent an area dominated by tall tussock grass species that are restricted to the high-altitude zones.
Cultivated land	Covered by plantation or fields of crop and fallow lands
Wetland/Riverine vegetation	The low-lying, uncultivated area usually is inundated with water for most of the year, marshes, swamps, peat, or bog.
Woodland	Represent an area with an assemblage of trees whose canopy ranges from 20% to 80% but rarely close many hectares entirely.
Scrub land	Mainly consist of vegetation that are multi-stemmed from one root base but do not grow more than 5 m tall nor have canopy cover >20%.

for three distinct time series: 2003–2013, 2013–2023, and 2003–2023. The analysis then calculated the corresponding percentages of losses and gains by utilizing pivot tables in Excel. This approach facilitated a systematic assessment of the temporal variations in land cover, enabling a clear identification of trends over the specified periods.

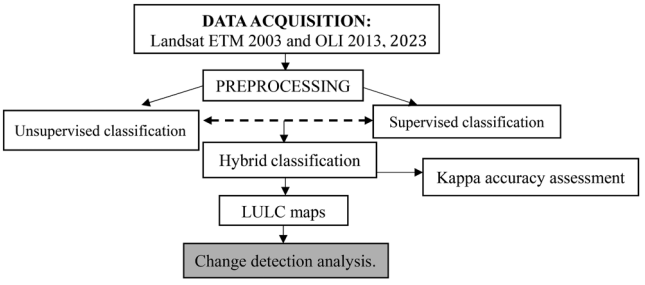

Figure 3. Analysis pathway.

Table 4. Losses and gains in land cover types in NCA between 2003 and 2023.

	2003–2013		2013–2023		2003–2023	
Land cover type	Ha	%	Ha	%	Ha	%
Cultivated Area (CA)	−3785	−0.392	10207	1.056	6422	0.665
Forest (FR)	−8919	−0.923	17918	1.855	8999	0.931
Grassland (GL)	27383	2.835	−13044	−1.350	14339	1.484
Highland Grassland (HG)	8360	0.865	2089	0.216	10449	1.082
Riverine Vegetation/Wetland (R/W)	−1865	−0.193	−2550	−0.264	−4415	−0.457
Scrubland (SL)	−87365	−9.044	110070	11.393	22705	2.350
Water (WA)	3551	0.368	−2218	−0.230	1333	0.138
Woodland (WL)	62740	6.495	−122473	−12.677	−59733	−6.183

5. Findings

The LULC analysis examined the NCA and its surrounding areas over a twenty-year period from 2003 to 2023. The results showed that the primary land cover types were grassland, which accounted for 49.7%, 52.6%, and 51.2% in 2003, 2013, and 2023, respectively, and shrubland, which covered 18.8% in 2023. Shrubland was particularly prevalent on the leeward sides, where pastoralism is the primary activity. Forests and highland grasslands dominated the Crater Highlands instead.

Table 4 presents the percentage gain or loss of each land use or land cover type in the past two decades; with negative values suggesting a loss while positive indicate a gain respectively. Specific findings revealed maximum gains in shrub land by 2.35% (22705 ha) and woodland loss by 6.183% (59733 ha). Other trends suggest a 1.5-point grassland increase between 2003 and 2023 (49.7% in 2003 to 51.2% in 2023), while woodland decreased from 15.3% to 9.1% in the same period. Interestingly, woodland experienced the highest loss (12.67%) in the last decade alone (2013–2023) most possibly as a result of the tourism expansion policy that demarcated 1500 km2 of disputed land in Loliondo and resumed the relocations of households to make way for elite tourism. Table 5 summarises the evolution of key land-realted policies and laws in Tanzania with effect in the Ngorongoro Area. Post-independence policies under Ujamaa socialism , promoted collective ownership and communal living as part of a broader vision for rural development and self-reliance. This era emphasized state-led land management and the integration of communities into planned villages, shaping early post-independence land governance. However, beginning in the 1980s, Tanzania shifted toward liberal market reforms, aligning with global neoliberal trends. These

Table 5. Evolution of land related policies in Tanzania with effect in the Ngorongoro Area (NCA).

Policy/law	Description
Pre-colonial Era	The control of land was vested in local groups—customary land tenure systems, characterized by the community ownership of land
Fauna Conservation Ordinance of 1951	This Act reinstated the Serengeti National Park (SENAPA) and residents' population relocated to NCA
NCA Ordinance of 1959	Establish NCA as a multi-use area to support wildlife and grazing of semi-nomadic Maasai who were resettled from the SENEPA
Independence and Socialism (1961 - 1980s)	After independence in 1961, Tanzania adopted a socialist development strategy through Ujamaa communities under President Julius Nyerere.
Ngorongoro Conservation Area Act No.14 of 1975	NCA Act aims at controlling entry into and residence within NCA
Market Reforms (1980s - 2000s)	In the 1980s, Tanzania began implementing economic reforms, shifting away from socialism towards a market-oriented economy.
National Land Policy of 1995	The policy emphasizes customary tenure systems and encourages community participation in decision-making.
National Rural Development Policy (1996)	Lay down the parameters for the Rural Development Strategy (RDS)
National Environmental Policy (1997; 2004)	Established framework for environmental management, creating the National Environmental Management Council (NEMC) and regional committees Policy—environmental pollution and land degradation.
Land Act of 1999	Established a framework for land management and regulation, recognizing diverse tenure systems, including customary rights.
Village Land Act of 1999	The Land Act categorizes land into different forms including public land, village land, and reserved land.
National Tourism Policy (1999 and 2008)	Seeks to support efforts, which promote the economy and livelihood of the people, essentially poverty alleviation
Forest Act of 1997, 2002	Governs forest management, conservation, and sustainable use of forest products, and community participation.
Wildlife Conservation Act of 2007 and 2009	Provides guidelines for establishing and managing national parks, game reserves, and wildlife zones, covering hunting, tourism, research, and endangered species conservation.
Land Use Planning Act No. 6 of 2007	Requires land uses to be organized in a planned fashion, with certain approvals from respective government authorities
Subsistence farming (2009)	Policy bans subsistence farming within of the NCA
Invasive species 2018	Invasive Alien Species Strategic management plan
Tourism strategy 2018	NCA Tourism Development Plan 2018/19–2022/23
Expansion policies 2013–2022	A policy to demarcating 1500 km^2 of disputed land in Loliondo and resume relocations of households to make way for elite tourism

Source: NCAA, 2018a.

reforms introduced new land, environmental, and tourism policies that emphasized sustainability, decentralization, and community participation, while opening opportunities for private investment. More recent policies reflect a shift toward exclusionary conservation and profit-driven (elite) tourism development through designated Strategic Plans. Bans on subsistence farming within the NCA, strategic tourism expansion plans, and controversial relocations of indigenous households to accommodate elite tourism interests have reignited debates over land rights and socio-environmental justice in the MLUM. These developments underscore the ongoing tensions between conservation imperatives and indigenous livelihoods, revealing the delegate balance between ecological protection and economic liberalization in a culturally and ecologically sensitive sites such as the UNESCO Biosphere Reserves (Masao, Makoba,& Sosovele (2015). (Table 5).

Table 6 land transitions from one cover type to another over the last two decades are summarised in Table 6. The diagonal values show areas that remain unchanged. The findings shows that the area under water remains largely unchanged (90.71%), followed by grassland (82.3%), forest (74.65%), cultivated area (35.10%), shrub land (24.83%), riverine and wetlands vegetation (23.62%), woodland (14.55%) and highland

Table 6. Transition matrix showing LULC change at NCA between 2003 and 2023.

Area (Ha)	LULC type	2023							
		CA	FR	GL	HG	RW	SL	WA	WL
2003	CA	9184.64	260.93	7857.94	72.28	75.48	5875.80	73.79	2762.96
	FR	1813.24	91447.95	797.54	104.88	221.46	20954.14	136.79	7026.45
	GL	1480.12	5924.84	395319.09	18214.48	394.79	44909.32	219.07	13856.17
	HG	298.18	3861.24	5226.68	467.37	28.15	4391.32	3.95	4922.74
	R/W	6.28	166.83	2108.08	564.58	2040.63	2896.70	772.56	82.91
	SL	5342.89	7156.87	66243.38	2987.66	42.70	39417.95	6.77	37550.84
	WA	67.20	5.87	82.72	12.30	21.60	76.89	2688.49	8.84
	WL	14387.86	22677.21	16963.95	7223.35	1407.27	62910.01	391.49	21441.65
(%)		**CA**	**FR**	**GL**	**HG**	**RW**	**SL**	**WA**	**WL**
2003	CA	35.10	1.00	30.03	0.28	0.29	22.46	0.28	10.56
	FR	1.48	74.65	0.65	0.09	0.18	17.11	0.11	5.74
	GL	0.31	1.23	82.30	3.79	0.08	9.35	0.05	2.88
	HG	1.55	20.11	27.22	2.43	0.15	22.87	0.02	25.64
	R/W	0.07	1.93	24.40	6.54	23.62	33.53	8.94	0.96
	SL	3.37	4.51	41.73	1.88	0.03	24.83	0.00	23.65
	WA	2.27	0.20	2.79	0.42	0.73	2.59	90.71	0.30
	WL	9.76	15.38	11.51	4.90	0.95	42.68	0.27	14.55

Table 7. Tourism facilities in NCA.

Category of tourists	Location	No. of tourism facility	Beds	Capacity occupancy revenue (25%)	Revenue Per bed	US$	No of employees per bed	Employees
International Tourists	Loliondo GCA	4	48	4,320	500	2,160,000	5	240
	Natron GCA	7	61	5,490	300	1,647,000	3	183
	Ngorongoro	25	535	48,150	400	19,260,000	4	2,140
	Total	**36**	**644**	**57,960**	**1200**	**23,067,000**	**12**	**2,563**
Local Travelers	Loliondo GCA	16	261	23,490	5.09	119,564	1	261
	Natron GCA	6	45	4,050	5.09	20,615	1	45
	Ngorongoro	4	38	3,420	5.09	17,408	1	38
	Total	**26**	**344**	**30,960**	**5.09**	**157,586**	**3**	**344**

Source: Adapted from Slootweg, 2017.

grassland (2.43%). Generally, water and grassland remain unchanged during the entire years of study. However, maximum transition occurred in highland grassland where it lost about 97.57% to grassland (27.22%), woodland (25.64%), shrub land (22.87%), forest (20.11%), cultivated area (1.55%), wetland (0.15%) and water (0.02%).

5.1. The interrelations between tourism, population density and LULCC

Slootweg (2017) presents a first record of the expansion of tourism facilities within NCA. In the duration of the twenty years studied, facilities have increased from 18 in 2003 to over 62 in 2023 and consequent increase in bed capacity to about 988 beds (See Table 7). Notably, tourism facilities have also emerged in other areas of tourism dispersal such as Loliondo and Oldupai. The number of lodges have increased from 3 in 1960 (Ndutu, Wildlife, and Rhino lodges) to 6 in 2018, whereas 12 permanent tented camps appeared by the end of 2018. Similarly, the number of campsites rose to 48 in 2018 (from 9 in the 1980s) further aggravating the ecological footprint associated to the specific type of accommodation (Figure 4).

The NCA is a prominent component of Tanzania's Northern safari circuit, alongside renowned destinations such as Serengeti and Tarangire National Parks. Together, these

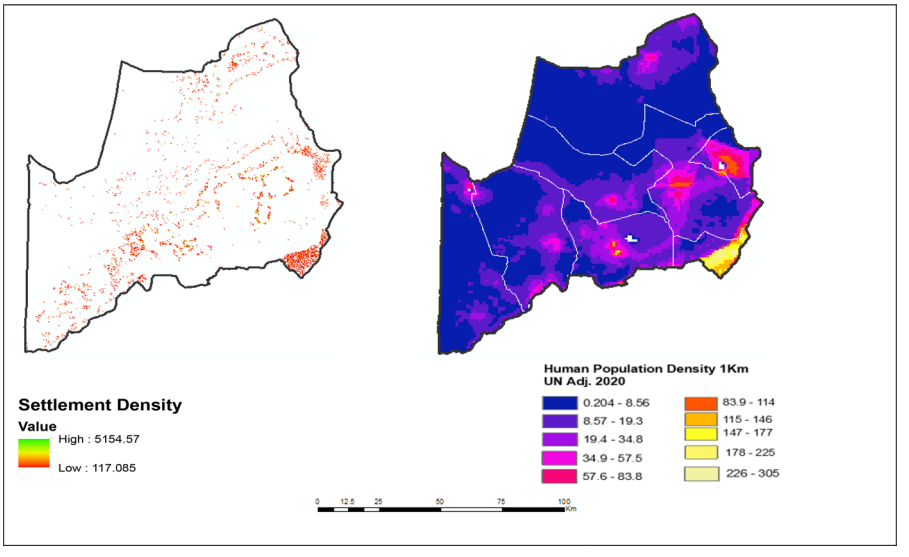

Figure 4. Settlement density along local population density maps.

Table 8. Tourist flows, local population and livestock in NCA.

Year	Tourists (arrivals)	Number of tourist vehicles	Local population	Livestock
1959	54518		8000	261,723
1966	54,935	–	8,700	–
1979	31,996	–	20,000	–
1989	140,000	–	–	–
1994	150,155	–	–	–
2000	210,257	–	60000	–
2007	359,259	–	64000	–
2010	523646	–	–	–
2014	611767	45,090	–	–
2015	567,990	33000	–	–
2016	600,349	36000	–	–
2017	640,466	56000	93136	809459
2018	680,514	73514	–	–
2019	725,535	–	–	–
2020	248,385	–	100,000	300,000
2021	327,112	–	–	–
2022	645,275	–	–	–

Livestock = Cattle, Sheep and goats.

attractions draw over half of the country's annual tourists' arrivals (NCAA, 2020). An analysis of the trends in tourism statistics in NCA over the past eight years shows a stable annual increase by 10% in tourist numbers with post-COVID recovery evident in the resurgence of tourism reaching 645,275 visitors in 2022. The major attraction in the area is the Ngorongoro Crater—a prominent geotouristic attraction in the NCA, renowned for its rich wildlife. Additionally, visitors are drawn to archaeological sites and museums in Olduvai Gorge—a 14 km long deep ravine showcasing the region's evolutionary history (Table 8).

Figure 5 illustrates the distribution of tourism facilities and infrastructure within the NCA and the ratio of tourism development to the land size in NCA. The results

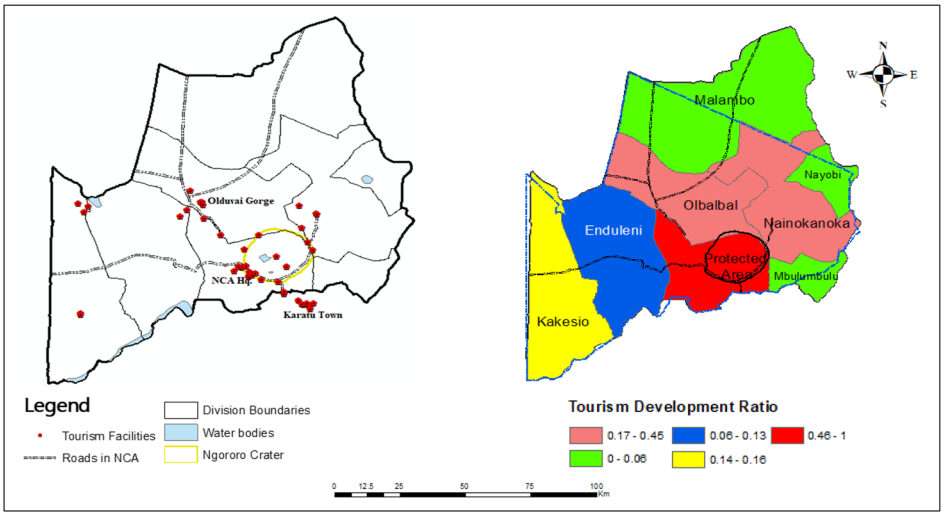

Figure 5. Distribution of tourism facilities and tourism development ratio in the NCA.

revealed that most tourism facilities are concentrated in the Ngorongoro Crater (0.46 to 1). This means over 46% of total tourism development in NCA is concentrated in the crater albeit the zone covering less than 5% of the NCA's total area. Other areas with high tourism development ratios include Olbalbal, particularly around Olduvai Gorge, which hosts archaeological footprints, museums, cultural bomas, camps, and Nainokanoka, with tourism development ratios ranging between 0.17 and 0.45. Conversely, certain divisions outside NCA such as Nayobi, Mbulumbulu, and Malambo, exhibit the lowest levels of tourism facilities and activities (Ratio 0 to 0.06).

Land cover changes have demonstrated a strong correlation with increasing human population. For instance, areas with high settlement and population density in the southeastern and eastern regions such as Mbulumbulu, Nainokanoka, Nayobi, and Malambo (Figure 5), predominantly exhibit land uses centered on crop cultivation and rangelands dominated by pastoralism. Similarly, intensive cultivation is evident in regions behind Embakai Crater, around Endulen, and along the slopes of the Ngorongoro Highlands, situated between the Crater and Serengeti National Park. The relationship between policy interventions and land use/land cover (LULC) changes appears inconsistent. For example, despite the implementation of policies aimed at prohibiting cultivation within the Ngorongoro Conservation Area (NCA), crop cultivation has paradoxically increased by 1.056% over the past decade (2013–2023), indicating potential challenges in enforcement or adherence to these regulations (Table 8).

Some areas of Ngorongoro Crater albeit dedicated for conservation and tourism zone has high human density of between 83 and 114 persons/km^2. Figure 6 illustrates the types of land use and land cover (LULC) along with the distribution of tourism facilities. The findings indicate that although tourism facilities were intended to be confined to specific zones, some have emerged in areas not designated for development, such as the crater rim. These facilities have altered land use and land cover types such as decline in highland grasslands (97.57%, and woodlands (85.78%).

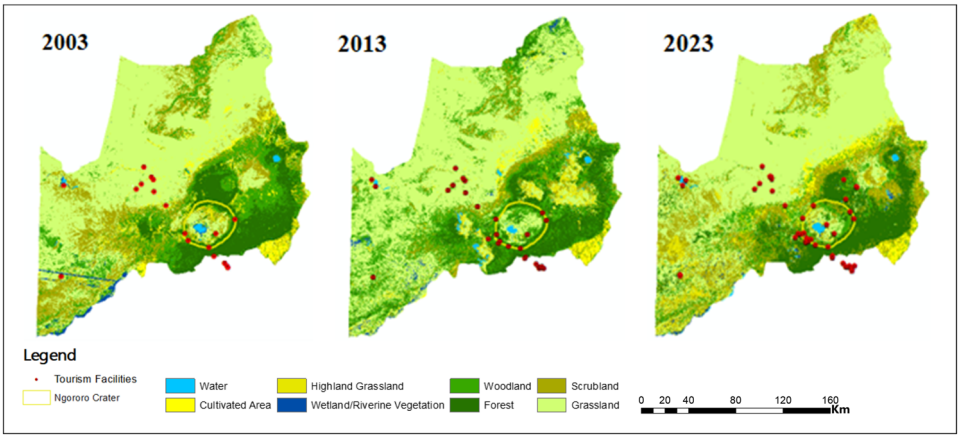

Figure 6. LULC maps and distribution of tourism facilities.

6. Discussion

6.1. Land use and land cover changes in the NCA Biosphere Reserve

The comprehensive LULC analysis reveals that grassland has remained the predominant land cover type throughout the entire study period, corroborating earlier findings by Niboye (2010). Transition analysis highlights that woodland experienced the most significant loss, whereas forest areas saw substantial growth between 2013 and 2023. Weldemichel (2022) ascribed these changes to the successful implementation of policies on subsistence agriculture and relocations, only showcasing the consequences of decisions might manifest many years later. Conversely, the degradation of highland grasslands is attributed to the frequent use of fires to enhance pasture quality and manage tick infestations (NCAA, 2011), a phenomenon which is still very prevalent and associated with the multiple uses of the site. Moreover, woody vegetation declined by over 12.7% from 2013 to 2023 primarily due to intense burns and wildfires. These events, common at the end of each dry season, inflict extensive long-term damage on woody vegetation in buffer zones (Mwabumba et al., 2022).

Recent studies indicate significant changes in the grassy vegetation of the crater floor, particularly in the southern and western regions, where it has become denser and taller compared to earlier observations (Kisingo et al., 2022). This increase is linked to the proliferation of the tall, stoloniferous grass—*Chloris gayana*. Ngondya and Munishi (2021) reported widespread infestation of the crater floor by invasive species such as *Gutenbergia cordifolia, Lantana camara*, and *Bidens schimperi*, which have displaced more palatable species like buffalo grass (*Eleusine jaegeri*). These invasive species have degraded forage quality, altered fire regimes, nutrient cycles, and the general ecology and habitats, affecting species such as the Black Rhino (Gadiye et al., 2016) and diminishing game viewing experience (Niboye, 2010). These iterative feedback loops demonstrate the dynamic and systemic nature of the biodiversity equilibrium and push the boundaries of the Biosphere's SES carrying capacity and resilience into new states whose rerilience needs to be further examined. Figure 6 summarises the evolution of LULC as a result of ongoing land use policies and tourism

development. Other than the transitions between woodlands, grasslands and cultivated areas challenging the ecosystem values and services, the obvious expansion of tourism development outside of the Crater area raises concerns around the expansion and intensity of the impact zone in the years to come.

Systems thinking within MLUMs is about collaborative schemes of governance. Despite the National Land Policy of 1995 emphasizing customary land tenure systems and promoting active local community involvement in land use practices, its ineffective implementation led to the enactment of the Land Act of 1999 (Boone et al., 2006). This Act defined the rights and responsibilities of private landowners in land use practices. However, increasing human populations and agricultural activities necessitated the banning of subsistence agriculture in 1999 and the implementation of expansion policies in 2013, resulting in relocations, suggesting once again the fragmentation of policy focus.

Initially, these policies led to a 0.923% (8919 ha) loss in forest cover, but from 2013 to 2023, forest areas experienced a significant gain of 1.855% (17918 ha). Conversely, crop land initially declined by 0.392% (2003–2013) but later increased by 1.056% (10207 ha) between 2013 and 2023, primarily at the expense of shrubland and woodland, which decreased by 20.21% and 2.87%, respectively. The expansion of agricultural fields reflects residents' increasing demands for resuming subsistence crop cultivation to achieve food self-sufficiency. This shift has heightened tensions between residents and conservation agencies (Masao et al., 2015). These trends align with Mwabumba et al. (2022), who reported significant gains in cultivated land, shrubland, and grassland, and notable declines in woodland areas.

6.2. Tourism development and land use and land cover changes in NCA

Over the past decade, the Ngorongoro Conservation Area has experienced a substantial increase in tourism volume and a diversification of tourism activities. These now include walking safaris, horseback riding, hot-air balloon rides, and geo-tourism, extending beyond traditional offerings (Twisa & Buchroithner, 2019). Systems thinking emphasizes the critical importance of integrative sustainable practices to mitigate the systemic pressure on fragile ecosystems within the SES absorbing and adaptive capacity. This is particularly crucial in densely populated areas within the NCA, such as Mbulumbulu, where settlement density reaches up to 117 houses per square kilometer, and human density ranges from 147 to 177 persons per square kilometer. The proliferation of tourism infrastructure in Ngorongoro Biosphere Reserve has been substantial, extending to unplanned sites such as crater rims and wildlife migratory corridors. Recent constructions, including the Belabela Lodge in the Western Corridor of the Msabi-Kirwaira area and the Melila Lodge in the Mbalageti Valley, exemplify this trend (Kyara et al., 2021; Masao et al., 2015).

These developments have induced significant land use and land cover changes, particularly the conversion of forests and woodlands into built environments. They have also exerted significant pressure on the environment, water resources, and waste management systems (Camilleri-Fenech et al., 2020). This transformation encompasses the establishment of administrative offices, road networks, airstrips (6), communication towers (10), recreational facilities, and accommodations and resurfacing of major roads

within the NCA against the recommendations from ICOMOS/IUCN advisory missions (ICOMOS/IUCN., 2017).

Adding to the complexity, tourism infrastructure is significantly concentrated within the Ngorongoro Crater, which, despite constituting less than 5% of the total area, hosts 46% of these facilities. This again only highlights the lack of integrative overview on system pressures. This disproportionate concentration strains the site's carrying capacity (Slootweg, 2017). Specific zones within the crater, such as the Hippo Pool and Ngoitokitok picnic site, which are critical habitats for species like the Black Rhino (*Diceros bicornis michaeli*), hippos, and various water birds often experience overcrowding. This overcrowding diminishes the quality of visitor experiences and can significantly strain the physical environment capacity of destinations (Tokarchuk et al., 2022). While the NCAA has implemented some ICOMOS/IUCN recommendations, such as imposing a high vehicle access fee (US$295) to limit the number of vehicles entering the crater, this strategy has not effectively reduced the influx of visitors and tour vehicles (NCAA, 2018a). UNESCO (2020) clearly identifies the absence of an integrated carrying capacity framework as a significant threat to the property's integrity. Yet, in the context of SES thinking, this finding highlights the need for a systemic framework of the absorptive capacity of the system changes and transitions to set benchmarks and guidelines for the limits of systemic acceptable change of the SES. Sustainable Intelligence can serve towards that direction (Lee et al., 2023). For instance, Gu and Jiang (2023) demonstrated that using technologies such as A* algorithms can provide optimal routes with shortest routes relative to environmental characteristics, and strong scalability to improve tourism carrying capacity, as seen in the Masai Mara National Reserve, Kenya. Additionally, models like the Zonation and Visitor Use Scheme in MMNR, which classify zones based on visitation statistics and ecosystem fragility, have proven successful in managing visitor impacts.

From a social perspective, the evictions within certain areas of this biosphere reserve have significantly disrupted the social fabric and pastoral economy, drawing condemnation from human rights activists regarding the proposed changes in the MLUM and the resettlement plan (Weldemichel, 2022). Proponents of these changes argue that they will aid in restoring previously degraded lands. The relocation plan, which aims to expand the NCA from 8,292 km^2 to 12,083 km^2, must strike a balance among community, conservation, and tourism development interests. Achieving this balance is crucial since improving conservation and tourism at the expense of community conditions is unlikely to yield the desired outcomes (NCAA, 2018b; Strzelecka et al., 2017). Furthermore, this imbalance contravenes UNESCO's criteria for integrity, which require that cultural values be adequately reflected in the SES values and services.

6.3. The effectiveness of the MLUM

The MLUM initially assumed that local communities would primarily engage in transhumance pastoralism as a means of conserving natural resources. However, this approach has encountered challenges due to the dynamic interactions among wildlife, human populations, and livestock, all of which compete for limited land resources (Veldhuis et al., 2019). The significant increase in human population—from

approximately 10,000 in 1959 to about 100,000 in 2020—and corresponding socio-economic activities have exacerbated conflicts with wildlife conservation interests (NCAA, 2020; Soszyński et al., 2018). This conflict is particularly evident in the hinterland areas, where agriculture is the predominant land use such as Lositete, Mbulumbulu, Kilimatembo, Rhotia, Marela, Tloma, Ayalabe, Kambi ya Simba, Slahamo, Kambi ya Nyoka, Oldeani, and Endamaghan villages in Karatu District, as well as Selela and Engaruka in Monduli District.

Over the last twenty years analysis, human activities have impacted the unique features and ecologically sensitive areas of NCA, contributing to biodiversity loss, putting in jeopardy the systemic integrity of the SES. Fyumagwa et al. (2007) linked changes in socio-ecology and livestock diseases to interactions between humans, livestock, and wildlife, where wild herbivores and domestic animals share parasites. To address tick infestations, prescribed burning of grasslands was reintroduced. Although the practice was successful in reducing tick infestation, it significantly altered land cover, with forbs and lush vegetation dominating the grasslands and affected the levels of land suitability for alternative uses.

Furthermore, the rising number of TLUs has intensified the competition for grazing and water resources (UNESCO, 2019). While the area covered by water remains unchanged, the increased competition for water resources between livestock and wildlife is likely to impact water catchment areas and wetlands overtime. Concurrently, the grassland declined and forbs dominate the landscape (Ngondya & Munishi, 2021). The degradation of grassland quality and restrictions on livestock access to specific zones like salt licks and pastures in the Northern Highland Forest Reserve, Empakaai, and Olmoti craters has contributed to reduction in TLUs (NCAA, 2020).

These SES transformations underline the delicate balance between biodiversity conservation and economic development and the importance of establishing a SES absorptive capacity framework to navigate the complex and uncertain transitions towards to a resilient Biosphere multi-use equilibrium. The theoretical contribution of this work lays in the evaluation of the effectiveness of the MLUM to systemically ensure a SES sustainability and resilience. Findings of this research highlighted the implementation gap of policy intentions to their outcomes over a twenty-year period, to demonstrate the necessity for coordinated, long-term strategies across the whole SES and its involved stakeholders. This affirms UNESCO (2019) recommendation of developing a strategic long-term land use plan to manage the expansion of cultivated lands and built-up areas sustainably by simultaneously considering the multi-dimensional feedback loops that transcend both the ecological and social system values and uses. On a managerial perspective, research findings can pave the way for the adoption of system thinking approaches in Biosphere management and for informed decision-making and policies that consider the long-term effectiveness and implications of interventions on the sustainability and resilience of the SES integrity.

7. Conclusions

This research aimed to examine the effectiveness of the MLUM in Biosphere Reserves, by assessing the last twenty years SES transitions in the Ngorongoro Biosphere Reserve. The research aim was established in the recognition of the considerable challenges

for the conservation efforts by ICOMOS/IUCN (2017) around the overlapping boundaries of zones within NCA. Abandoning the principle of human-wildlife coexistence would not only potentially reduce tourist numbers but also jeopardize the integrity of the Biosphere Reserves (Reed, 2019). Biosphere Reserves seem like constant experimentation areas of humanity's ability to harmoniously coexist with nature, aiming to scientifically enhance this relationship between people and their environment. The NCA, renowned as the cradle of humankind, holds significant cultural and scientific value, ranking sixth among tourist motivations (Melita & Authority, 2014). However, the increasing demands for natural resources by both tourists and growing resident population, along the behavioural shifts resulting from the societal and cultural modernization create a volatile threat mix for the sustainability of the MLUM (UNESCO, 2020).

Initially, the MLUM was structured around three primary pillars: conservation of natural resources, tourism development, and community development. However, the rapid growth in human population has exposed the model's inherent unsustainability, necessitating the exploration of alternative approaches. This includes expanding the biosphere reserve through relocations to Game Control Areas (GCA) such as Loliondo and Lake Natron GCA. Such relocations highlight the delicate balance required among conservation priorities, tourism development, and the interests of indigenous populations. Relocations have effectively promoted tourism and conservation objectives, but concerns remain over the rights and interests of indigenous communities, considering the NCA's designations as a UNESCO Biosphere Reserve, Geopark, and a Mixed natural and cultural heritage site. Proponents of relocations argue for establishing new restricted areas within conservation zones, aiming to prohibit local communities from activities such as grazing, settlement, and crop cultivation (Niboye, 2010). However, achieving a balance among these competing interests remains a significant challenge in the ongoing development of conservation and sustainable strategies within the NCA. The tension between conservation priorities, tourism development, and the socio-economic needs of indigenous communities underscores the complexity of managing the property while upholding the cultural and environmental integrity. Research findings clearly highlight the necessity of applying systems thinking in the context of managing MLUs systemic resilience and values. Policy interventions that addressed NCA concerns in isolation (e.g. bans in farming) only resolved challenges temporarily to exacerbate systemic impacts of food insecurity and tense relations between local communities and conservation authorities in the long term. Inconsistent and fragmented enforcement of regulations as a result of administrative imbalances and inefficiencies further hindered the effectiveness of the MLUM. The twenty-year data analysis allowed for a retrospective policy intervention (Table 8) impact assessment at different time scales. Findings only reiterate that importance of multi-stakeholder participation in the decision making to nurture a feeling of long-term commitment, trust and ownership of the SES as a whole. Systems thinking should be an integral part of MLUM to allow for the dynamic consideration and adaptation to the ever changing social, economic and environmental realities while calibrating the system's adaptive capacity through reinforcing and/or balancing feedback loops. This further highlights the necessity for integrative institutional capacity, consistent policy frameworks and long-term monitoring mechanisms that capture the effectiveness of all interventions.

The research recognises its limitations of the sole use of secondary (land data) to assess the effectiveness of the MLUM model. The twenty-year time-series analysis along the policy interventions in the NCA was deemed as a more credible method to assess the transitions of the SES of two decades. The attempt to complement the analysis with primary data on multiple stakeholders' perceptions and experiences around the overtime SES transitions and the acceptable boundaries in its absorptive capacity turned futile as it was obvious from the attempted interviews the incoherence in the understanding of the definitions of key terms such as change, sustainability and boundaries. Establishing a coherent and clear communication terminology across all involved stakeholders is paramount for the exploration of systemic approaches in political ecology. Even if this is beyond the focus of this current paper, it emerged as a key challenge in completing this study to its full extent. A follow up research that better contextualises these terms in the specifics of the Biosphere integrity will enable a more credible triangulation of the research findings and the establishment of a SES absorptive capacity framework. Current findings ensure that the NCA can serve as a good pilot to explore limits of acceptable change and system boundaries under the MLUM.

Notes

1. Earth resource observation system data centre (http://glovis.usgs.gov).
2. MIT Libraries https://libguides.mit.edu/gis/world.
3. From WGS 1984 to UTM Zone 36.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Alfayo Koskei, born and raised in Kenya, commenced his career as a researcher and educator in 2016. Since then, he has contributed to publication in fields of tourism, remote sensing, and conservation biology. Notably, he has contributed to a book chapter in Tropical Forests and contributed to peer review process for the Asian Journal of Geological Research.

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Appendix 1. Accuracy assessment

	2003		2013		2023	
LULC TYPE	UA	PA	UA	PA	UA	PA
Water (WA)	100	100	91	100	100	88
Cultivated area (CA)	82.3	100	100	92.3	93.3	100
Highland Grassland (HG)	100	100	89	100	86	100
Riverine/Wetland vegetation (RW)	100	100	100	89	100	100
Woodland (WL)	86	100	95.5	91.3	100	100
Forest (FR)	100	92.3	100	100	100	100
Scrublands (SL)	100	100	100	100	100	94
Grassland (GL)	100	84	95.45	100	96	96
Overall	**95**		**96**		**97**	
Kappa	**0.94**		**0.95**		**0.96**	