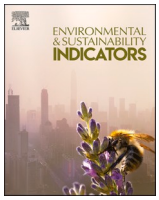
Environmental and Sustainability Indicators 32 (2026) 101614



Contents lists available at ScienceDirect

Environmental and Sustainability Indicators

journal homepage: www.sciencedirect.com/journal/environmental-and-sustainability-indicators



Designing regenerative landscapes: Using spatial indicators to diagnose landscape reorganization under alternative policies and management

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ARTICLE INFO

Keywords:
Sustainability indicators
Landscape configuration
Functional adjacency
Land tenure
Regenerative planning
Spatial modeling

ABSTRACT

Multifunctional arid and semi-arid landscapes are increasingly stressed by climate variability interacting with long-standing land use change and shifting land tenure systems, reshaping landscape structure, altering resilience and diminishing regenerative capacity. These dynamics create an urgent need for sustainability indicators that capture how alternative policy and management pathways reorganize spatial patterns linked to resilience and multifunctionality. We apply a spatially explicit scenario framework to evaluate configuration-based landscape indicators across contrasting land tenure regimes (group ranch governance versus privatization) and regenerative land management strategies in a multifunctional dryland landscape in southern Kenya. We quantify indicators of landscape heterogeneity, forest fragmentation, and functional adjacency (cropland-forest and rangeland-forest proximity) to diagnose how interventions reorganize spatial structure relevant to regenerative processes. Results show that land tenure regime alone exerts strong control over baseline configuration indicators, with group ranch governance associated with higher landscape heterogeneity and connectivity than privatization. Regenerative management strategies systematically improve configuration indicators; however, their magnitude and expression vary by tenure context. Strategies prioritizing small forest patch conservation and targeted water access yield the largest gains in adjacency-based and heterogeneity indicators, particularly under group ranch tenure, while bundled, multi-component interventions produce modest or offsetting effects. These findings demonstrate the utility of landscape configuration indicators as a decision-relevant lens for evaluating regenerative pathways and reveal that tenure context conditions the magnitude of indicator responses to spatial management strategies. The indicator-based framework supports tenure-sensitive planning and monitoring by treating configuration-based indicators as diagnostic signals of regenerative potential, rather than direct measures of regenerative outcomes.

1. Introduction

Arid and Semi-Arid Landscapes (ASALs) globally, face intensifying climate-related stressors including more frequent and prolonged droughts, heightened rainfall variability, and interacting hydroclimatic extremes that erode ecological stability and threaten long-term productivity (Ning et al., 2024; IPCC, 2023; Barthwal et al., 2025; Hoover et al., 2022). These multifunctional landscapes support diverse pastoral and smallholder livelihoods, biodiversity conservation, and a range of ecosystem services, making their integrity essential for climate-resilient futures (Estrada-Carmona et al., 2024; Schilling and Werland, 2023; IPCC, 2022). Yet, decades of land use change and evolving governance, have progressively reshaped landscape structure (replacing complex, heterogeneous land use mosaics with increasingly simplified and disconnected patterns), thereby diminishing resilience and regenerative capacity of social ecological systems (SES) (Peng et al., 2025). In Kenya, the increasing vulnerability of ASAL systems has elevated the importance of coordinated, landscape-based adaptation:

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https://doi.org/10.1016/j.indic.2026.101614
Received 10 June 2026; Received in revised form 8 October 2026; Accepted 28 October 2026
Available online 3 November 2026
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the national adaptation plan prioritizes climate-resilient water infrastructure to support pastoral livelihoods during droughts (Government of Kenya, 2016), while national conservation strategies emphasize protecting wildlife corridors and dispersal areas across mixed land tenure landscapes where most wildlife ranges outside protected areas (Ministry of Tourism and Wildlife, 2018). These national priorities underscore the need to manage spatial pattern (heterogeneity, connectivity, and cross-scale linkages) across human-dominated mosaics, and engage place-based, participatory scenario planning to navigate trade-offs under environmental uncertainty (Zandlová et al., 2023; Jennings et al., 2020). This approach is increasingly recognized as essential for sustaining SES resilience and regenerative pathways in ASALs.

While landscape-scale planning is increasingly recognized as essential for sustaining multifunctionality and resilience under climate change, existing sustainability indicator frameworks remain limited in their ability to diagnose how regenerative capacity emerges from spatial structure. Most widely used indicators emphasize land-cover extent, vegetation condition, or aggregated ecosystem service supply, but typically underrepresent landscape configuration, including the spatial arrangement, fragmentation, and adjacency of land uses that regulate ecological flows and adaptive responses (Xi et al., 2024; Lavorel et al., 2022). Recent syntheses in landscape sustainability science highlight that heterogeneity, connectivity, and cross-scale linkages remain persistently under integrated in sustainability assessments, despite their central role in landscape multifunctionality and resilience (Qiu et al., 2025; Dade et al., 2025). This limitation is particularly consequential in arid and semi-arid landscapes, where fine-scale spatial relationships such as proximity to remnant vegetation or water access can disproportionately influence buffering capacity, refugia provision, and livelihood resilience under climate stress (Richards et al., 2024; Jay and Plieninger, 2025). Addressing this gap requires configuration-based indicators that explicitly capture fragmentation, connectivity, and functional adjacency as diagnostic signals for sustainability planning and monitoring. What remains underdeveloped are indicators that translate spatial reorganization into interpretable, policy-relevant diagnostics of regenerative capacity.

Landscape pattern (the composition, heterogeneity, configuration, and connectivity of land uses) (Turner and Gardner, 2015) organizes the flows of organisms, energy, water, and information that collectively produce ecosystem multifunctionality and condition system resilience at landscape scales (Jay and Plieninger, 2025; Mitchell et al., 2013; Field and Parrott, 2022; Cumming, 2011; Tscharntke et al., 2012). In multifunctional landscapes, spatial pattern shapes bundles of landscape services and their trade-offs (Yao and Yang, 2025; Chen et al., 2023; Zhou et al., 2025). Consequently, conservation and restoration strategies increasingly target landscape-level multifunctionality rather than single outcomes (Jay and Plieninger, 2025). Heterogeneous, well-connected mosaics foster complementary niches and cross-habitat spillovers (e.g., pollination, pest regulation, water regulation), creating cross-scale buffering effects that stabilize multiple functions through time (Tscharntke et al., 2012). These pattern-process linkages scale up to resilience. That is, SES are more likely to absorb disturbance and reorganize without losing identity when they exhibit appropriate diversity, redundancy, modularity, and cross-scale connectivity (Folke, 2016; Folke et al., 2010).

Practically, this means that designing for multifunctionality and resilience in ASALs hinges on retaining or restoring spatial heterogeneity and functional connectivity (while avoiding homogenization and fragmentation). Biodiverse communities support multiple ecosystem functions through species complementarity and response diversity (Lefcheck et al., 2015; Li et al., 2024; Neyret et al., 2023). For example, a global meta-analysis of grazed grasslands found that higher plant diversity can buffer grazing-induced losses in multifunctionality, especially in dry climates (Zhang et al., 2022). At the landscape scale, spatial configuration including the size, shape, and arrangement of patches (and the corridors that connect them) modulate synergies and trade-offs among services. Connectivity and core areas often strengthen service bundles, whereas fragmentation and isolation degrade them (Field and Parrott, 2022; Karimi et al., 2021). Connected landscapes also enhance resilience by enabling species movement, adaptive responses to disturbances and the maintenance of ecological networks (Brennan et al., 1979). Conversely, fragmentation often produces trade-offs where provisioning gains (e.g., intensive agriculture) undermine regulating and cultural services and increase disservices such as pests and diseases, reducing overall resilience (Haddad et al., 2015; Li and Carter, 2025). Therefore, planning for connectivity, while accounting for spatial interactions and trade-offs, is critical for sustaining ecosystem services and long-term resilience in multifunctional landscapes under accelerating climate and land use pressures.

Translating the importance of heterogeneity and connectivity into actionable planning insights requires exploring how alternative interventions reorganize landscape patterns under realistic policy contexts. Our previously calibrated spatially explicit land-use model for Narok County, southern Kenya, captures context-specific transitions shaped by policy, spatial adjacency, and biophysical gradients (Kotikot et al., 2026). In this study, we use this model (Land Change Modeler, LCM) as the basis for our scenario simulations. The model captures the volatile dynamics typical of arid multifunctional landscapes, such as opportunistic, reversible shifts in humid-arid ecotones tied to wet and dry years and fluid forest-cropland interfaces influenced by rising demand for arable land. These insights help structure scenarios that contrast tenure regimes, neighborhood effects, and climate stressors, and guide the allocation of interventions to the subregions and transition zones where they are most needed. Spatially explicit land use modeling therefore offers a powerful heuristic approach for exploring alternative futures and testing the consequences of potential interventions on landscape pattern. This allows diagnosis of how different configurations of land use might enhance or erode a system's regenerative capacity (Beller et al., 2019; Smithwick et al., 2023). By linking spatial patterns to indicators of social-ecological resilience, this approach helps illuminate pathways toward landscapes that can sustain ecological function while supporting human livelihoods under increasing environmental stress. Taken together, these capabilities position spatially explicit land-use modeling as a practical framework for diagnosing how alternative configurations influence regenerative capacity through measurable spatial indicators.

Leveraging this diagnostic approach, we apply our calibrated model within a scenario framework to explore how alternative land policy and management strategies reshape spatial configuration and functional adjacencies in human-dominated multifunctional ASALs. Our goal is to identify the policy and management combinations that most strongly shift configuration indicators toward states associated with regenerative potential. We address three research questions: 1) How do contrasting land tenure regimes (group ranching vs. privatization) influence long-term landscape configuration and functional adjacencies? We hypothesize that privatization will consolidate cropland and reduce small forest patches, producing more homogenized landscapes, whereas group ranch tenure will maintain more heterogeneous mosaics and stronger connectivity. 2) How do regenerative management strategies (small versus large forest patch conservation, enhanced connectivity corridors, and strategic water-pan placement) modify spatial configuration and functional adjacencies when implemented under contrasting land tenure regimes? We hypothesize that the effects of regenerative management strategies on spatial configuration and functional adjacencies will vary systematically by land tenure regime, with strategies producing larger increases in landscape heterogeneity, connectivity, and functional adjacencies under group ranch tenure than under privatization. 3) How do combined policy and management strategies compare in their ability to enhance regenerative landscape processes? We hypothesize that integrating supportive tenure contexts with targeted regenerative strategies will yield the largest gains in heterogeneity, connectivity, and

adjacency-mediated functions, outperforming policy or management interventions applied independently. The study demonstrates the utility of spatial modeling tools as an effective approach for guiding coordinated, place-based strategies for sustainable land management in ASALs. Ultimately, the research contributes to a deeper understanding of how spatial design and policy integration can foster resilient and regenerative futures in climate-vulnerable landscapes.

1.1. Conceptual framework: indicators of regenerative capacity

This study is grounded in a conceptual framework that positions landscape configuration as the key intermediary through which policy and management interventions influence regenerative landscape processes (Fig. 1). The framework distinguishes between interventions (e.g., tenure policies, forest patch conservation, connectivity enhancement, and water-pan placement), configuration outcomes (measurable spatial pattern states), and regenerative processes (landscape services) supported by those configurations.

Within this framework, spatial metrics serve as operational indicators of how interventions reorganize landscape structure, capturing shifts toward distinct configuration states. These include heterogeneous mosaics characterized by high edge density arising from small patch retention; increased cross-habitat adjacency reflecting closer spatial coupling of land uses; permeable networks produced by enhanced connectivity; enlarged core areas associated with larger forest patches; localized resource nodes emerging from improved water access; and diversified microhabitats resulting from greater landscape heterogeneity.

These configuration states are theorized to mediate regenerative processes (and landscape services) by shaping the flows of organisms, resources, and energy across the landscape. Such processes include edge-mediated functions (e.g., pollination, pest regulation, microclimate buffering), refugia provision (e.g., emergency forage, wildlife shelter, seed banks), agroforestry-related productivity gains (soil fertility, shade moderation, yield stability), connectivity-dependent processes (wildlife movement, gene flow, pastoral mobility), and broader ecosystem-regulating services such as water retention, erosion reduction, and carbon storage. By explicitly linking interventions, configuration states, and regenerative processes, this conceptual framework provides the analytical foundation for evaluating how alternative policy and management strategies shape regenerative capacity in multifunctional landscapes.

2. Materials and methods

2.1. Study area characteristics

The study focuses on Narok County in southern Kenya, a region emblematic of the socio-ecological complexity found across ASALs globally. Situated along sharp ecological gradients, from humid, crop-suitable highlands to arid and semi-arid rangelands, Narok is a highly diverse and multifunctional landscape, supporting intertwined pastoral, agropastoral, and farming livelihoods (Kotikot et al., 2025a). Narok concentrates climate-sensitive livelihoods and ecosystem services, making it a bellwether for resilience and regeneration challenges in the region. Its land system mirrors broader policy transitions in sub-Saharan African rangelands, characterized by colonial land use legacies, including shifts from communal tenure to group ranches and subsequent privatization that drove cropland expansion, fencing, and rangeland/forest fragmentation (Thompson et al., 2009). These governance legacies interact with intensifying ecological pressures, most notably increasingly erratic rainfall (Palmer et al., 2023; Kotikot et al., 2024) to reshape landscape patterns and productivity in ways that are highly localized yet regionally representative of sub-Saharan African drylands (Kotikot et al., 2025a). Narok's diversity of land uses, tenure regimes, and climate stresses provides a powerful and regionally representative setting for modeling regenerative pathways under accelerating environmental stressors (Oteros-Rozas et al., 2015). Its juxtaposition of fragmented privatized parcels, degraded rangelands, wildlife corridors, and integrative conservancy landscapes presents distinct spatial regimes that allow testing how land policy and management strategies can promote patterns that enhance regenerative landscape processes.

2.2. Data sources and preprocessing

Water pans: To develop a comprehensive dataset of existing water pans, we integrated two complementary data sources: georeferenced water pan locations (1800) downloaded from OpenStreetMap and additional points (215) collected through systematic field observations. Before combining the two datasets, we performed a manual assessment of the OpenStreeMap dataset through Google Earth to verify the existence of the water pans. The merged dataset provided a reliable baseline for assessing current water access across the landscape. Building on this inventory, we applied a spatial multi-criteria siting framework to identify potential locations for additional water pans within arid and semi-arid zones, where water scarcity is most acute and demand for multi-sectoral water use is high. Candidate locations were restricted to areas characterized by clay/silt soils and gently sloping terrain (<25% slope),

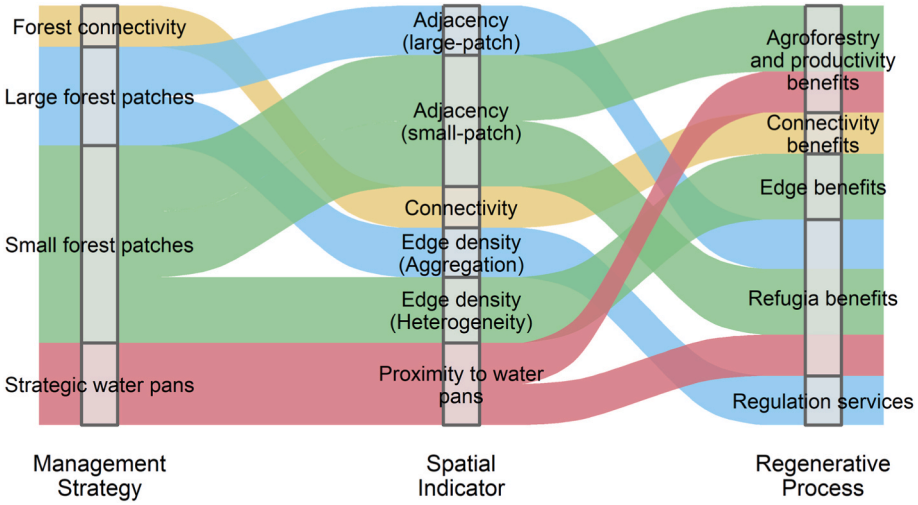


Fig. 1. Conceptual pathways linking management strategies, spatial indicators, and regenerative landscape processes (landscape services).

while forested areas were excluded to avoid ecological disturbance and construction challenges. To promote efficient spatial distribution and avoid redundancy, a minimum distance of 2 km from any existing water pan was enforced. To assign specific locations for proposed water pans, we employed a random spatial allocation procedure that distributed 500 point locations across the delineated suitable areas while ensuring that locations were at least 2 km apart to avoid redundancy. In addition to maximizing utility for livestock and wildlife, the selection process also incorporated considerations for community needs (near human settlement), prioritizing locations capable of supporting livelihood diversification, including small-scale irrigation and other water-dependent activities. Collectively, this approach ensured that newly proposed water pans align with ecological suitability, socio-economic priorities, and broader landscape-level resource management objectives.

Spatial policy map: To construct the policy dataset, we developed a harmonized policy map by merging digitized land tenure segments from Wales & Chabari (Wales and Chabari, 1979) with additional spatial layers obtained from the Maasai Mara Wildlife Conservancies Association (MMWCA) website, producing a consolidated representation of land administration boundaries. Because historical land use policy in the region has been highly dynamic, with tenure arrangements shifting considerably over time (Kotikot et al., 2025b), the resulting map reflects tenure conditions during a specific historical window rather than an unchanging baseline. Drawing on literature documenting long-term policy transitions in rangeland management and Maasai land adjudication (Santini, 2025; Seno and Shaw, 2002), the combined dataset was subsequently adjusted to approximate a snapshot of the tenure structure for the period 2000-2010, ensuring consistency with the era most relevant to the broader analysis. Furthermore, available records indicate that the only major tenure changes between 2000 and 2020 involved the establishment of new wildlife conservancies, allowing the policy map to be interpreted as a stable foundation for understanding land use governance throughout this period.

To further account for the influence of long-term policy transitions on contemporary land use patterns, we incorporated historical policy categories into the dataset to distinguish areas with different tenure trajectories. Specifically, we identified and mapped zones that were historically organized as group ranches but have since transitioned to private ownership (Fig. 2a - historical group ranch), differentiating them from areas that were historically private and have remained private (Fig. 2a - private). This categorization allowed us to capture path-dependent effects of past policy regimes, particularly the breakup of group ranches on current land configuration. By explicitly encoding these historical tenure shifts within the policy map, the dataset not only represents the spatial distribution of land tenure during the 2000-2010 reference period but also provides a basis for evaluating how legacy policy decisions continue to shape ecological and socio-economic outcomes across the landscape.

2.3. Methodology

We implement scenario modeling to explore how management strategies under contrasting land tenure regimes reorganize landscape configuration. We utilize the TerrSet Land Change Modeler (LCM) previously calibrated for Narok in our earlier work, and which achieved ~83% overall correctness against the 2018 reference map (Kotikot et al., 2026). Briefly, in the LCM, land use transition potentials were estimated with multilayer perceptron sub-models defined per dominant transition (e.g., forest-cropland, rangeland-cropland) and trained on predetermined drivers of land use change. Predicted quantities of change are derived via a Markov chain process, then allocated through a competitive land-allocation routine with spatial constraints to limit unpermitted transitions. Additional model information relevant to the present analysis is provided in Appendix A.1. For full details of model development, calibration, validation, and sensitivity assessment, refer to Kotikot et al. (2026). In the current analysis, scenarios are encoded by adjusting (i) demand (expected class proportions) and (ii) spatial allocation multipliers that represent policy/management rules (e.g., group ranch vs. privatization; small-patch conservation, connectivity corridors, strategic water pans).

2.3.1. Scenario design

To explore configuration outcomes, we developed scenarios based on two interacting dimensions: land policy and regenerative management strategies (Table 1). Land policy was represented by two contrasting approaches: (i) a model emphasizing group ownership and (ii) a model characterized by increasing privatization. Regenerative strategies were modeled as either absent (no regenerative strategies, reflecting limited adaptation) or present (with regenerative strategies, reflecting climate adaptation through spatial adjacencies, and improved access to water). Combining these dimensions yielded four distinct scenarios: Scenario 1 (group ranch policy without regenerative strategies), Scenario 2 (privatization policy without regenerative strategies), Scenario 3 (group ranch policy with regenerative strategies), and Scenario 4 (privatization policy with regenerative strategies). Each scenario was used to parameterize land use models to assess how management interventions under contrasting tenure influence spatial configuration.

2.3.2. Baseline tenure context and divergent tenure pathways

Baseline conditions reflect the contemporary mosaic of land tenure arrangements in the study area (Fig. 2a). This baseline tenure configuration serves as the reference against which alternative tenure pathways are evaluated. To examine how divergent tenure structures condition landscape outcomes, we constructed contrasting scenarios that reorganize this baseline into simplified, policy-relevant tenure regimes.

Under Scenario 1 (Group Ranch Governance), all areas historically designated as group ranches remain under collective ownership, while historically private lands retain private tenure (Fig. 2b). This scenario represents the persistence of group ranch governance structures. Based on documented land use patterns associated with group ranch tenure,

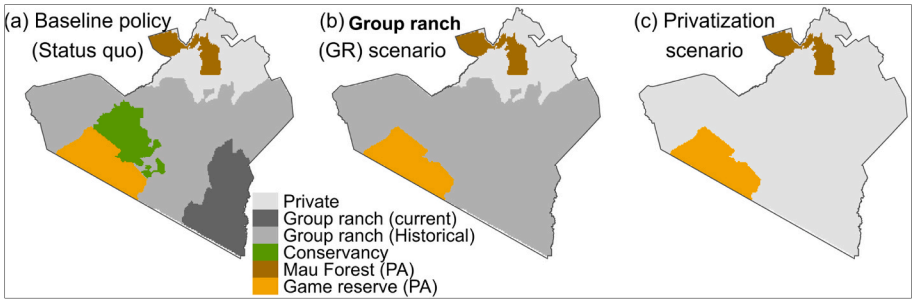


Fig. 2. Spatial policy maps representing a) current land policy (baseline scenario), b) policies as modeled under the group ranch scenario, and c) privatization scenario.

Table 1
Scenario design for land-use simulations. Columns indicate the land-tenure regime (Group ranch vs. Privatization) and rows the management strategy. Scenarios 1 and 2 apply tenure rules only; Scenarios 3 and 4 add one of six regenerative interventions (a–f), each implemented identically under both tenure regimes, yielding 14 alternative scenario simulations in addition to the Baseline prediction.

	Management strategy	Spatial intervention	Intended configuration response	Group ranch (GR)	Privatization (PR)
No regenerative strategies	No regenerative strategies	No additional spatial management rule	Tenure-driven configuration only	**Scenario 1 (S1)**	**Scenario 2 (S2)**
Regenerative strategies	(a) Small forest patches	Increased persistence of small forest patches	Fine-scale heterogeneity, cross-habitat adjacency	**S3a**	**S4a**
	(b) Large forest patches	Increased persistence of large forest patches	Forest core area; reduced internal fragmentation	**S3b**	**S4b**
	(c) Forest connections	Forest persistence/establishment in connectivity-priority locations	Structural connectivity; network permeability	**S3c**	**S4c**
	(d) Strategic water pans	Addition of water-access nodes in suitable locations	Resource proximity and local land-use adjacency	**S3d**	**S4d**
	(e) All forest strategies	Joint implementation of (a) + (b) + (c)	Combined forest-configuration effects	**S3e**	**S4e**
	(f) All strategies combined	Joint implementation of (a) + (b) + (c) + (d)	Combined forest and water-access effects	**S3f**	**S4f**

this scenario is expected to constrain cropland expansion within group ranches, reflecting restrictions on cultivation, while allowing greater forest-rangeland flexibility relative to the baseline. In contrast, cropland expansion is expected to remain concentrated in private lands. Under Scenario 2 (Privatization), all unprotected land is assumed to be privately owned, representing landscape-wide consolidation of individual tenure (Fig. 2c). Relative to the baseline, this policy is expected to promote broader cropland expansion and higher rates of forest-to-cropland conversion. These tenure-specific expectations informed scenario-specific adjustments to land use demand and transition probabilities, enabling assessment of how alternative tenure structures condition spatial configuration indicators.

2.3.3. *Regenerative management strategies as spatial interventions*

Under scenarios incorporating regenerative strategies (Scenarios 3 and 4 - Table 1), we operationalized management actions as spatial interventions designed to reorganize landscape configuration, consistent with the conceptual framework that positions configuration as the intermediary between intervention and regenerative processes (Fig. 3). These interventions target specific configuration states through three mechanisms: (i) modification of forest patch size distributions to alter edge density and fine-scale heterogeneity, (ii) enhancement of structural connectivity among forest patches to increase network permeability, and (iii) introduction of localized water-access nodes to reorganize land-use proximity and adjacency. Each strategy was implemented under the two contrasting tenure regimes, allowing assessment of how tenure conditions the spatial expression of interventions.

2.3.4. *Forest-patch conservation and connectivity interventions*

Forest-based strategies were encoded as spatial rules that directly alter patch size distributions, adjacency relationships, and connectivity structure. Separate interventions prioritized the retention of small forest patches, the stabilization of large forest patches, or the creation of new forest cover in strategic locations to enhance connectivity among existing patches. Small-patch interventions were intended to increase the density and dispersion of forest edges, thereby increasing cross-habitat adjacency and landscape heterogeneity. Large-patch interventions were designed to maintain or expand forest core areas while reducing internal fragmentation. Connectivity interventions targeted narrow gaps between patches by increasing the likelihood of forest persistence or establishment within low-cost corridor candidates, thereby reducing patch isolation and increasing network permeability. To facilitate the specification of these forest-based strategies, we conducted a forest connectivity analysis following the approaches described under Appendix A.2.

Within the Land Change Modeler, these interventions were implemented by modifying baseline transition potentials to (i) reduce the probability of forest loss in patches belonging to specified size classes and (ii) increase the probability of transitions to forest in spatial locations identified as important for enhancing structural connectivity. Together, these rules translate management intent into explicit configuration outcomes including changes in adjacency, edge density, aggregation, and connectivity, that are subsequently diagnosed using configuration-based indicators.

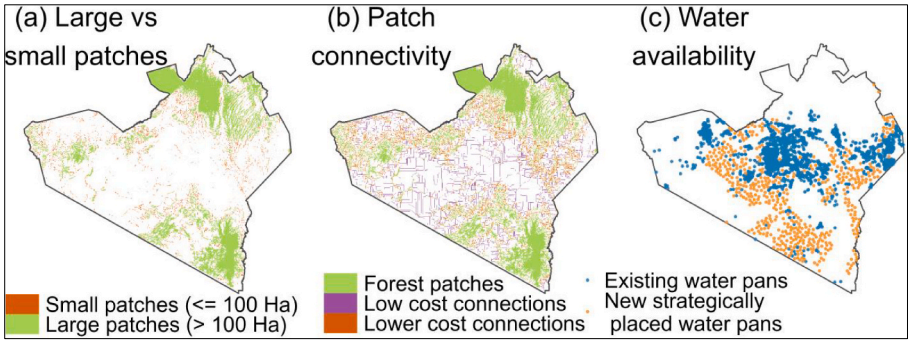


Fig. 3. Regenerative strategy layers used to parameterize scenarios. (a) Large vs. small forest patches. (b) Forest patch connectivity. Existing forest patches (green) with candidate least-cost linkages forming a corridor network between patches. (c) Increased water access through strategic location of water pans. Existing water pans (blue) and new strategically placed water pans (orange) as sited following a suitability analysis.

2.3.5. Water-pan placement as a spatial reorganization of resource proximity

Water access interventions were implemented as localized spatial inputs designed to modify proximity relationships and adjacency patterns across rangeland and agricultural areas. Rather than representing water availability as a scalar variable, water pans were treated as discrete resource nodes capable of reorganizing land use decisions and spatial coupling among land uses. New water-pan locations were strategically distributed across arid zones to avoid excessive clustering and to minimize degradation risks associated with localized overuse.

In the model, water-pan placement was incorporated by adjusting transition probabilities in surrounding areas, increasing the likelihood of forest persistence or establishment near water points, and facilitating irrigation where suitable. These rules were not intended to predict specific livelihoods or production outcomes but to generate configuration states characterized by increased forest adjacency, localized heterogeneity, and altered resource proximity. The resulting spatial patterns allow evaluation of how water infrastructure interventions interact with tenure context to reshape adjacency-based indicators and other configuration metrics central to regenerative capacity.

2.4. Indicators as diagnostics of configuration outcomes

Consistent with the conceptual framework (Fig. 1), this study treats landscape configuration as the intermediary through which policy and management interventions shape regenerative landscape processes. Each management strategy is designed to reorganize specific aspects of landscape configuration such as patch size distributions, cross-habitat coupling, network permeability, and access to localized resource nodes. Accordingly, we operationalize configuration outcomes using spatial indicators that capture how interventions reorganize heterogeneity, adjacency, connectivity, and access to critical resource nodes under contrasting tenure contexts.

Functional adjacency serves as a key indicator of how management strategies reorganize spatial coupling among land uses targeted by forest patch and water access interventions. It captures the extent to which cropland and rangeland are positioned in proximity to forest patches such that recurring edge-mediated functions, refugia provision, and agroecological spillovers can occur.

We operationalize adjacency using two spatial indicators. First, the proportion of cropland with $\geq$10% forest cover within a 500 m neighborhood represents functional proximity sufficient to support pollination services, microclimate buffering, and soil retention benefits. Second, the proportion of rangeland occurring within 500 m of a forest patch captures the potential for refugia provision and forage-related spillover functions relevant to pastoral systems. Together, these indicators translate the concept of spatial coupling into measurable configuration states.

Complementary indicators characterize related configuration outcomes, including forest network permeability (connectivity), proximity to water pans as localized resource nodes, and landscape-level heterogeneity and aggregation/fragmentation, quantified using landscape- and class-level edge density metrics calculated with the *landscapemetrics* (Hesselbarth et al., 2019) package in R.

Together, these indicators capture shifts toward configuration states theorized in the framework, such as increased cross-habitat adjacency, diversified microhabitats, and enhanced refugia potential. Because all indicators are empirically measurable and applied consistently across scenarios, they enable comparison of how alternative intervention pathways translate into regenerative capacity through spatial structure.

2.5. Spatial modeling implementation

In the model, we specified scenarios by adjusting two key components: land use demand and spatial allocation of land use transitions. These adjustments were made to ensure consistency between predicted land-cover proportions and spatial patterns.

2.5.1. Land use demand

Land use demand refers to the expected proportion of each land-cover category in the simulation year. Under alternative policy scenarios, we expected that the proportions of land cover categories in the outcome simulation would be different from those simulated under current (baseline) policy conditions. Based on an analysis of observed land cover change trajectories within specific policy areas, we determined rates of land use transitions and used that information to adjust expected land use demand for each of our policy scenarios. For example, under a scenario of complete privatization, cropland expansion rates were estimated based on observed transitions in existing private lands, normalized by the area of private land under that scenario. This normalization ensured that transition rates reflected both historical trends and the spatial extent of land use types under alternative policy conditions. Similarly, scenarios maintaining group ranches assumed reduced cropland expansion and increased persistence of rangeland cover. These adjustments were encoded in the Markov transition matrix, which governs the expected quantity of each land-cover type in the simulated map. Markov transition matrices corresponding to the policy scenarios are provided in Appendix A.3.

2.5.2. Spatial allocation of transitions

Spatial allocation determines where land use transitions occur to meet scenario-specific demand. We modified baseline transition probabilities using a spatial multiplier map that incorporated policy constraints, incentives, and disincentives. Each pixel in the multiplier map acted as a weight applied to the base transition probability for a given land cover change. Values greater than 1 served as incentives (increasing transition likelihood), values between 0 and 1 acted as disincentives (reducing likelihood), and values of 0 imposed strict constraints (preventing transitions). For example, under the group ranch scenario, transitions to cropland are reduced relative to baseline conditions. In this case, protected areas were assigned a value of 0 to prohibit conversion, group ranches were assigned values < 1 to limit cropland expansion, and private lands were assigned values > 1 to increase agricultural expansion. See supplementary Figure A.1 for an illustration of the privatization scenario case. This approach ensured that spatial allocation was consistent with policy-driven land use dynamics while maintaining ecological plausibility. By integrating demand adjustments with spatial allocation rules, the model produced scenario-specific land-cover maps that reflect both quantitative targets and spatial policy conditions.

2.6. Spatial comparison of tenure scenarios

To visualize where tenure scenarios diverged from the Baseline, we calculated net change in land-cover class share using a regular spatial grid. The 90-m predicted land-cover maps were summarized within approximately 2-km grid cells (22×22 pixels). For each land-cover class k, net change was calculated as the proportion of a grid cell occupied by class k under the tenure scenario minus its proportion under the Baseline, expressed as percentage points of the cell area. Cells with less than 50% of their area within Narok County were excluded. We report percentage-point rather than relative percentage change because relative change can become unstable where the baseline proportion of a land-cover class is small. To assess whether the observed spatial patterns were sensitive to grid resolution, the analysis was repeated using a coarser 5-km grid, which produced consistent spatial patterns (supplementary Figure A.2).

2.7. Assessing model sensitivity

To evaluate the sensitivity of the model to uncertainty in transition dynamics, we systematically perturbed the modeled transition

probabilities across a range of plausible variation. Specifically, for scenarios in which the expected land use outcomes implied higher transition tendencies than those produced by the baseline model, we increased the corresponding transition probabilities by +25%, +50%, and +75%. Conversely, where expectations suggested lower transition tendencies, we applied proportional reductions of −25%, −50%, and −75%. These adjustments enabled us to assess how directional changes in transition intensity influence spatial outcomes. All modifications were implemented using the spatial multiplier procedure described in Section 2.5.2, which recalibrates transition likelihoods in a spatially explicit manner while preserving underlying biophysical and policy constraints.

3. Results

Results emphasize the diagnostic behavior of configuration-based indicators. We first assess indicator response to land tenure context under non-regenerative conditions, then evaluate how targeted management strategies modify indicators within each tenure regime. Figures are read comparatively, showing indicator direction and magnitude relative to baseline conditions and synthesizing multi-indicator performance across tenure-strategy combinations. Throughout the results, we interpret indicator magnitudes as signals of configuration change rather than direct measures of ecological outcomes.

3.1. Effects of land-tenure regimes on landscape composition, fragmentation, and spatial adjacencies

To evaluate how contrasting land tenure regimes shape the landscape in the absence of adaptive regenerative strategies, we compared the Baseline prediction under current policy with scenarios emphasizing GR tenure versus PR. This analysis isolates the response of configuration-based indicators to tenure context alone. At the landscape scale, differences in composition were modest (Fig. 4a–c). Relative to the Baseline (18.4% forest, 56.1% rangeland, 25.4% cropland), GR increased forest (+2.3 percentage points, pp) and rangeland (+3.0 pp) while reducing cropland (−5.3 pp). PR reduced rangeland (−2.4 pp) and slightly increased forest (+1.3 pp) and cropland (+1.2 pp). Urban area was identical across scenarios. In total, 11.5% of the landscape changed class under GR relative to the Baseline, compared with 7.7% under PR.

Mapping net change in class share on a ~2 km grid showed that these modest landscape-level differences come from spatially concentrated

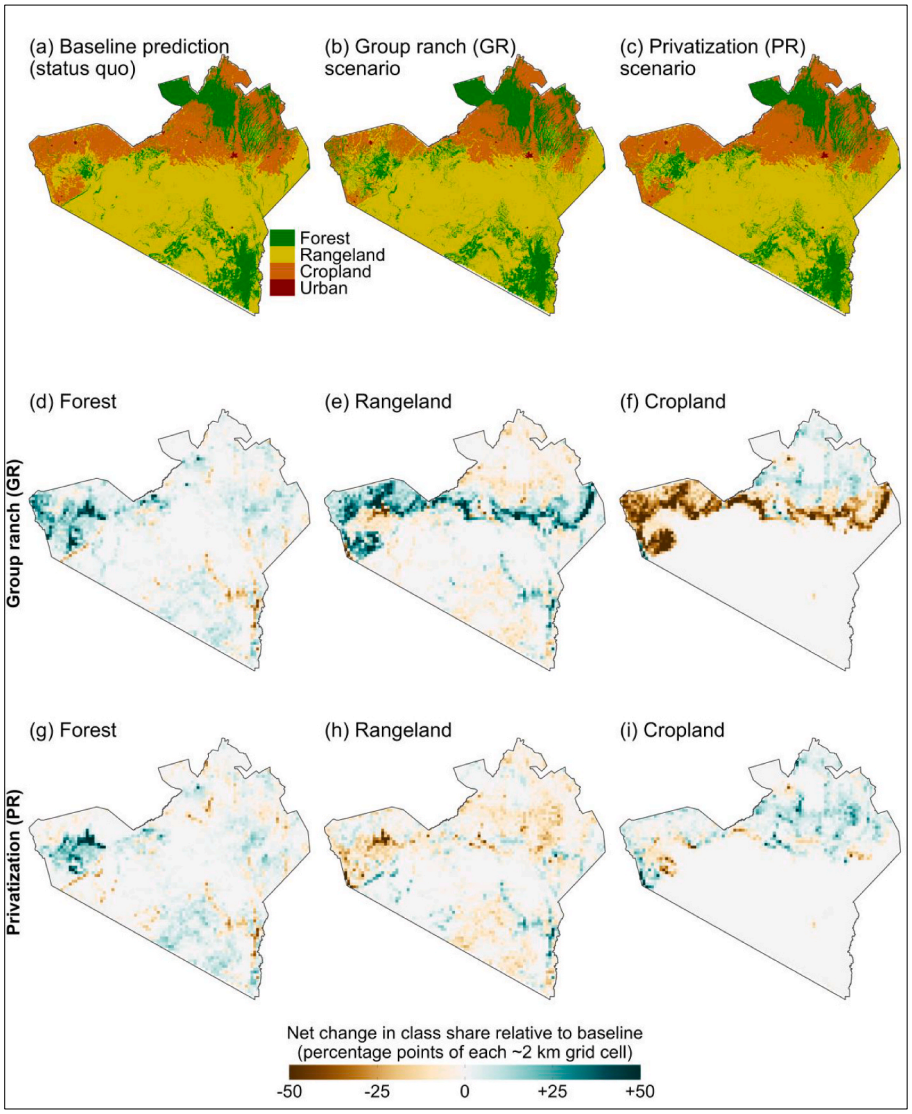


Fig. 4. Predicted LULC under (a) Baseline (current), (b) Group ranch (GR), and (c) Privatization (PR) policies. Net change in land-cover class share relative to the Baseline under (d-f) GR and (g-i) PR tenure scenarios, summarized within approximately 2-km grid cells. Values represent percentage-point differences in class share between each tenure scenario and the Baseline; teal indicates gains and brown indicates losses. Urban cover was unchanged across scenarios and is not shown.

reorganization rather than uniform shifts (Fig. 4d–i). Under GR, cropland losses were concentrated along the cropland-rangeland frontier and in the west, with local declines of more than 25 pp (Fig. 4f). These losses were largely offset by rangeland gains in the same cells (Fig. 4e) and by forest gains concentrated in the north-west (Fig. 4d). Small cropland gains in the north-east show expansion being redirected toward areas that remain privately held. Under PR, change was more diffuse: rangeland declined across much of the north and center, with 47% of grid cells losing more than 1 pp (Fig. 4h). The matching cropland gains were concentrated in the northern area (Fig. 4i), and forest gains were confined mainly to a single cluster in the west (Fig. 4g). Outside these zones, both scenarios showed only small, scattered forest-rangeland exchanges.

At the configuration level, tenure regimes produced distinct indicator responses. Landscape-level edge density, interpreted here as an indicator of fine-scale heterogeneity, was substantially higher under the GR scenario compared to the Baseline, indicating a more spatially heterogeneous configuration (Fig. 5a). In contrast, edge density under the PR scenario was slightly lower than the baseline, reflecting a more aggregated landscape structure. When assessed specifically for the forest class, the pattern remained consistent: forest edge density was higher under GR than PR, indicating greater forest patch subdivision under group tenure relative to privatized landscapes.

Functional adjacency potential differed accordingly. Baseline cropland-forest and rangeland-forest adjacency values were lower than those observed under both policy scenarios (Fig. 5b and c), indicating that baseline conditions provide limited spatial coupling among land uses regardless of tenure. Under PR, cropland-forest adjacency increased only slightly above the baseline value, whereas under GR the increase was substantially larger, indicating a higher proportion of cropland occurring within 500 m of forest cover. For rangeland-forest adjacency, both PR and GR exceeded baseline values, with GR producing the largest increase, reflecting a greater proportion of rangeland occurring in close proximity to forest patches.

3.2. Comparative performance of combined policy and management scenarios on spatial configuration and spatial adjacencies

To evaluate the combined influence of land-tenure context and regenerative management on landscape structure, we compared indicator responses across policy-strategy combinations. This section focuses on comparative indicator performance, emphasizing relative magnitude, ranking, and consistency across tenure regimes rather than individual scenario narratives. Indicator responses varied systematically between GR and PR scenarios, with larger magnitudes observed under GR across strategies.

Under the GR tenure, strategies that prioritized small forest patches or connectivity produced the largest increases in landscape level edge density (Fig. 5a). Under the PR scenario, most strategies produced edge-density values at or below baseline value, with only small-patch and connectivity strategies yielding slight increases. Strategy rank ordering was similar under both tenure regimes, though magnitudes differed with GR being consistently greater than PR.

All the strategies under GR increased forest adjacency to cropland above baseline levels, with the largest gains observed under strategies prioritizing small forest patches and combined strategies (Fig. 5b). Under PR policies, improvements in cropland-forest adjacency were more modest and clustered near baseline value, except for the small-patch strategy, which produced the largest increase among PR scenarios. In contrast, combined forest-based strategies yielded lower cropland adjacency than targeted small-patch interventions alone.

Baseline rangeland-forest adjacency was low across all scenarios (Fig. 5c). Both policy environments showed increases relative to baseline, with higher values consistently observed under GR than PR. Small-patch conservation produced the highest rangeland-forest adjacency under both tenure regimes, while water-pan placement generated comparable increases. Integrated multi-component strategies produced lower adjacency values than targeted interventions.

3.3. Integrated effects of tenure-strategy combinations on regenerative landscape processes

Across indicators, most scenarios incorporating targeted spatial interventions showed higher values than baseline (Fig. 6). Comparisons between policy environments indicate consistently higher indicator magnitudes under GR than under PR. Under PR (dashed lines), indicator values were generally lower across scenarios.

Strategy rank ordering was similar across tenure regimes. Strategies emphasizing small-patch conservation produced the highest overall indicator values, followed by water-pan placement and connectivity interventions. Integrated multi-component strategies produced lower values across several indicators under both tenure regimes.

The scenario prioritizing conservation of small forest patches exhibited the largest radial extent under both GR and PR, with the highest values for heterogeneity and adjacency indicators. This strategy produced the largest increases in cropland-forest and rangeland-forest adjacency relative to other interventions. Water-pan placement and connectivity interventions showed more moderate increases, with changes limited to specific indicators rather than across all indicators simultaneously.

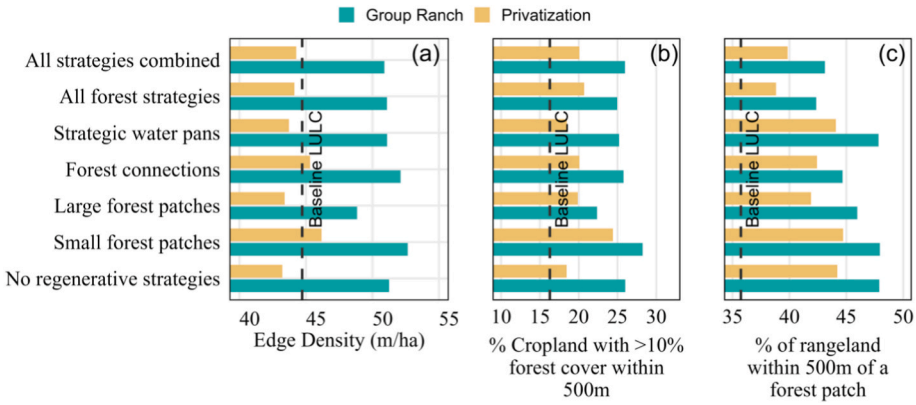


Fig. 5. a) Edge density for non-regenerative and regenerative strategy scenarios under privatization and group ranch tenure systems. The dashed line indicates baseline LULC edge density. b) Percentage of cropland with >10% forest cover within 500 m under different policy and management strategies. The vertical dashed line indicates values for the baseline LULC. c) Percentage of rangeland within 500 m of a forest patch under different policy and management strategies. The vertical dashed line indicates values for the baseline LULC.

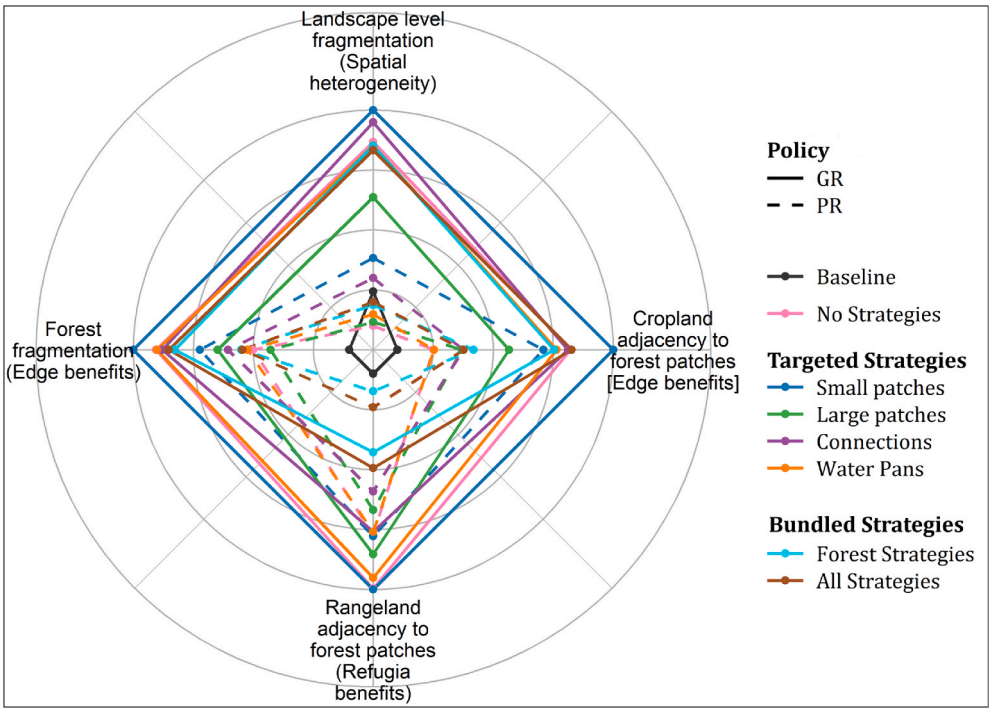


Fig. 6. The radar chart summarizes how eight management scenarios perform across four indicators of regenerative landscape processes, landscape-level fragmentation, cropland adjacency to forest patches, rangeland adjacency to forest patches, and forest fragmentation, under two policy environments (GR, solid lines; PR, dashed lines). Together, these indicators represent spatial heterogeneity, edge benefits, and refugia potential within the landscape.

3.4. Indicator sensitivity to transition uncertainty

Sensitivity analysis across ±25%, ±50%, and ±75% perturbations of transition probabilities showed consistent patterns in configuration-based indicators (Fig. 7). Across all sensitivity levels, Group Ranch (GR) scenarios maintained higher values than Privatization (PR) scenarios for edge density (GR: 44.72-52.65; PR: 43.03-46.18), cropland-forest adjacency (GR: 16.28%-28.24%; PR: 16.28%-24.41%), and rangeland-forest adjacency (GR: 35.73%-47.95%; PR: 35.73%-44.94%). Strategy rankings remained completely unchanged; small forest patch conservation consistently produced the highest indicator values (e.g., GR edge density held fixed at 52.65), followed sequentially by connectivity and water-pan strategies, while combined strategies exhibited lower overall responses. Indicator magnitudes varied modestly with increasing perturbation, but no reversals in indicator direction or scenario ranking occurred. Edge density showed minimal variation (~1.14 absolute point shift, a 2.6% relative change from its initial value, associated with the combined multi-strategy (all strategies) scenario under PR), whereas adjacency indicators demonstrated greater sensitivity to perturbation, particularly rangeland-forest adjacency with a maximum shift of ~2.22 percentage points (a 5.6% relative change from its initial value) also associated with the combined multi-strategy (all strategies) scenario under PR.

4. Discussion

Arid and semi-arid landscapes (ASALs) face intensifying drought, rainfall variability, and compounding extremes that challenge

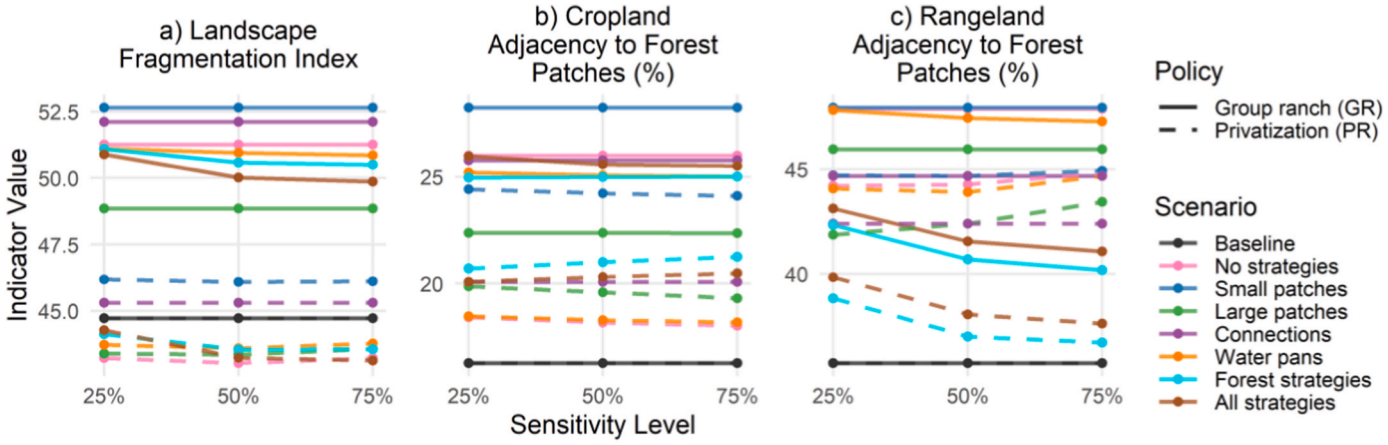


Fig. 7. Sensitivity analysis of landscape performance indicators across varying levels of transition probability perturbations (25%, 50%, 75%). Panels display changes in (a) Landscape fragmentation index, (b) Cropland adjacency to forest patches (%), and (c) Rangeland adjacency to forest patches (%) across eight land-use change scenarios under Group ranch (GR, solid lines) and Privatization (PR, dashed lines) governance frameworks. Note that indicator scales vary across panels to maximize trend visibility.

ecosystem functioning and livelihoods, underscoring the need for spatially explicit adaptation planning at landscape scales. This study contributes a generalizable, decision-focused workflow that integrates a calibrated land-change model with policy and management rules to evaluate regenerative pathways, showing how configuration-based indicators can diagnose how design choices reorganize landscape structure to support multifunctionality and social-ecological resilience in mixed-use drylands. In doing so, the study responds to calls in conservation and restoration science (Lavorel et al., 2022; Jay and Plieninger, 2025) to plan for landscape multifunctionality, rather than sector-specific outcomes, and to explicitly manage landscape configuration using indicator-based planning approaches.

4.1. Land tenure regimes as first order controls on landscape configuration

Our results show that land tenure regime exerts a first-order influence on landscape configuration, with group ranch governance producing more heterogeneous and better-connected mosaics than privatization, even in the absence of regenerative strategies. These contrasts establish tenure as a contextual modifier shaping baseline configuration states against which indicator responses to management strategies are evaluated. This pattern aligns with empirical evidence that subdivision and fencing in southern Kenyan rangelands have proliferated under privatization, fragmenting habitats and weakening pastoral drought resilience (Tyrrell et al., 2022). These modeled configurations are also consistent with historical accounts of tenure change in Kenyan arid agropastoral landscapes (KareriMwangi, 2024).

Although the Community Land Act of 2016 sought to formalize customary tenure, it triggered divergent outcomes across regions (Santini, 2025). In some contexts, tenure formalization has coincided with increased parcelization and enclosure through fencing, while in others it has supported collective stewardship through conservancies and co-management arrangements. This divergence is reflected in the configuration-based indicator contrasts observed here, where privatization scenarios exhibit more aggregated land use patterns and lower functional adjacency than group ranch configurations. Importantly, these differences are expressed as changes in indicator magnitude rather than directional reversal, highlighting tenure as a modifier of interpretability rather than a causal driver of regenerative processes.

Empirical work across southern Kenyan rangelands further shows that privatization and fencing are associated with rangeland fragmentation, reduced access to dry season grazing and water, and declines in wildlife connectivity (Mwiu et al., 2019). These documented associations provide context for interpreting the privatization scenarios modeled here, which consistently exhibit lower heterogeneity and weaker adjacency signals. By contrast, group ranch governance and related co-management approaches tend to sustain heterogeneous mosaics and spatial coupling among land uses, conditions reflected in higher edge density and adjacency indicators in our GR scenarios.

These indicator patterns suggest that tenure context conditions how landscape structure is expressed and measured, influencing baseline configuration states that frame subsequent management outcomes. As such, tenure functions as a first-order modifier of indicator responsiveness rather than a direct driver of regenerative processes. This distinction is critical for sustainability assessment, as it highlights the importance of interpreting configuration-based indicators relative to underlying governance contexts when diagnosing regenerative capacity and comparing alternative planning pathways.

4.2. Tenure context conditions indicator responses to regenerative management strategies

Across modeled scenarios, landscape configuration responses to regenerative management strategies varied systematically by tenure context. Group ranch (GR) landscapes consistently exhibited stronger indicator responses than privatized (PR) landscapes, reflecting differences in land use rights and restrictions governing fencing and enclosure, cultivation, and grazing across policy regimes. Because tenure was held constant and treated as contextual rather than causal, these patterns are best interpreted as variation in indicator sensitivity across governance contexts, rather than as differences in intrinsic strategy effectiveness.

Under GR tenure, strategies emphasizing small forest patches, connectivity, and water access were associated with pronounced increases in heterogeneity and cross habitat adjacency indicators. These indicator responses are consistent with land use contexts characterized by shared access and limited enclosure, in which dispersed forest structure and mixed land use mosaics remain spatially intact. In contrast, under PR tenure, where parcelization, fencing, and land use consolidation are more prevalent, the same strategies were associated with more attenuated indicator responses. This attenuation indicates reduced sensitivity of configuration-based indicators within more aggregated spatial contexts.

Tenure conditioned differences were most pronounced for functional adjacency indicators. Under GR tenure, cultivation typically occurs within a predominantly pastoral landscape, and forest patches often remain interspersed within agricultural areas due to shared access and limits on enclosure. In this context, most management strategies were associated with increased cropland-forest adjacency, with the strongest associations observed under small patch conservation. Under PR, cropland expansion more often proceeds through consolidation, producing lower local adjacency and more homogeneous configurations. Accordingly, strategies emphasizing forest conservation were associated with larger, more concentrated forest blocks and weaker local cropland-forest adjacency. These results highlight the importance of interpreting spatial indicators comparatively within tenure contexts, rather than against universal benchmarks.

Rangeland-forest adjacency showed the strongest contrasts between tenure regimes. Baseline adjacency was low across both contexts but increases associated with management strategies were consistently larger under GR than under PR. Small patch conservation and strategically placed water pans produced comparable adjacency responses under GR, indicating that multiple targeted levers can generate similar indicator gains when underlying access and mobility conditions permit spatial reorganization. Under PR, the same strategies yielded smaller increases, reflecting constrained reconfiguration within fenced and parcelized landscapes.

Across both tenure regimes, integrated multi component strategy bundles were consistently associated with weaker configuration responses than the most effective targeted strategies. Such bundles produced configuration trade-offs that reduced the expression of adjacency- and heterogeneity-based indicators, particularly under PR where baseline consolidation further limited fine-scale reorganization.

Collectively, these patterns indicate that tenure context shapes both baseline configuration and the degree to which management strategies are reflected in the indicators. Tenure therefore functions as a persistent modifier of indicator responsiveness rather than a determinant of overall strategy effectiveness. This distinction underscores the importance of interpreting regenerative management performance through comparative indicator behavior that explicitly accounts for governance context.

4.3. Integrated effects of tenure-strategy combinations on regenerative functions in ASALs

The modeled scenarios show that changes in spatial configuration, particularly indicator-relevant attributes such as heterogeneity, patch adjacency, and connectivity, are consistently associated with configuration states linked to regenerative capacity in multifunctional arid and semi-arid landscapes. A central implication is that heterogeneity and connectivity operate as spatial design levers that are directly captured by configuration-based indicators, providing diagnostic signals of how

landscapes are reorganized under alternative policy and management pathways as climate and land use change.

Across simulations, the small-patch strategy produced the strongest increases in heterogeneity and adjacency indicator values (forest-cropland and forest-rangeland), reflecting configuration states widely interpreted as supporting buffering capacity and spatial redundancy under stress. This pattern aligns with evidence that networks of small patches can deliver high cumulative biodiversity value by functioning as stepping stones in human-dominated landscapes (Riva and Fahrig, 2022). At the same time, long-term experiments caution that fragmentation and edge proliferation can undermine biomass, nutrient retention, and species persistence when configuration is altered indiscriminately (Haddad et al., 2015). Together, these findings reinforce the need to interpret heterogeneity indicators diagnostically, increasing fine-scale diversity without amplifying isolation or adverse edge effects.

Prioritizing patches that matter most for connectivity rather than focusing solely on expanding core areas, further supported network cohesion. This result is consistent with graph-theoretic and optimization analyses highlighting the importance of strategically placed stepping-stone nodes (Naidoo et al., 2025). Our corridor design extends this logic with low-cost linkages that produced indicator-detectable reductions in patch isolation, hence maintaining landscape permeability. This approach aligns with climate adaptation guidance linking structural connectivity indicators to governance pathways and with Kenya's national emphasis on protecting wildlife corridors and dispersal areas across mixed tenure landscapes. More broadly, evidence suggests that combining porous mosaics (via small-patch retention or creation) with targeted corridors offers a robust, decision-focused adaptation pathway under accelerating climate and land-use change (Costanza and Terando, 2019).

The water-pan scenario generated moderate but spatially concentrated indicator responses, particularly through increased rangeland-forest adjacency and localized refugia signals during dry periods. Water infrastructure functioned as a spatial reorganization of resource proximity, producing localized gains in adjacency-based indicators rather than system-wide configuration shifts. These responses align with Kenya's National Adaptation Plan (Government of Kenya, 2016), which prioritizes climate-resilient water infrastructure to stabilize pastoral livelihoods during drought. Strategic siting of water pans can limit localized overgrazing while yielding measurable gains in permeability-related indicators and supporting national goals to reduce human-wildlife conflict by shifting water resource access away from protected areas.

Overall, focused, tenure-aware interventions (e.g., small-patch conservation paired with core area protection and context-aware corridors) produced stronger and more consistent configuration-based indicator responses than broad, bundled packages, particularly where privatization and fencing constrained connectivity. Although small-patch strategies elevated adjacency indicators, excessive edge density risks eroding interior-dependent biodiversity, underscoring the importance of pairing fine-grain actions with core protection and corridor integrity (Haddad et al., 2015; Teixeira et al., 2025). We also observed a bundle paradox in which multi-component packages yielded weaker cumulative indicator signals than targeted strategies, likely due to configuration-level offsetting and spatial competition among interventions (Yao and Yang, 2025). These trade-offs argue for indicator-informed optimization: prioritizing targeted small-patch interventions for refugia and arranging actions as coordinated symbiotic units whose spatial relationships are deliberately made mutualistic rather than competitive, thereby maintaining high-value refugia under increasing environmental stress (Jay and Plieninger, 2025; Kéfi et al., 2024).

4.4. Implications for sustainability indicator design and use

The results show that configuration-based indicators function most effectively as diagnostic signals of spatial structure rather than as standalone measures of system state or performance. This aligns with a growing body of sustainability assessment literature emphasizing that indicators are most effective when they function as decision-support tools embedded in planning and evaluation processes (Lavorel et al., 2022; Waas et al., 2014). In landscape sustainability research, this perspective has motivated increasing attention to structural indicators (e.g., heterogeneity, fragmentation, and connectivity) that capture the spatial organization through which multifunctionality and resilience emerge (Jay and Plieninger, 2025; Turner and Gardner, 2015; Cushman and McGarigal, 2019). Recent reviews further note that configuration metrics remain underutilized in applied sustainability indicator frameworks, despite their relevance for diagnosing trade-offs and synergies in multifunctional landscapes (Xi et al., 2024; Dade et al., 2025).

By explicitly framing configuration-based indicators as diagnostic signals rather than direct measures of regenerative outcomes, this study contributes to calls for indicator systems that can anticipate system trajectories and guide planning under uncertainty, particularly where ecological responses lag behind spatial interventions. This interpretation is supported by the sensitivity analysis, which showed that indicator direction and relative ranking were preserved across substantial perturbations of transition probabilities, indicating that these indicators capture stable structural patterns rather than model-specific parameter effects.

Our results further reinforce emerging arguments that sustainability indicators must be interpreted in relation to governance and institutional context, rather than as context-independent measures (Alberti et al., 2018). The strong conditioning effect of land tenure on indicator responsiveness observed here is consistent with recent evidence that property regimes and access rights shape landscape morphology and spatial pattern, thereby influencing the magnitude and sensitivity of configuration-based indicators (Lavorel et al., 2022; Zhou et al., 2025). The persistence of these tenure-dependent differences across sensitivity levels further suggests that indicator comparisons are most meaningful when interpreted relatively within governance contexts, rather than as absolute benchmarks. Accordingly, indicator comparisons should focus on relative performance within governance contexts rather than on universal thresholds or standalone benchmarks.

Moreover, the weaker and sometimes offsetting performance of bundled interventions is consistent with findings from ecosystem-service and multifunctionality assessments showing that integrated strategies can obscure spatial trade-offs when multiple objectives are combined (Yao and Yang, 2025; Haddad et al., 2015). At the same time, the greater variation observed for adjacency-based indicators under increasing perturbation highlights their sensitivity to localized spatial interactions, reinforcing the need to interpret these indicators alongside broader configuration metrics such as heterogeneity and connectivity.

Together, these insights argue for sustainability indicators that emphasize clarity of interpretation, contextual sensitivity, and key spatial signals, enabling adaptive, tenure-aware planning and monitoring across climate-vulnerable landscapes.

4.5. Limitations, uncertainty, and future directions for indicator-based scenario planning

This study highlights both the strengths and the boundaries of using configuration-based indicators for regenerative planning. The spatial indicators applied here diagnose structural conditions associated with regenerative capacity, but they do not directly measure ecological regeneration, ecosystem service provision, or livelihood outcomes (Li and Wu, 2004; Tischendorf, 2001; Liczner et al., 2024; Li and Wu, 2004; Tischendorf, 2001; Liczner et al., 2024). For example, greater forest connectivity or forest-cropland and forest-rangeland adjacency

may create spatial conditions favorable to species movement, refugia provision, pollination, or other cross-habitat processes, but the indicators do not establish that these functions actually occur or quantify their magnitude. Realized ecological responses also depend on factors not represented by land-cover configuration alone, including vegetation composition and condition, species-specific responses, management intensity, climate variability, disturbance history, and ecological time lags (Haddad et al., 2015; Watts et al., 2020). Our results should therefore be interpreted as identifying the relative potential of alternative interventions to create spatial conditions conducive to regenerative processes, rather than as direct predictions of ecosystem-service outcomes. Future work should pair configuration indicators with field-based and remotely sensed measures of ecosystem function, such as vegetation productivity and condition, soil moisture, biodiversity, animal movement, and pollination, to test whether predicted configuration gains translate into realized ecological and livelihood benefits.

The results also point to the importance of embedding indicator-based scenarios within participatory planning processes. Co-developing scenarios with county planners, conservancies, group ranch committees, and private landholders would help align indicators with decision needs and support the design of tenure-appropriate incentives, such as corridor leases, conservation easements, or rotational access at water points. Given the documented role of fencing in restricting pastoral mobility and disrupting regional connectivity (Mwiu et al., 2019; Schwandner et al., 2025), incorporating indicators of fence density, removability, and alternative boundary practices represents a near-term opportunity to operationalize connectivity as natural infrastructure.

Although prior model calibration supports the credibility of the scenario framework, for indicator-based planning we emphasize robustness rather than precise prediction. Sensitivity analysis showed that indicator direction and relative ranking were preserved across substantial perturbations of transition probabilities (±25-75%), indicating that observed differences among tenure and strategy combinations reflect stable structural patterns rather than model-specific parameter choices. At the same time, variation in indicator magnitude under increasing perturbation, particularly for adjacency metrics, highlights the importance of interpreting results comparatively rather than as precise forecasts.

Future applications should therefore continue to stress-test indicator responses across uncertainty in land use demand, management rules (e.g., anti-fencing provisions), and compound climate extremes that may alter transition dynamics. Framed in this way, indicator-based regenerative planning becomes an adaptive tool; one that guides learning and adjustment as spatial signals emerge, rather than a one-time forecast of landscape outcomes.

5. Conclusions

This study demonstrates the value of configuration-based sustainability indicators as diagnostic tools for evaluating regenerative landscape pathways in multifunctional, climate-vulnerable drylands. By coupling spatially explicit scenario modeling with indicators of heterogeneity, connectivity, and functional adjacency, we show that spatial configuration provides an interpretable and decision-relevant lens for assessing how alternative land-tenure regimes and management strategies shape regenerative potential. Treating these indicators as diagnostic signals rather than as direct proxies for ecological or livelihood outcomes, supports early assessment of planning trajectories in contexts where system responses emerge gradually and under high uncertainty.

Across scenarios, land tenure emerged as a first-order contextual modifier of indicator responsiveness. Group ranch governance consistently supported higher heterogeneity and stronger functional adjacencies than privatization, while the relative ranking of management strategies remained broadly conserved across tenure regimes. These findings highlight the importance of interpreting indicator performance comparatively within specified governance contexts, rather than against universal benchmarks. They also indicate that tenure influences the strength, but not necessarily the direction of configuration change captured by the indicators.

The analysis shows that targeted, spatially focused interventions, particularly small forest patch conservation, produced stronger and more consistent indicator responses than bundled, multi-component strategies. Integrated interventions often created offsetting configuration effects that weakened diagnostic clarity, underscoring the value of indicator systems that prioritize specificity, interpretability, and key spatial processes such as patch dispersion, functional adjacency, connectivity, and access to localized resource nodes. Together, these results suggest that sustainability assessments are best supported by focused indicators that reveal how specific design choices reorganize landscape structure, rather than by aggregated metrics that obscure spatial trade-offs.

More broadly, this work contributes a transferable framework for indicator-based planning and monitoring that can be adapted to other multifunctional landscapes facing coupled climate and governance pressures. By treating configuration as the intermediary between intervention and regenerative capacity, the approach offers a practical pathway for integrating spatial design, policy context, and sustainability assessment. Such diagnostic indicators can support adaptive, tenure-aware planning by guiding iterative decision-making as spatial signals emerge, helping to sustain multifunctionality and resilience in rapidly changing landscapes.

CRediT authorship contribution statement

Susan M. Kotikot: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Erica A.H. Smithwick:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Sarah E. Gergel:** Writing – review & editing, Writing – original draft, Conceptualization. **Jedidah Nankaya:** Writing – review & editing. **Romulus Abila:** Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used Microsoft Copilot for language editing and refinement. The authors reviewed and edited the output as needed and take full responsibility for the content of the published article.

Funding

This work was supported by the National Science Foundation BCS Award No. 2149244.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2026.101614.

Data availability

The data supporting this study are publicly available on Zenodo at https://doi.org/10.5281/zenodo.20382346

References

Alberti, M., McPhearson, T., Gonzalez, A., 2018. Embracing urban complexity. In: Elmqvist, T., Bai, X., Frantzeskaki, N., Griffith, C., Maddox, D., McPhearson, T., Parnell, S., Romero-Lankao, P., Simon, D., Watkins, M. (Eds.), Urban Planet: Knowledge Towards Sustainable Cities. Cambridge University Press, Cambridge, pp. 45–67. https://doi.org/10.1017/9781316647554.004.

Barthwal, P., Dobhal, S., Manaula, S., Bhatt, S., Chamoli, R.T., Lal, P., Pratap, U.B., Kumar, A., Kumar, R., 2025. Natural resources management in semi-arid region: current practices, challenges, and future strategies. In: Singh, A.K., Kumar, P., Singh, S.S. (Eds.), Sustainable Agriculture Management in Semi-arid Climates, vol. 2. Springer Nature Switzerland, Cham, pp. 71–87. https://doi.org/10.1007/978-3-031-94066-8_4.

Beller, E.E., Spotswood, E.N., Robinson, A.H., Anderson, M.G., Higgs, E.S., Hobbs, R.J., Suding, K.N., Zavaleta, E.S., Letitia Grenier, J., Grossinger, R.M., 2019. Building ecological resilience in highly modified landscapes. Bioscience 69, 80–92. https://doi.org/10.1093/biosci/biy117.

Brennan, A., Naidoo, R., Greenstreet, L., Mehrabi, Z., Ramankutty, N., Kremen, C., 1979. Functional connectivity of the world's protected areas. Science 376 (2022), 1101–1104. https://doi.org/10.1126/science.abl8974.

Chen, J., Qi, Q., Wang, B., He, S., Li, Z., Wang, L., Li, K., 2023. Response of ecosystem services to landscape patterns under socio-economic-natural factor zoning: a case study of Hubei Province, China. Ecol. Indic. 153. https://doi.org/10.1016/j.ecolind.2023.110417.

Costanza, J.K., Terando, A.J., 2019. Landscape connectivity planning for adaptation to future climate and land-use change. Curr. Landsc. Ecol. Rep. 4, 1–13. https://doi.org/10.1007/s40823-019-0035-2.

Cumming, G.S., 2011. Spatial resilience: integrating landscape ecology, resilience, and sustainability. Landsc. Ecol. 26, 899–909. https://doi.org/10.1007/s10980-011-9623-1.

Cushman, S.A., McGarigal, K., 2019. Metrics and models for quantifying ecological resilience at landscape scales. Front. Ecol. Evol. 7, 1–21. https://doi.org/10.3389/fevo.2019.00440.

Dade, M.C., Bonn, A., Eigenbrod, F., Felipe-Lucia, M.R., Fisher, B., Goldstein, B., Holland, R.A., Hopping, K.A., Lavorel, S., lede Polain Waroux, Y., MacDonald, G.K., Mandle, L., Metzger, J.P., Pascual, U., Rieb, J.T., Vallet, A., Wells, G.J., Ziter, C.D., Bennett, E.M., Robinson, B.E., 2025. Landscapes—A lens for assessing sustainability. Landsc. Ecol. 40. https://doi.org/10.1007/s10980-024-02007-7.

Estrada-Carmona, N., Carmenta, R., Reed, J., Betemariam, E., DeClerck, F., Falk, T., Hart, A.K., Jones, S.K., Kleinschroth, F., McCartney, M., Meinzen-Dick, R., Milder, J., Quintero, M., Remans, R., Valbuena, D., Willemen, L., Zanzanaini, C., Zhang, W., 2024. Reconciling conservation and development requires enhanced integration and broader aims: a cross-continental assessment of landscape approaches. One Earth 7, 1858–1873. https://doi.org/10.1016/j.oneear.2024.08.014.

Field, R.D., Parrott, L., 2022. Mapping the functional connectivity of ecosystem services supply across a regional landscape. eLife 11, e69395. https://doi.org/10.7554/eLife.69395.

Folke, C., 2016. Resilience (Republished). Ecol. Soc. 21. https://doi.org/10.5751/ES-09088-210444.

Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., Chapin, T., Rockstrom, J., 2010. Resilience Thinking: Integrating Resilience, Adaptability and Transformability.

Government of Kenya, 2016. Kenya National Adaptation Plan: 2015-2030.

Haddad, N.M., Brudvig, L.A., Clobert, J., Davies, K.F., Gonzalez, A., Holt, R.D., Lovejoy, T.E., Sexton, J.O., Austin, M.P., Collins, C.D., Cook, W.M., Damschen, E.I., Ewers, R.M., Foster, B.L., Jenkins, C.N., King, A.J., Laurance, W.F., Levey, D.J., Margules, C.R., Melbourne, B.A., Nicholls, A.O., Orrock, J.L., Song, D.X., Townshend, J.R., 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. Sci. Adv. 1. https://doi.org/10.1126/sciadv.1500052.

Hesselbarth, M.H.K., Sciaini, M., With, K.A., Wiegand, K., Nowosad, J., 2019. Landscapemetrics: an open-source R tool to calculate landscape metrics. Ecography 42, 1648–1657.

Hoover, D.L., Hajek, O.L., Smith, M.D., Wilkins, K., Slette, I.J., Knapp, A.K., 2022. Compound hydroclimatic extremes in a semi-arid grassland: drought, deluge, and the carbon cycle. Glob. Change Biol. 28, 2611–2621. https://doi.org/10.1111/gcb.16081.

IPCC, 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009325844.

IPCC, Deserts, 2023. Semiarid areas and desertification. In: Climate Change 2022 – Impacts, Adaptation and Vulnerability. Cambridge University Press, pp. 2195–2232. https://doi.org/10.1017/9781009325844.020.

Jay, M., Plieninger, T., 2025. Addressing landscape multifunctionality in conservation and restoration. Nat. Rev. Biodivers. 1, 717–732. https://doi.org/10.1038/s44358-025-00091-4.

Jennings, M.K., Haeuser, E., Foote, D., Lewison, R.L., Conlisk, E., 2020. Planning for dynamic connectivity: operationalizing robust decision-making and prioritization across landscapes experiencing climate and land-use change. Land 9. https://doi.org/10.3390/LAND9100341.

Kareri Mwangi, D., 2024. Land-tenure shifts in the Maa landscapes, Kenya, and the impacts on social-cultural relations, structural power and social economic differentiation. Nat. Anthropol. 2. https://doi.org/10.35534/natanthropol.2024.10016, 10016–10016.

Karimi, J.D., Corstanje, R., Harris, J.A., 2021. Understanding the importance of landscape configuration on ecosystem service bundles at a high resolution in urban landscapes in the UK. Landsc. Ecol. 36, 2007–2024. https://doi.org/10.1007/s10980-021-01200-2.

Kéfi, S., Génin, A., Garcia-Mayor, A., Guirado, E., Cabral, J.S., Berdugo, M., Guerber, J., Solé, R., Maestre, F.T., 2024. Self-organization as a mechanism of resilience in dryland ecosystems. Proc. Natl. Acad. Sci. U. S. A. 121. https://doi.org/10.1073/pnas.2305153121.

Kotikot, S.M., Smithwick, E.A.H., Gergel, S., Nankaya, J., Abila, R., Mabwoga, S., 2025b. Historical land policies influence contemporary landscape patterns in agropastoral landscapes. Landsc. Ecol. 40. https://doi.org/10.1007/s10980-025-02178-x.

Kotikot, S.M., Smithwick, E.A.H., Gergel, S.E., Nankaya, J., Abila, R., 2026. Modeling multifunctional landscape change in southern Kenya: spatial trade-offs and drivers in an arid and semi-arid landscape. Ecol. Inform. 98. https://doi.org/10.1016/j.ecoinf.2026.103959.

Kotikot, S.M., Smithwick, E.A.H., Greatrex, H., 2024. Observations of enhanced rainfall variability in Kenya, East Africa. Sci. Rep.

Kotikot, S.M., Smithwick, E.A.H., Nankaya, J., Gergel, S., Zimmerer, K.S., Abila, R., 2025a. Heterogeneous perceptions of rainfall patterns among agropastoral land users in Sub-Saharan Africa. Ann. Assoc. Am. Geogr.

Lavorel, S., Grigulis, K., Richards, D.R., Etherington, T.R., Law, R.M., Herzig, A., 2022. Templates for multifunctional landscape design. Landsc. Ecol. 37, 913–934. https://doi.org/10.1007/s10980-021-01377-6.

Lefcheck, J.S., Byrnes, J.E.K., Isbell, F., Gamfeldt, L., Griffin, J.N., Eisenhauer, N., Hensel, M.J.S., Hector, A., Cardinale, B.J., Duffy, J.E., 2015. Biodiversity enhances ecosystem multifunctionality across trophic levels and habitats. Nat. Commun. 6. https://doi.org/10.1038/ncomms7936.

Li, H., Wu, J., 2004. Use and misuse of landscape indices. Landsc. Ecol. 19, 389–399. https://doi.org/10.1023/B:LAND.0000030441.15628.d6.

Li, L., Carter, J., 2025. Exploring the relationship between urban green infrastructure connectivity, size and multifunctionality: a systematic review. Landsc. Ecol. 40. https://doi.org/10.1007/s10980-025-02069-1.

Li, Y., Schuldt, A., Ebeling, A., Eisenhauer, N., Huang, Y., Albert, G., Albracht, C., Amyntas, A., Bonkowski, M., Bruelheide, H., Bröcher, M., Chesters, D., Chen, J., Chen, Y., Chen, J.T., Ciobanu, M., Deng, X., Fornoff, F., Gleixner, G., Guo, L., Guo, P. F., Heintz-Buschart, A., Klein, A.M., Lange, M., Li, S., Li, Q., Li, Y., Luo, A., Meyer, S. T., von Oheimb, G., Rutten, G., Scholten, T., Solbach, M.D., Staab, M., Wang, M.Q., Zhang, N., Zhu, C.D., Schmid, B., Ma, K., Liu, X., 2024. Plant diversity enhances ecosystem multifunctionality via multitrophic diversity. Nat. Ecol. Evol. 8, 2037–2047. https://doi.org/10.1038/s41559-024-02517-2.

Liczner, A.R., Pither, R., Bennett, J.R., Bowman, J., Hall, K.R., Fletcher, R.J., Ford, A.T., Michalak, J.L., Rayfield, B., Wittische, J., Pither, J., 2024. Advances and challenges in ecological connectivity science. Ecol. Evol. 14. https://doi.org/10.1002/ece3.70231.

Ministry of Tourism and Wildlife, 2018. National Wildlife Strategy 2030.

Mitchell, M.G.E., Bennett, E.M., Gonzalez, A., 2013. Linking landscape connectivity and ecosystem service provision: current knowledge and research gaps. Ecosystems 16, 894–908. https://doi.org/10.1007/s10021-013-9647-2.

Mwiu, S., Edebe, E., Akoto, S., Waiguchu, G., Nyaga, V., Wall, J., 2019. Status and Viability of Wildlife Corridors in Masai Mara Ecosystem: Initiative for Conservation of Mara - Serengeti Transboundary Ecosystem Project, Narok.

Naidoo, R., Aylward, C., Elliott, W., Keeley, A., Kinnaird, M., Knight, M., Papp, C.R., Thapa, K., Antelo, R., 2025. From science to impact: conserving ecological connectivity in large conservation landscapes. Proc. Natl. Acad. Sci. U. S. A. 122. https://doi.org/10.1073/pnas.2410937122.

Neyret, M., Peter, S., Le Provost, G., Boch, S., Boesing, A.L., Bullock, J.M., Hölzel, N., Klaus, V.H., Kleinebecker, T., Krauss, J., Müller, J., Müller, S., Ammer, C., Buscot, F., Ehbrecht, M., Fischer, M., Goldmann, K., Jung, K., Mehring, M., Müller, T., Renner, S.C., Schall, P., Scherer-Lorenzen, M., Westphal, C., Wubet, T., Manning, P., 2023. Landscape management strategies for multifunctionality and social equity. Nat. Sustain. 6, 391–403. https://doi.org/10.1038/s41893-022-01045-w.

Ning, S., Yan, T., Luo, W., Tao, S., Zou, X., Li, Y., Shangguan, Z., Wu, Y., Zhang, Z., He, J. S., 2024. Aridity-dependent resistance but strong resilience of grassland ANPP to naturally occurring precipitation extremes. J. Plant Ecol. 17. https://doi.org/10.1093/jpe/rtae084.

Oteros-Rozas, E., Martín-López, B., Daw, T.M., Bohensky, E.L., Butler, J.R.A., Hill, R., Martin-Ortega, J., Quinlan, A., Ravera, F., Ruiz-Mallén, I., Thyresson, M., Mistry, J., Palomo, I., Peterson, G.D., Plieninger, T., Waylen, K.A., Beach, D.M., Bohnet, I.C., Hamann, M., Hanspach, J., Hubacek, K., Lavorel, S., Vilardy, S.P., 2015. Participatory scenario planning in place-based social-ecological research: insights and experiences from 23 case studies. Ecol. Soc. 20. https://doi.org/10.5751/ES-07985-200432.

Palmer, P.I., Wainwright, C.M., Dong, B., Maidment, R.I., Wheeler, K.G., Gedney, N., Hickman, J.E., Madani, N., Folwell, S.S., Abdo, G., Allan, R.P., Black, E.C.L., Feng, L., Gudoshava, M., Haines, K., Huntingford, C., Kilavi, M., Lunt, M.F., Shaaban, A., Turner, A.G., 2023. Drivers and impacts of eastern African rainfall variability. Nat. Rev. Earth Environ. 4, 254–270. https://doi.org/10.1038/s43017-023-00397-x.

Peng, J., Xu, D., Tang, H., Jiang, H., Dong, J., Wu, J., 2025. A landscape ecological approach to spatial conservation planning – ecological security pattern. Trends Ecol. Evol. 40, 1010–1022. https://doi.org/10.1016/j.tree.2025.07.014.

Qiu, J., Nassauer, J.I., Ahern, J., Huang, L., Reed, J., Ding, S., Guo, J., Liu, Z., Ou, W., Ouyang, Z., Shi, P., Tao, Y., Yang, R., Zheng, X., Wu, J., 2025. Advancing landscape sustainability science: key challenges and strategies for integration with landscape design and planning. Landsc. Ecol. 40. https://doi.org/10.1007/s10980-024-02042-4.

Richards, D., Etherington, T.R., Herzig, A., Lavorel, S., 2024. The importance of spatial configuration when restoring intensive production landscapes for biodiversity and

ecosystem service multifunctionality. Land 13. https://doi.org/10.3390/land13040460.
Riva, F., Fahrig, L., 2022. The disproportionately high value of small patches for biodiversity conservation. Conserv. Lett. 15. https://doi.org/10.1111/conl.12881.
Santini, G., 2025. The community land act and the subdivision of Kenya's Maasailand's remaining commons: implications for community conservation, Pastoralism 15. https://doi.org/10.3389/past.2025.14918.
Schilling, J., Werland, L., 2023. Facing old and new risks in arid environments: the case of pastoral communities in Northern Kenya. PLOS Clim. 2. https://doi.org/10.1371/journal.pclm.0000251.
Schwandner, I.A., Morrison, T.A., Hopcraft, J.G.C., Wall, J., Hughey, L., Boone, R.B., Ogutu, J.O., Jakes, A.F., Kifugo, S.C., Limo, C., Ndambuki Mwiu, S., Nyaga, V., Olff, H., Ojwang, G.O., Sairowua, W., Sasine, J., Senteu, J.S., Sopia, D., Worden, J., Stabach, J.A., 2025. Predicting the impact of targeted fence removal on connectivity in a migratory ecosystem. Ecol. Appl. 35. https://doi.org/10.1002/eap.3094.
Seno, S.K., Shaw, W.W., 2002. Land tenure policies, Maasai traditions, and wildlife conservation in Kenya. Soc. Nat. Resour. 15, 79–88. https://doi.org/10.1080/089419202317174039.
Smithwick, E.A.H., Baka, J., Bird, D., Blaszscak-Boxe, C., Cole, C.A., Fuentes, J.D., Gergel, S.E., Glenna, L.L., Grady, C., Hunt, C.A., Iulo, L.D., Kaye, J., Keller, K., 2023. Regenerative landscape design: an integrative framework to enhance sustainability planning. Ecol. Soc. 28. https://doi.org/10.5751/ES-14483-280405.
Teixeira, M.L.S., Pessoa, M.S., Souza, T.B., Hambuckers, A., Lopes, P.P., 2025. Forest loss and increased edge density reduce diversity and ecological functionality of dung beetle assemblages in the tropical Atlantic Forest. Biodivers. Conserv. 34, 619–642. https://doi.org/10.1007/s10531-024-02990-y.
Thompson, D.M., Serneels, S., Kaelo, D.O., Trench, P.C., 2009. Maasai Mara – land privatization and wildlife decline: can conservation pay its way? In: Homewood, K., Kristjanson, P., Trench, P.C. (Eds.), Staying Maasai? Livelihoods, Conservation and Development in East African Rangelands. Springer New York, New York, NY, pp. 77–114. https://doi.org/10.1007/978-0-387-87492-0_3.
Tischendorf, L., 2001. Can landscape indices predict ecological processes consistently? Landsc. Ecol. 16, 235–254. https://doi.org/10.1023/A:1011112719782.
Tscharntke, T., Tylianakis, J.M., Rand, T.A., Didham, R.K., Fahrig, L., Batáry, P., Bengtsson, J., Clough, Y., Crist, T.O., Dormann, C.F., Ewers, R.M., Fr"und, J., Holt, R. D., Holzschuh, A., Klein, A.M., Kleijn, D., Kremen, C., Landis, D.A., Laurance, W., Lindenmayer, D., Scherber, C., Sodhi, N., Steffan-Dewenter, I., Thies, C., van der Putten, W.H., Westphal, C., 2012. Landscape moderation of biodiversity patterns and processes: eight hypotheses. Biol. Rev. 87, 661–685. https://doi.org/10.1111/j.1469-185X.2011.00216.x.
Turner, M.G., Gardner, R.H., 2015. Landscape Ecology in Theory and Practice: Pattern and Process.
Tyrrell, P., Buitenwerf, R., Brehony, P., Løvschal, M., Wall, J., Russell, S., Svenning, J.C., Macdonald, D.W., du Toit, J.T., Kamanga, J., 2022. Wide-scale subdivision and fencing of southern Kenyan rangelands jeopardizes biodiversity conservation and pastoral livelihoods: demonstration of utility of open-access landDX database. Front. Conserv. Sci. 3. https://doi.org/10.3389/fcosc.2022.889501.
Waas, T., Hugé, J., Block, T., Wright, T., Benitez-Capistros, F., Verbruggen, A., 2014. Sustainability assessment and indicators: tools in a decision-making strategy for sustainable development. Sustainability 6, 5512–5534. https://doi.org/10.3390/su6095512.
Wales, M., Chabari, F.N., 1979. District ranch development briefs, Nairobi, Kenya. https://hdl.handle.net/10568/4462.
Watts, K., Whytock, R.C., Park, K.J., Fuentes-Montemayor, E., Macgregor, N.A., Duffield, S., McGowan, P.J.K., 2020. Ecological time lags and the journey towards conservation success. Nat. Ecol. Evol. 4, 304–311. https://doi.org/10.1038/s41559-019-1087-8.
Xi, H., Huang, C., Ou, W., Li, J., Wang, F., Tao, Q., Tao, Y., 2024. An assessment framework for landscape sustainability based on ecosystem service supply-flow-demand. Landsc. Ecol. 39. https://doi.org/10.1007/s10980-024-01855-7.
Yao, Y., Yang, Y., 2025. Spatiotemporal effects of landscape structure on the trade-offs and synergies among ecosystem service functions in Yangtze River Economic Belt, China. Sci. Rep. 15. https://doi.org/10.1038/s41598-025-99295-z.
Zandlová, M., Skokanová, H., Trnka, M., 2023. Landscape change scenarios: developing participatory tools for enhancing resilience to climate change. Environ. Manag. 72, 631–656. https://doi.org/10.1007/s00267-023-01840-x.
Zhang, R., Tian, D., Chen, H.Y.H., Seabloom, E.W., Han, G., Wang, S., Yu, G., Li, Z., Niu, S., 2022. Biodiversity alleviates the decrease of grassland multifunctionality under grazing disturbance: a global meta-analysis. Global Ecol. Biogeogr. 31, 155–167. https://doi.org/10.1111/geb.13408.
Zhou, J., Chen, W., Cai, Y., Meng, Y., Wang, Y., Liu, Q., Luo, S., Peng, J., 2025. Effects of landscape pattern changes on ecosystem services: a case study of Ruoergai Plateau. Sci. Rep. 15. https://doi.org/10.1038/s41598-025-28635-w.