Land cover scenarios in four Kenyan arid and semi-arid regions by 2050

SEI working paper
July 2024

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Published by

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www.sei.org

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IMARA project team in Kanyerus, West Pokot county © Beatrice Adoyo (World Agroforestry)

DOI: https://doi.org/10.51414/sei2024.029

The Integrated Management of Natural Resources for Resilience in Arid and Semi-Arid Lands (IMARA) is a program implemented by World Vision Kenya in collaboration with Stockholm Environment Institute (SEI), Northern Rangelands Trust (NRT), Safer World and Maasai Mara Wildlife Conservancies Association (MMWCA) to enhance resilience of ASAL through the restoration of degraded natural resources. Founded in 2018 with a primary goal of exploring the interconnections among water, energy and food systems, the IMARA program has concentrated on community-driven initiatives for land restoration and regeneration. The aim is to boost carbon sequestration, reduce the carbon footprint in program-operations areas, advocate for clean water and sanitation, advance gender equity and inclusion, and address disaster management challenges.

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Summary

Transitions in land use and land cover (LULC) are key indicators of human activities, impacting both the environment and human well-being. Spatiotemporal analysis and the projection of future LULC trends under various scenarios are crucial tools for monitoring past changes, predicting future developments, and guiding management interventions to achieve desired LULC trajectories.

This study used the freely available, open source LULC maps for 2001 (when the dataset was first available), 2011 and 2021 to perform a spatiotemporal analysis of LULC changes in key areas in Kenya where changes in forest cover could help to prevent land degradation. Three scenarios were generated and used to project LULC in 2050: achieving a 10% forest cover, converting forests to croplands, and restoring degraded forests. The analysis was conducted for four counties that are primarily arid and semi-arid lands (ASAL), and in which the Integrated Management of Natural Resources for Resilience in Arid and Semi-Arid Lands (IMARA) program is implemented. These counties are Turkana, West Pokot, Elgeyo Marakwet and Narok.

Based on the findings of this study, the distribution of LULC classes among the four counties varies considerably. This suggests that decisions regarding the selection and implementation of sustainable land management interventions should be tailored to the specific geographical context. For counties with conditions similar to Turkana, the focus should be on increasing tree cover and restoring degraded lands. In contrast, for counties resembling Narok, West Pokot and Elgeyo Marakwet, halting deforestation may be a more effective starting point for environmental conservation.

As a signatory to multilateral agreements addressing climate change and its impacts, the Kenyan government is committed to achieving a 10% forest cover due to its critical role in climate regulation and environmental protection. Our study found that adopting interventions to maintain a 10% forest cover (scenario 1) would yield the most favourable environmental outcomes by 2050. In all four counties, this scenario not only increased forest cover but was also associated with an expansion in croplands.

Our modelling also indicates that by 2050, the cropland proportion attained under scenario 1 (achieving 10% forest cover) will not be significantly different from that under scenario 2 (forest-to-cropland conversion). This is attributed to the significant role of healthy forest cover in providing favourable conditions to croplands through climate regulation, conservation of underground water (groundwater resources) and protection of soils from erosion.

We observed the occurrence of croplands along rivers, especially in Turkana and West Pokot counties, which implies that forests are likely to be converted to cropland in these areas due to the availability of water resources for cultivation. Coupled with the conversion of wetlands to croplands, as identified in our analysis, we anticipate possible wetland degradation through over-extraction and pollution of water resources.

Likewise, the observed proximity of farmlands to forest also could promote deforestation through forest-to-cropland conversion. This potential outcome

underscores the importance of zoning to clearly demarcate forest lands from cultivable parcels. Such zoning can help prevent encroachment into forests and support sustainable conservation efforts. According to scenario 2, the "*Shamba* system", in which farmers are allowed to cultivate within forests, is expected to significantly contribute to the loss of forest cover.

Spatial mapping of LULC also reveals the linear distribution of forest cover along water bodies, especially in Turkana County. Owing to the challenges of invasive species, and the fact that the severity of their implications increases with their spread, it is important for the local communities to understand the long-term implications of invasive species and the approaches to contain their extent to an acceptable threshold. Capacity-building programs aimed at building consensus on the definition, impacts and management of invasive species can be valuable tools for early detection and rapid response to invasions by "alien" or "non-native" species.

Scenario analysis of LULC provides insight into the implications of alternative management strategies. However, while spatiotemporal LULC analysis is important in monitoring the implications of alternative LULC changes, integrating local knowledge and experience can enhance our understanding of the drivers behind the observed and projected land cover transitions. Consequently, land management interventions should be context-specific and evidence-based for them to yield practical and sustainable solutions.

Abbreviations

AFR100	African Forest Landscape Restoration Initiative
ASAL	Arid and semi-arid land
DEM	Digital elevation model
ESA	European Space Agency
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic information system
IMARA	Integrated Management of Natural Resources for Resilience in Arid and Semi-Arid Lands
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IUCN	International Union for Conservation of Nature
LULC	Land use and land cover
MMWCA	Maasai Mara Wildlife Conservancies Association
MODIS	Moderate Resolution Imaging Spectroradiometer
NRT	Northern Rangelands Trust

1. Introduction

Anthropogenic activities are considered one of the key driving forces of environmental disturbances, often reflected in the changes of land use and land cover (LULC) (Abbas et al., 2021; Bajocco et al., 2012). Transitions in LULC can serve as an indicator of the interactions between human activities and the natural environment (Zhou et al., 2008).

In arid environments, which are dominated by fragile ecosystems, land cover change often reflects the most significant impact on the environment due to human activities. Anthropogenic pressure on fragile arid and semi-arid land (ASAL) ecosystems has often translated into competition for these regions' limited resources, resulting in resource-based conflicts and loss of life and property (World Bank, 2020).

The analysis of historical patterns of LULC change and their association with other environmental and human drivers is vital to the understanding of human impacts on the natural environment. The availability of extensive sets of remote sensing imagery has facilitated the examination of spatiotemporal patterns of environmental components and the influence of human actions (Zhou et al., 2008).

A spatiotemporal analysis of LULC change can inform context-specific land management decisions. Such snapshots of change over time can provide an understanding of underlying drivers of change. However, while crucial, such spatiotemporal analyses have limitations regarding predicting future resource statuses or determining optimal strategies for achieving desired LULC changes. To address this, pairing LULC analyses with scenarios becomes advantageous. Scenarios help in assessing the potential impacts of past and current land management decisions on future LULC trends. They aid in evaluating different management strategies, including shifts in land use patterns, establishment of various land use configurations, and analysing the effects of diverse land use approaches (Abbas et al., 2021; FAO, 2016; Sharma et al., 2018; Sohl et al., 2012).

According to Kangas et al. (2018), prevalent scenarios utilized in LULC modelling can be classified into statistical-trend extrapolations or predictive models foreseeing transitions among LULC classes. The choice between these methods depends on the analysis purpose. This study employed a predictive model to simulate future land cover, considering changes in other land cover or land use classes. The study is a part of the Integrated Management of Natural Resources for Resilience in Arid and Semi-Arid Lands (IMARA), a seven-year program (2018–25), implemented by World Vision in collaboration with SEI, Northern Rangelands Trust (NRT), Safer World and Maasai Mara Wildlife Conservancies Association (MMWCA), meant to enhance resilience of ASAL through the restoration of degraded natural resources, through exploring the interconnections among water, energy and food systems.

In this report, we focused on alterations in forest cover, which are considered to have significant consequences on the environment (Deribew & Dalacho, 2019; Kissinger et al., 2012; Teng et al., 2019). This is due to their high capacity to define climatic conditions by sequestering carbon, conserve soils and provide habitats. Consequently, understanding their potential use, which is contingent on forest management strategies, and evaluating alternative approaches and their consequences in terms of future forest products and services are integral to participatory and collaborative decision-making processes and policy formulation (FAO, 2016, 2021; UNCCD, 2019).

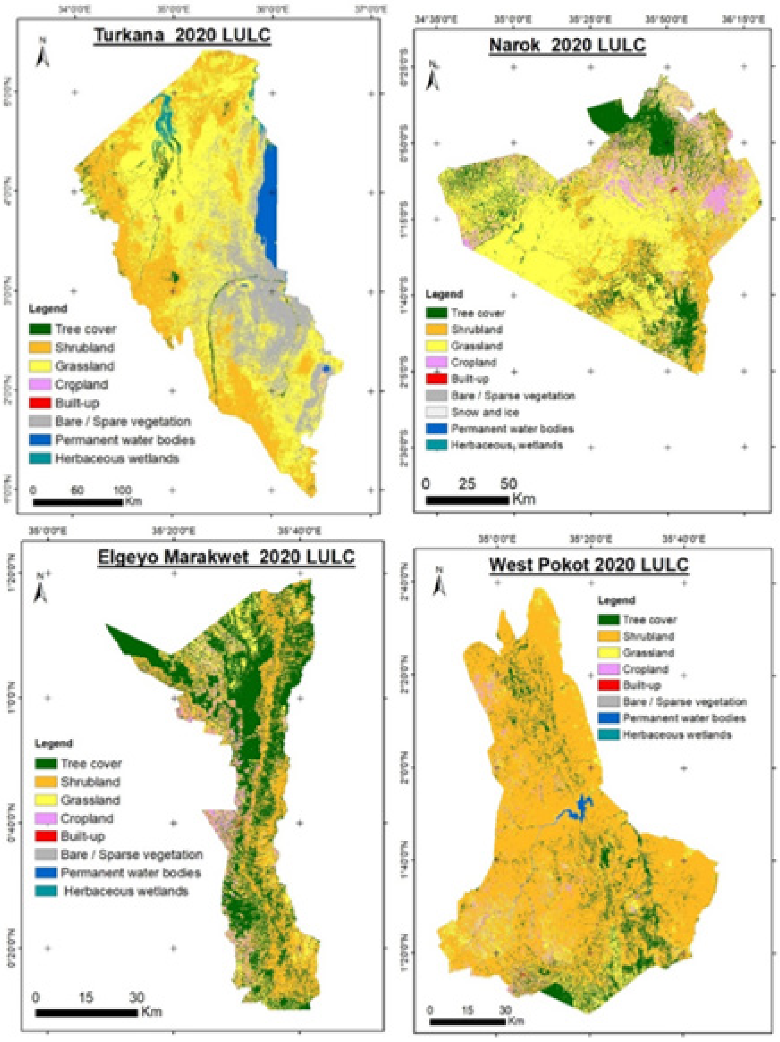
To inform sustainable land management interventions, we analysed LULC trends within the study area from 2001 to 2021, using historical changes in land cover. We then generated key scenarios that are relevant in forest management, and then we projected future LULC based on these scenarios.

2. Methodology

2.1 Study area

This analysis was carried out in four Kenyan counties within which IMARA programs are being implemented: Elgeyo Marakwet, Turkana, West Pokot and Narok (Figure 1). All four counties are mostly composed of ASALs within the Great Rift Valley and are characterized by their vulnerability to the impacts of climate change and land degradation in Kenya (Broeck, 2009; Odhiambo, 2013; Shanguhyia & Koster, 2014). The ASAL regions also are more prone to impacts from invasive plant species, where non-endemic trees and shrub species displace endemic ones and pose adverse impacts on ecosystem services and livelihoods, as well as hinder effective ecosystem restoration. One such species, *Prosopis juliflora,* dominates ASAL regions, posing a net negative impact on ecosystem services (Adoyo et al., 2022; Maundu et al., 2009; Mwangi & Swallow, 2008; Wakie et al., 2016).

Figure 1: IMARA project implementation sites: Turkana, Narok, Elgeyo Marakwet and West Pokot counties.



Source: Authors' own, based on ESA LULC dataset.

2.2 Data sources and analysis

We used the most recent European Space Agency (ESA) LULC data available, at a fine spatial resolution of 10 m, to map the current LULC classes in the project sites. Based on satellite imagery that detects different land cover, including vegetation type and water bodies, the dataset has a classification accuracy of 73% and is available just for the year 2000.

This was supplemented with years for when data are available from the Moderate Resolution Imaging Spectroradiometer (MODIS) LULC maps, for 2001, 2011 and 2021. Using ArcGIS software version 10.3, we clipped the shapefiles for the study sites, performed LULC change detection analysis, and calculated the area for each LULC class.

Scenario generation

We generated LULC scenarios using the proximity-based scenario generator in the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software. The proximity-based scenario generator creates different patterns of LULC based on user-defined convertible LULC (LULC class to be converted to other classes) and focal points classes (the intended LULC class into which the convertible LULC class is converted to during a scenario generation). The user determines which habitat can be converted and what these habitats are converted to, as well as type of pattern, based on proximity to the edge of a focal habitat. In this manner, an array of land use change patterns can be generated, such as cropland encroaching into the forest from the forest edge. The resulting land use maps can then be used as inputs to InVEST models or other spatial analyses to project future LULC based on the generated scenarios (InVEST, 2016).

To identify the user-defined focal points and convertible LULC classes, we conducted a trajectory analysis of forest cover in ArcMap. A LULC trajectory is a sequential transition of LULC over multiple timeframes (Zhou et al., 2008). Unlike LULC change, which assesses changes between two timeframes, land cover trajectories evaluate successive LULC changes over more than two timeframes.

Using the ArcMap's “combine tool”, we integrated the LULC for the three timeframes to produce a map showing all the possible combinations of forest cover over the selected timeframes. For instance, one possible combination may indicate areas with the presence of forest cover in all the three timeframes (T1, T2, and T3), while another combination may represent areas with the presence of forests in T1 and T2, but the absence of forests in T3, indicating its conversion to other land uses. We then categorized the output into three major trends, to illustrate potential forest cover according to the modelling:

- **Stable forest cover (trajectory trend 1):** areas exhibiting consistent forest cover since the establishment of the forest or tree cover. These areas indicate successful forest management and are less prone to deforestation.

- **Projected deforestation (trajectory trend 2):** areas with a consistent presence of forest cover until the most recent year (2021), but with projected absence of forest cover by 2050. These areas are under threat of future degradation and require prioritized forest restoration measures.

- **Consistent deforestation (trajectory trend 3):** parcels that initially had forest cover but have consistently lost it over time, with no attempt at restoration or replacement. This trend indicates ongoing deforestation or failure to undertake reafforestation measures on previously deforested land.

The above three trajectories were then applied to produce scenarios for forest management initiatives. The three scenarios considered were: the attainment of a recommended tree cover of 10% (the national goal), conversion of forest cover to croplands through the "*Shamba* system" (in which farmers are allowed to cultivate crops in forests), and maintaining existing forest cover while restoring degraded forestland. Each of these scenarios is presented below.

Scenario 1: attainment of the recommended 10% tree cover

Kenya has committed to achieving a 10% tree cover by 2030 (Government of Kenya, 2007) as part of its commitment to multilateral agreements such as the Bonn Challenge and the African Forest Landscape Restoration Initiative (AFR100). In this scenario, we projected potential locations for implementing afforestation interventions to fulfil the 10% tree cover commitment.

For each county, the current forest cover was calculated and subtracted from the recommended 10% forest cover within the respective counties. The result is equal to the deficit needed to fill, to meet the 10% target. This was then used to generate scenario 1 as the maximum convertible land, using these areas as representations of places to convert to achieve 10% forest cover.

Scenario 2: integrating crops into forest lands through the Shamba system

There are conflicting findings on the integration of crops into forests. On the one hand, previous studies have reported forest-to-cropland conversion as the most dominant transition advancing deforestation (Berrahmouni & Mansourian, 2021; Oberle, 2020). On the other hand, the *Shamba* system, allowing communities to cultivate within forests while tending young seedlings, has been considered an inclusive approach to communal participation in forest conservation (Odieny, 2022). However, in forest areas such as the Mau Forest, where the *Shamba* system has been adopted, there are potential challenges in achieving long-term forest management objectives. Farmers are often tempted to engage in illegal logging within the forest instead of conserving tree seedlings.

Given the increasing occurrences of famine and drought in Kenya, there is a likelihood of reintroducing the *Shamba* system approach to enhance food security in the country. Therefore, evaluating its potential future impacts is crucial in providing guidance to decision-makers regarding sustainable and integrated forest management interventions.

This scenario was generated by considering the worst-case scenario, where farmers, instead of planting trees alongside crops to attain the 10% tree cover, “fill the deficit” by converting forest land into croplands. The code corresponding to croplands was used as the replacement land cover, while the code for forests was applied as the convertible land cover. The additional area needed to meet the 10% forest cover was used as the convertible acreage.

Scenario 3: maintenance of existing forest cover and restoring degraded forest land

This scenario projects LULC status if consistently degraded forest lands are restored and conserved. The scenario generation was therefore limited to areas experiencing trajectories 2 and 3, which are considered as either deforested or vulnerable to deforestation. The maximum convertible land was calculated as areas under forest trajectory trend 3 above, which have experienced consistent forest loss. As a precondition, land cover under trajectory 2 (vulnerable forest cover) and trajectory 1 (consistent forest cover) were maintained under forest cover and hence excluded from convertible land cover.

2.3 Projection of LULC

The land change modeller in TerrSet software (Eastman, 2016) was used in projecting future LULC for the year 2050, while considering the generated scenarios in section 2.2 above. The LULC simulation model was trained based on landscape features (elevation, population density, distance to roads, distance to rivers, rainfall, soil data and LULC; see Table 1) that have been considered significant in predicting LULC change transitions (Baig et al., 2022; Eckert et al., 2020), owing to their likelihood of influencing a change from one LULC to another. In generating LULC transition potential, the MODIS LULC land cover maps for 2011 and those of each generated scenario were used to produce LULC change maps. These maps illustrate transitions in LULC between the two input maps.

Markov chain analysis was then applied to project the 2050 LULC maps. Using the transition potential maps that define the probability of a LULC changing to another LULC class, Markov chain analysis competitively assigns a LULC class for each pixel for the future scenario. The output was exported to Displayr software, where a Sankey chart representing the temporal flow among LULC classes was produced to analyse trajectories in LULC changes.

Table 1. Variables used in modelling future LULC

Variable used	Link to the parameter applied
Soil types	https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/446ed430-8383-11db-b9b2-000d939bc5d8 Accessed on 2 June 2022
Population density	https://energydata.info/dataset/kenya-population-density-2015/resource/a57fce6f-b00c-428f-b1f9-86855c64b9df Accessed on 8 January 2022
Distance to rivers (Euclidean distance in metres)	https://www.wri.org/data/kenya-gis-data Accessed on 17 June 2022
Distance to roads (Euclidean distance in metres)	https://www.wri.org/data/kenya-gis-data Accessed on 17 June 2022
Elevation in metres	https://www.worldclim.org/ Accessed on 12 May 2022
2021 LULC map	https://developers.google.com/earth-engine/datasets/catalog/modis Accessed on 17 July 2022
Mapped forest reserves	https://opendata.rcmrd.org/datasets/rcmrd::kenya-gazetted-forest-dataset/explore?location=-0.720060%2C37.762785%2C6.72Site Accessed on 2 June 2022
Amount of water found within 150 m of the soil surface. The proportion of rain infiltrates into the soil and the soil's storage capacity. Pixel size: 30 m	https://power.larc.nasa.gov/ Accessed on 12 May 2022

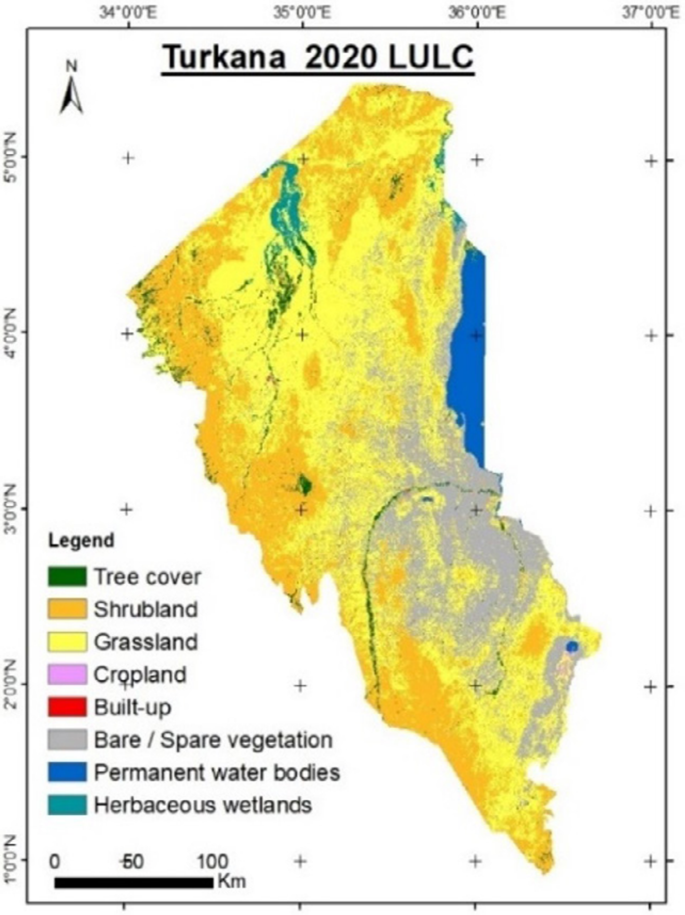
3. Observed LULC between 2001 and 2021

3.1 Turkana County

The main LULC classes in Turkana County are grasslands, shrublands, bare lands, water bodies, tree cover, herbaceous wetlands, croplands and built-up areas such as settlements and buildings in the order of their dominance (Figure 2). Approximately half (46%) of Turkana County is covered by grasslands, which is the most dominant LULC, while built-up areas are the least dominant.

In 2021, a significant increase in most LULC classes was registered, including a sharp rise in croplands, wetlands and water bodies (Figure 2). The only LULC class that experienced a sharp decline was the bare ("barren") land. The observation confirms the positive correlation between water availability and farming practices (Bandyopadhyay et al., 2009; Nkomoki et al., 2018).

Figure 2: Distribution of LULC in Turkana County derived from ESA 2020 LULC dataset

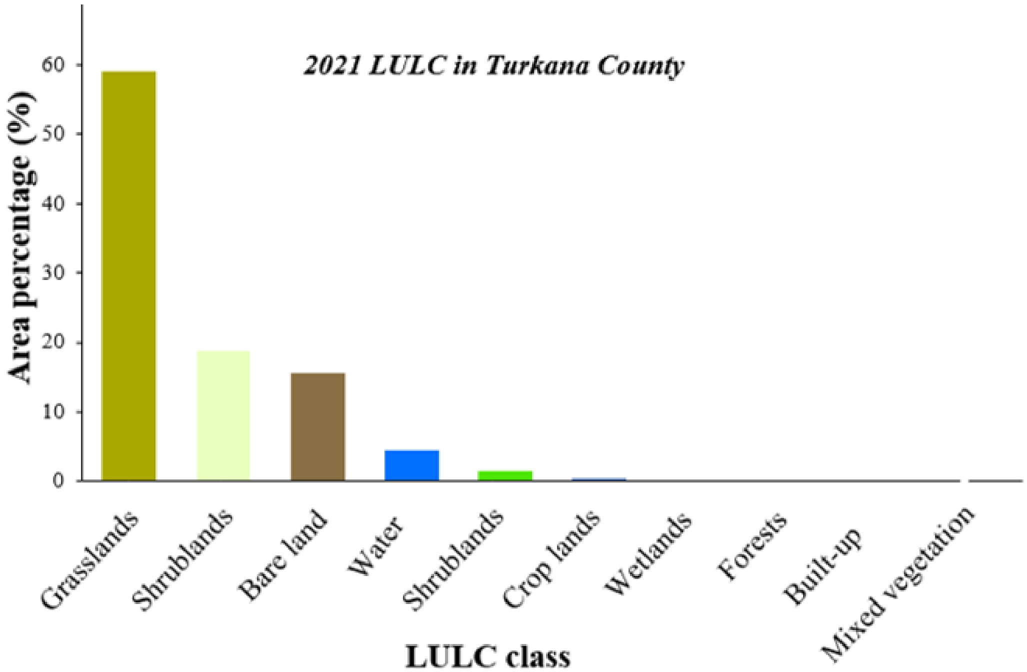


Source: Authors' own, adapted from ESA dataset.

A considerable amount of the Turkana land mass (15%) is bare or barren land indicating that the majority (60%) of such areas are non-vegetated, or covered by rocks, sand or soil (Gray et al., 2019), thus making them vulnerable to soil erosion and its impacts. An integrated soil management approach should therefore be a key element of land management strategies within the county.

While the Kenyan government is committed to attaining 10% tree cover, due to its significance in regulating climate and protecting the environment, the forest cover in Turkana County occupies less than 1% of the total LULC (Figure 3). Parallel analysis with ESA LULC, which is the most accurate owing to its fine spatial resolution of 10 m, showed 1.8% forest cover, which is not significantly different from outputs derived from the 250-m resolution MODIS data. This confirms a very low forest cover within the vast Turkana County, which is 68 233 km^2.

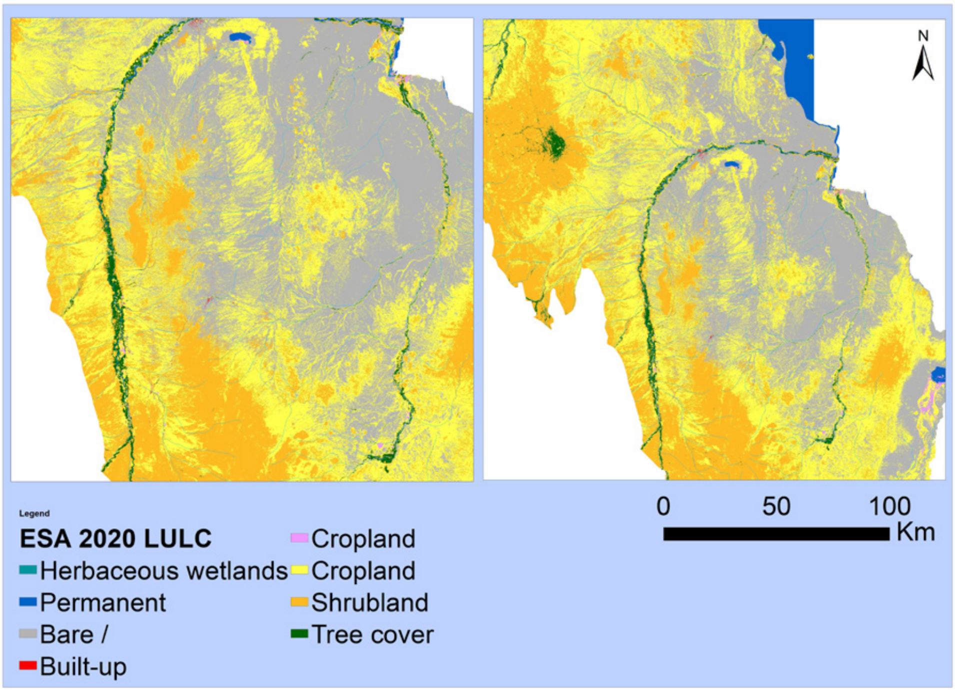
Figure 3: Percentage coverage of LULC in Turkana County in 2021.



Source: Authors' own, based on ESA datasets.

Among the four counties studied, Turkana has the least forest cover, with nearly half (46%) of its forests located within 1 km of river channels (Figure 4). The linear distribution of tree cover along rivers (Figure 4) indicates their likelihood of being invasive species. According to Eckert et al. (2020), invasive tree species such as *P. juliflora* are mainly found within a distance of between 500 and 1000 m from rivers and pathways, which often act as dispersal agents for their seeds.

Figure 4: Linear distribution of tree cover along rivers in Turkana County



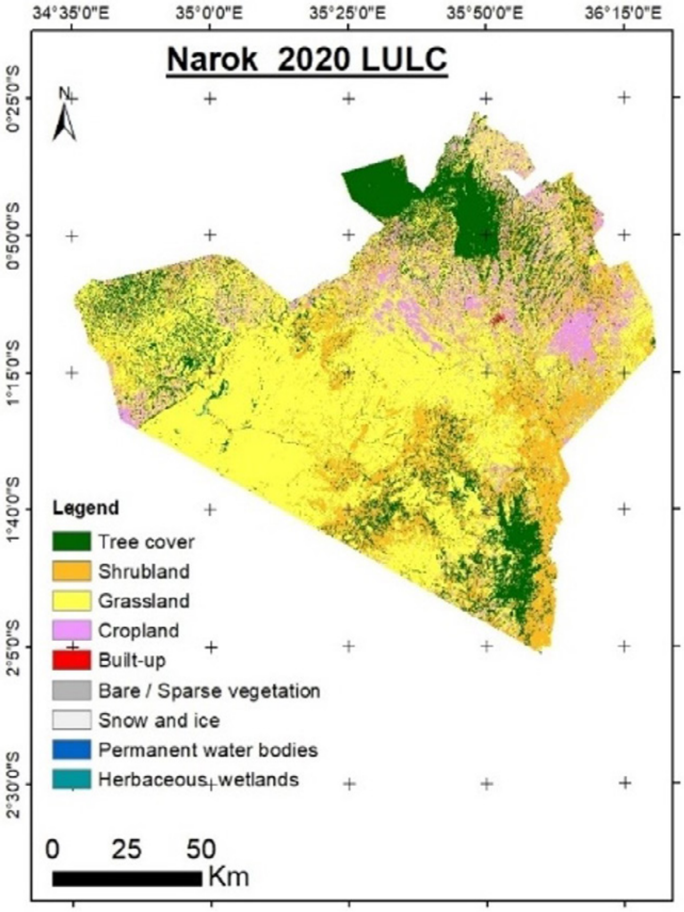
Source: Authors' own.

3.2 Narok County

The LULC classes present in Narok County are grasslands, shrublands, bare lands, water bodies, tree cover, herbaceous wetlands, croplands and built-up areas (Figure 5). The majority of the county is covered by grasslands, with dense patches of forest or tree cover in the north and southeast, as well as some parts of the west. Major towns characterized by settlement and human activities are centralized in the northeastern areas, while croplands are observed to be spreading towards forest areas (Figure 5).

Forest covers 7% of the county. Savanna and grasslands are observed surrounding the edges of the forest. Croplands are majorly confined to the central parts, which are largely lowlands and characterized by gentle terrain.

Figure 5: Spatial distribution of LULC in Narok County in the year 2020.

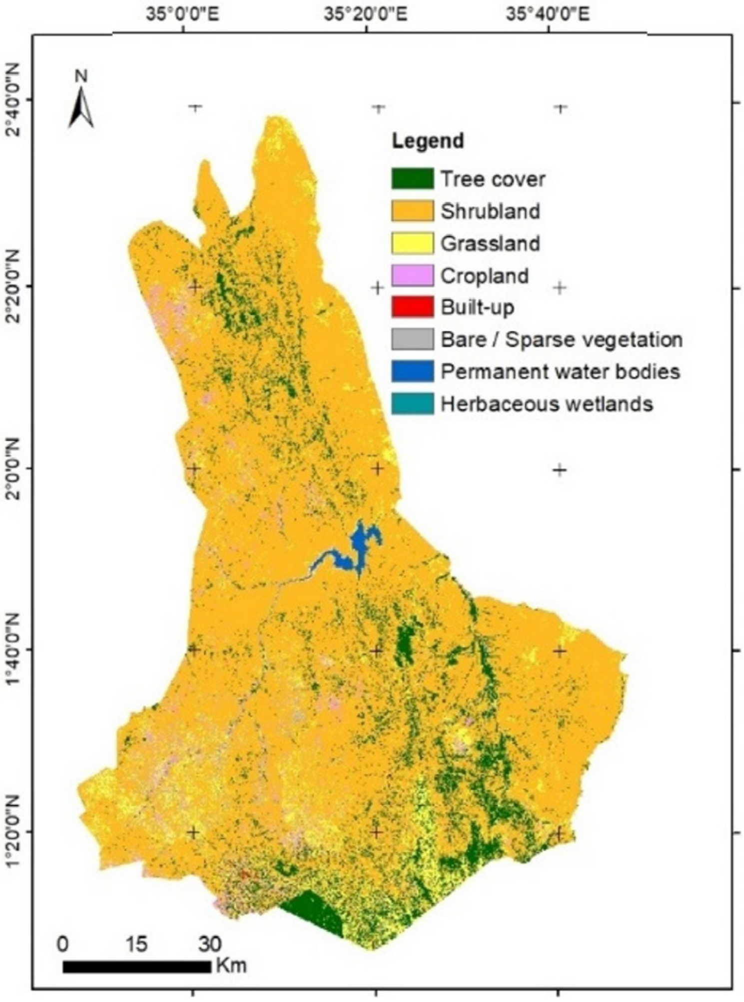


Source: Authors' own. Derived from ESA 2020 LULC dataset.

3.3 West Pokot County

West Pokot County is dominated by shrublands that are evenly spread throughout the county, apart from the southern and northern parts, which have patches of dense tree cover and grasslands (Figure 6). Based on the ESA LULC dataset, the most dominant LULC is shrublands, which occupy more than three-quarters (77%) of the entire county.

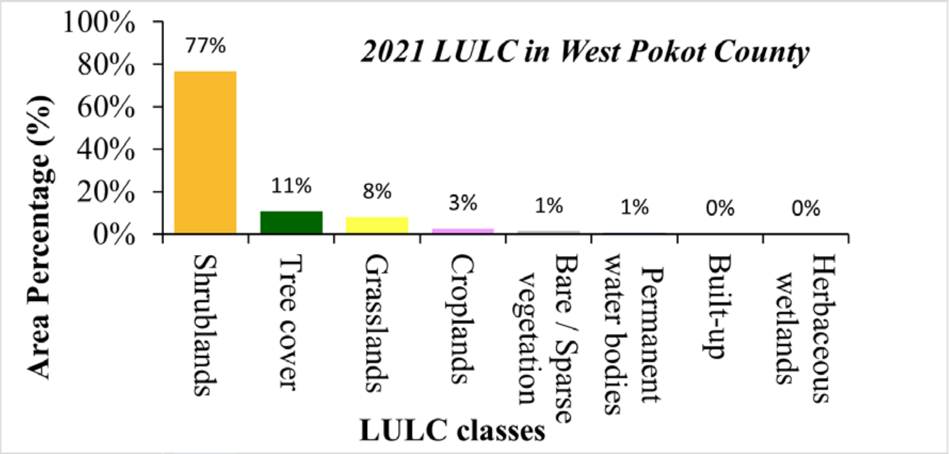
Figure 6: West Pokot LULC classes as of 2021.



Source: Author's own, adapted from ESA dataset.

Tree cover (not forest cover) occupies 11% of the overall land mass in the county (Figure 7). However, out of this, only 2% of the total LULC constitutes forests (Figure 7), which is only slightly less than the area under cultivation within the entire county. Likewise, bare land accounts for less than 1% of the total LULC; this implies low susceptibility in the county to severe impacts of soil erosion, based on the soil cover (González-Morales et al., 2018; Pandey et al., 2021).

Figure 7: Percentage coverage of different LULC classes in West Pokot County.

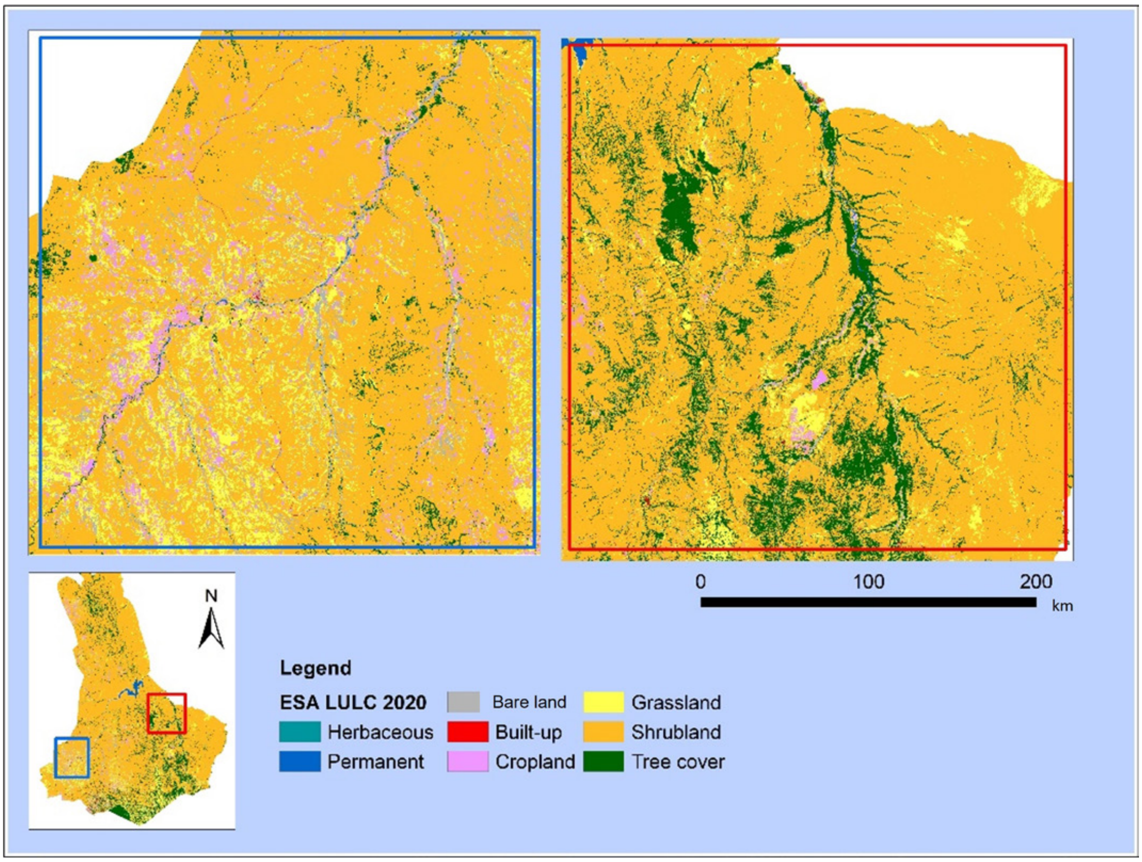


Source: Author's own, adapted from ESA dataset.

We observed that croplands and tree cover occur mostly adjacent to water bodies such as rivers (Figure 8). This occurrence is consistent with previous findings (Bandyopadhyay et al., 2009; Nkomoki et al., 2018), which linked access to water as an incentive to crop cultivation as well as to a suitable environment for the establishment of trees. As also reported, management interventions aiming to encourage agriculture and forest planting, for example, should take into consideration the availability of water sources to ensure their success.

Forest cover composes at most 2% of the total land cover in West Pokot County. Water, bare land and built-up areas constitute the least LULC in the county.

Figure 8: Distribution of croplands and tree cover along rivers in West Pokot County.

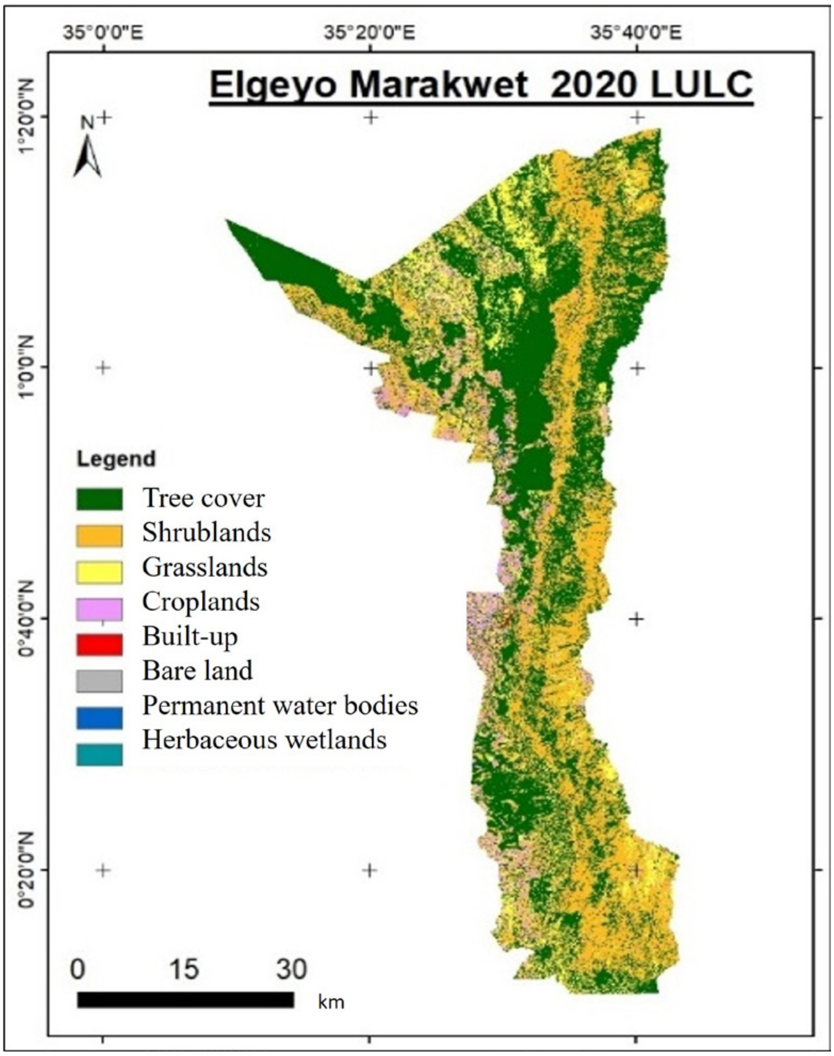


Source Authors' own, derived from ESA dataset.

3.4 Elgeyo Marakwet County

Based on ESA LULC datasets, LULC classes found in Elgeyo Marakwet County are grasslands, shrublands, bare lands, water bodies, tree cover, herbaceous wetlands, croplands and built-up areas (Figure 9). A temporal analysis of MODIS LULC points to savannas as the most dominant land cover in Elgeyo Marakwet, covering 60% of the total in 2020.

Figure 9: LULC classes in Elgeyo Marakwet County.



Source: Authors' own, adapted from ESA dataset.

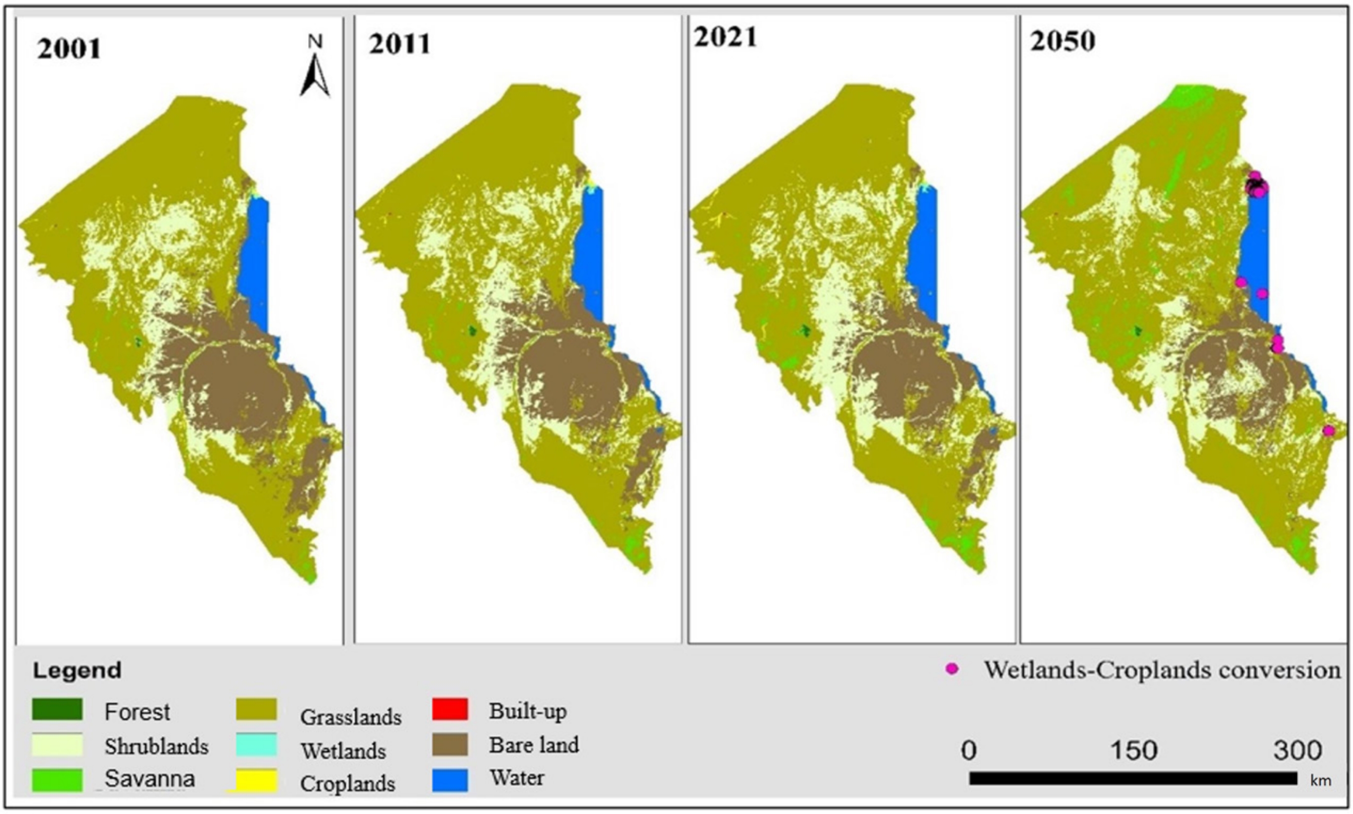
4. Projections of LULC for the year 2050 under different scenarios

Here we present projections of LULC in 2050 under the three scenarios for each county. Based on MODIS LULC datasets, we used the TerrSet software to project the LULC for 2050 and conducted a spatiotemporal analysis of LULC changes. We offer key insights from our findings and the scenarios as to how management might be steered to achieve desired outcomes.

4.1 Turkana County

The findings indicate the persistence of grasslands as a dominant land cover, an increase in savannas, and a decline in bare lands, especially in areas close to Lake Turkana, along which portions of wetlands are projected to be converted to croplands (Figure 10).

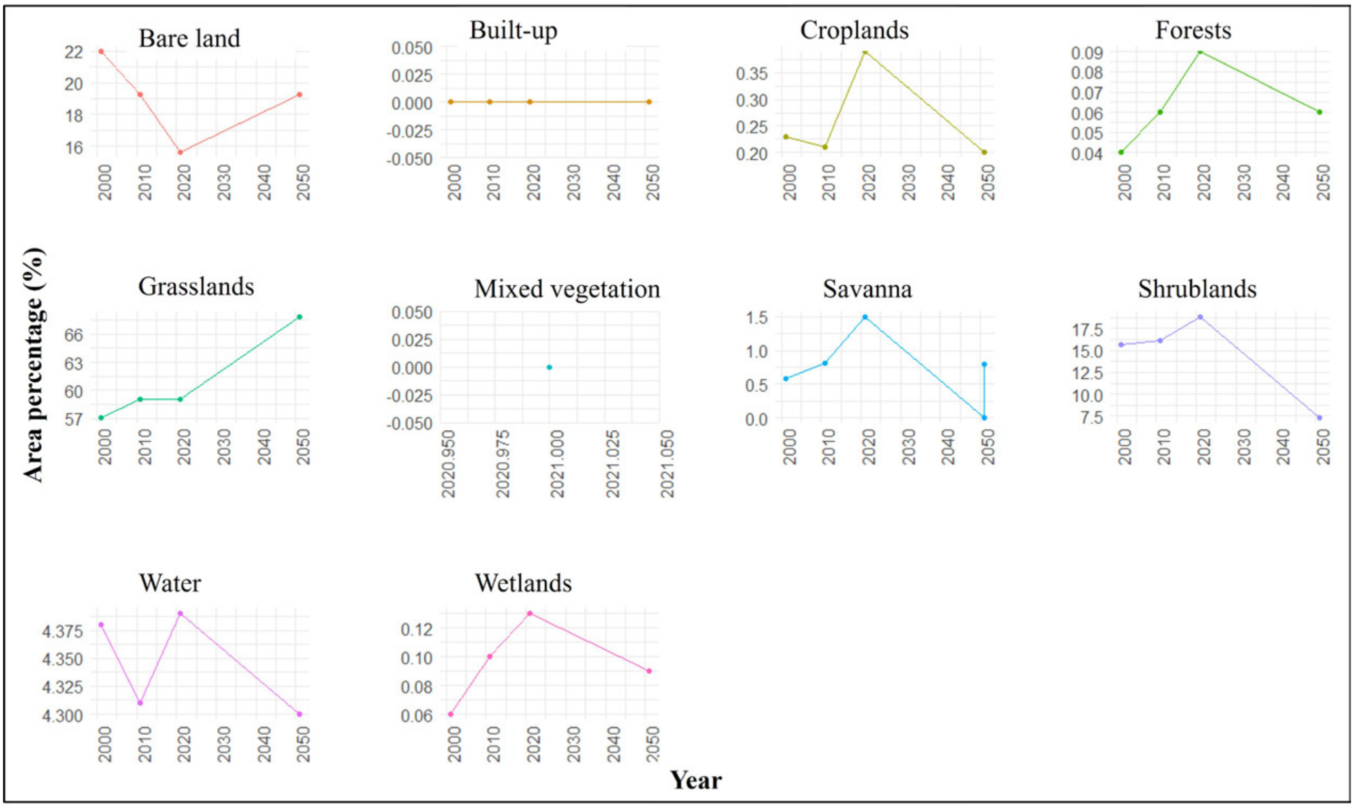
Figure 10: LULC between 2001 and 2021, with projections for 2050, in Turkana County.



Source: Authors' own, adapted from MODIS LULC dataset.

Four LULC classes – croplands, forests, built-up areas and wetlands – are projected to be less than 1% throughout the years considered in this analysis (Figure 11) with a projected decline by the year 2050. The results also indicate that between 2001 and 2021, forest cover has consistently increased (Figure 11). However, based on the biophysical and social factors used in the model, forest cover is projected to decline by 2050. The most probable explanation for this occurrence may be projected decline in rainfall and increasing temperatures, also reflected in the projected decline in the area covered by water and wetlands by 2050 (Figure 11).

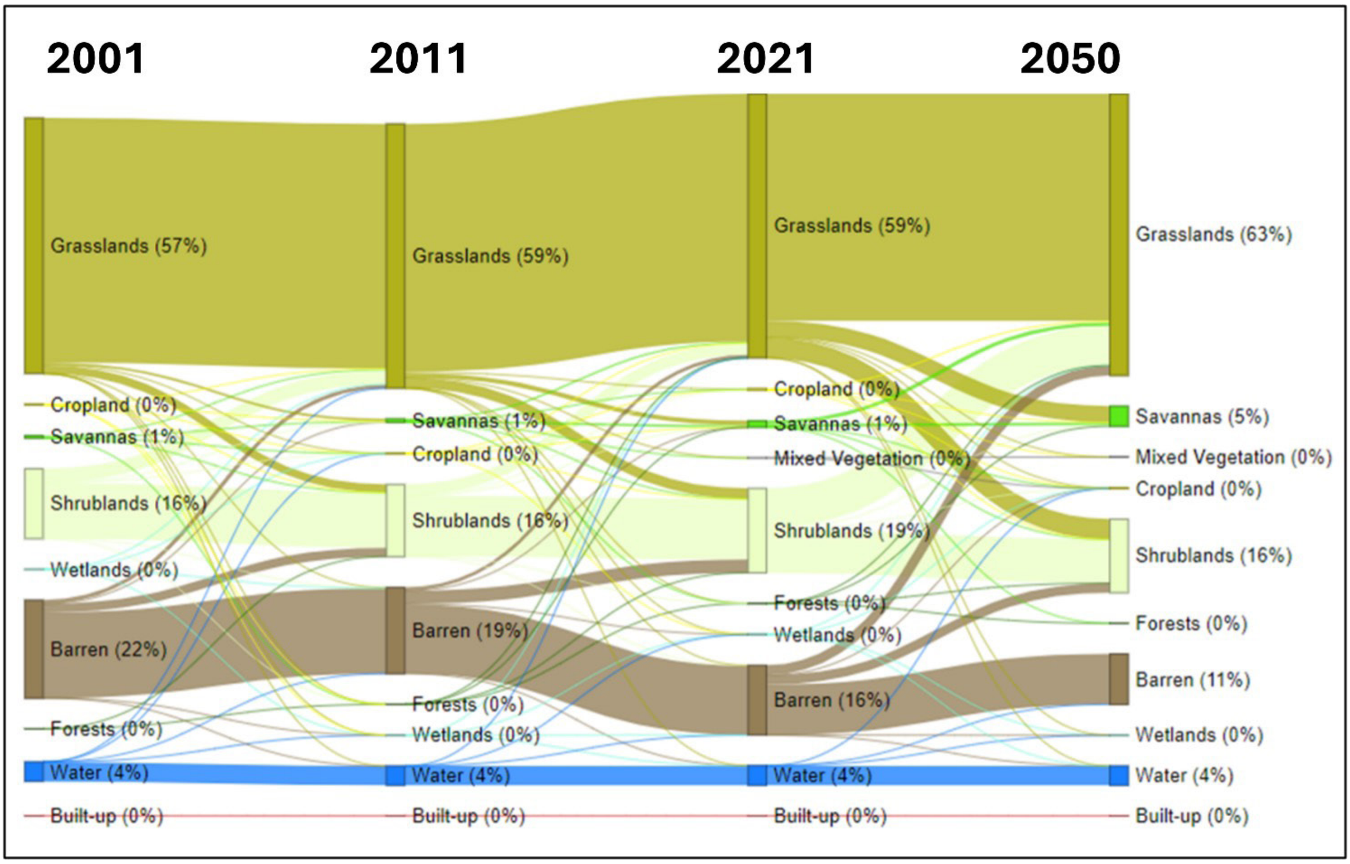
Figure 11: Temporal LULC change in Turkana.



Source: Authors' own.

All the observed changes in forest cover, whether gains or losses, were attributed to either grasslands or shrublands (Figure 12), with none of the losses in forest cover being attributed to croplands. On the contrary, any gains in croplands by 2050 are likely to be attributed to grasslands, shrublands, wetlands and bare land. While this suggests areas suitable for crop cultivation, it also indicates that areas currently occupied by forest cover in Turkana County might not be suitable for cultivation. This is because the tree cover composition in Turkana County includes more invasive species. According to Mwangi and Swallow (2008), invasive woody tree species such as *P. juliflora* extract underground water, making it impossible for any crop to grow where *P. juliflora* becomes established.

Figure 12: Trajectories of LULC in Turkana County between 2001 and 2050.



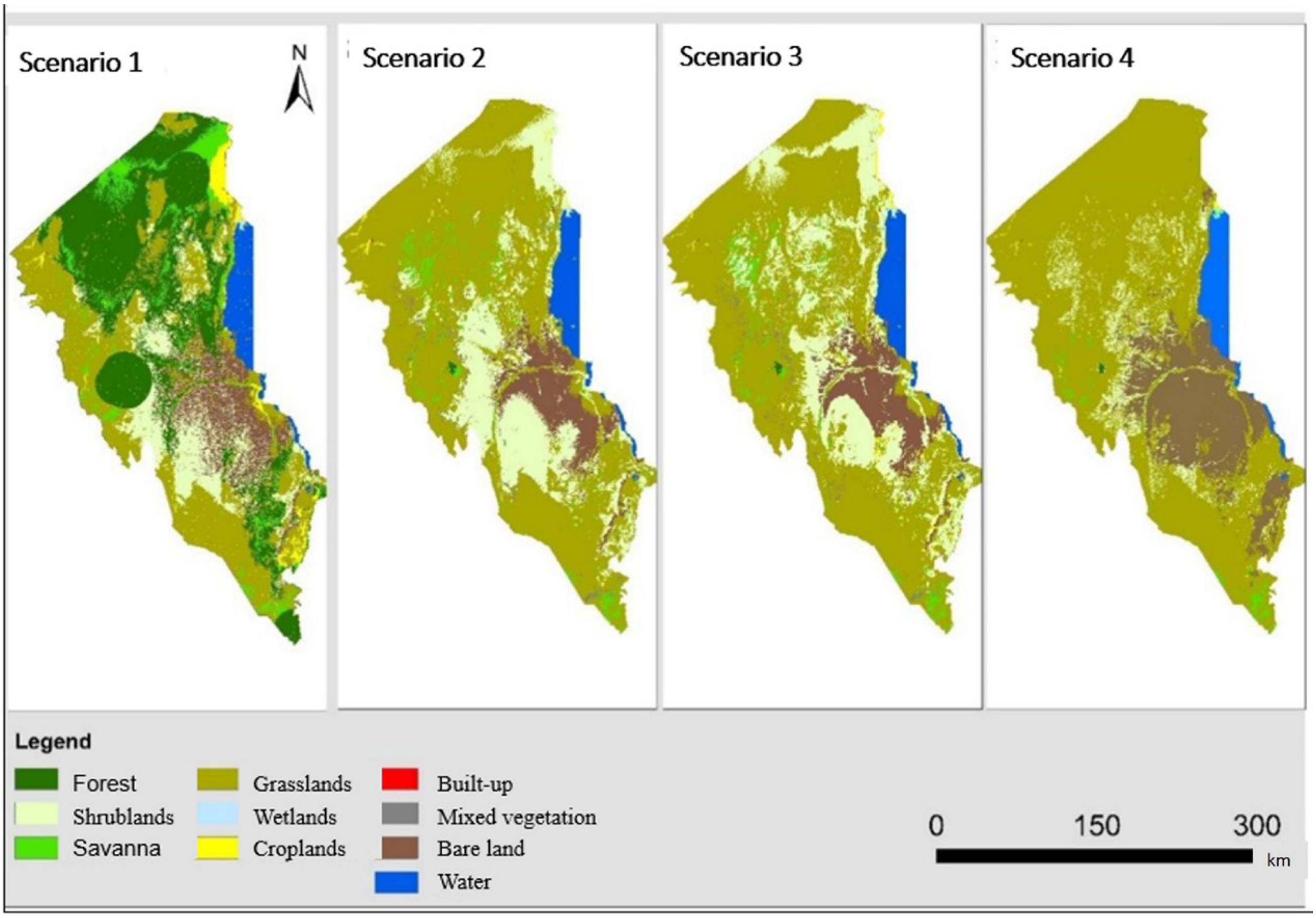
Source: Authors' own.

Although croplands seem not to encroach forest cover, their gains from wetland areas especially along Lake Turkana indicate the significance of proximity to water bodies as a determinant for suitable croplands. Thus, precautions should be taken in ensuring appropriate farming practices to minimize the degradation of such wetlands. Alternatively, owing to the observed and expected conversion of shrublands and savannas into croplands, interventions for establishing irrigation schemes on such parcels should be explored. All in all, empirical studies are needed to analyse the cropland suitability areas before implementing such interventions.

LULC scenarios

Scenario modeling and mapping (Figure 13) indicate that the most ambitious but desirable trajectory can be achieved if management interventions transition towards scenario 1, which aims to achieve a 10% forest cover. In this case, immediate interventions are channelled toward achieving a 10% forest cover, and the trend maintained until 2050. The results indicate that Turkana County will be subjected to continued vulnerability to land degradation, as indicated by widespread bare land (Figure 14).

Figure 13: A map of projected LULC under different scenarios in Turkana County by 2050.

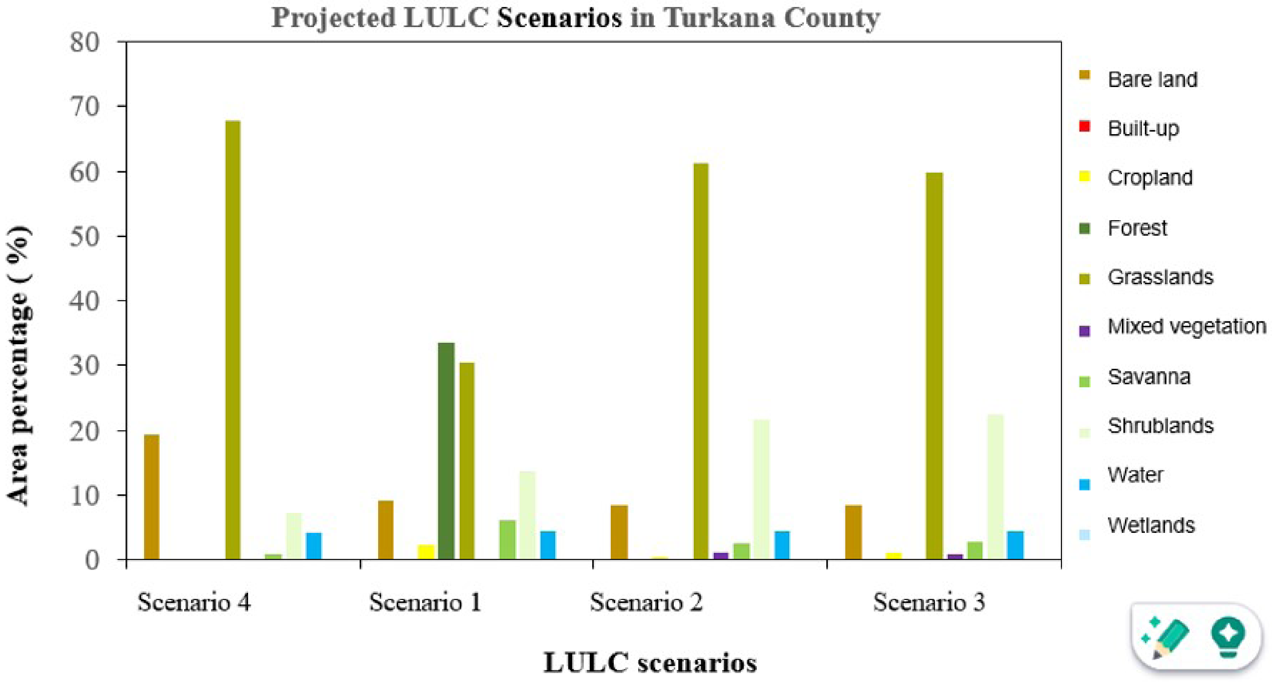


Source: Authors' own, adapted from MODIS LULC dataset.

Note: scenario 1: 2050 LULC projection if 10% tree cover is attained in 2021 and maintained; scenario 2: 2050 projection under forest-to-cropland conversion; scenario 3: 2050 projection if degraded lands are restored; and scenario 4 representing projected 2050 LULC under prevailing LULC trends, "business as usual".

Employing forest management interventions aimed at achieving 10% forest cover, such as tree planting initiatives and conservation of existing forests, is projected to yield 33% forest cover by 2050 (Figure 14). Likewise, the greatest cover of bare land (19%) is projected to be observed under the business-as-usual scenario.

Figure 14: Projected LULC under different scenarios in Turkana County by 2050, with 2021 for comparison.



Source: Authors' own.

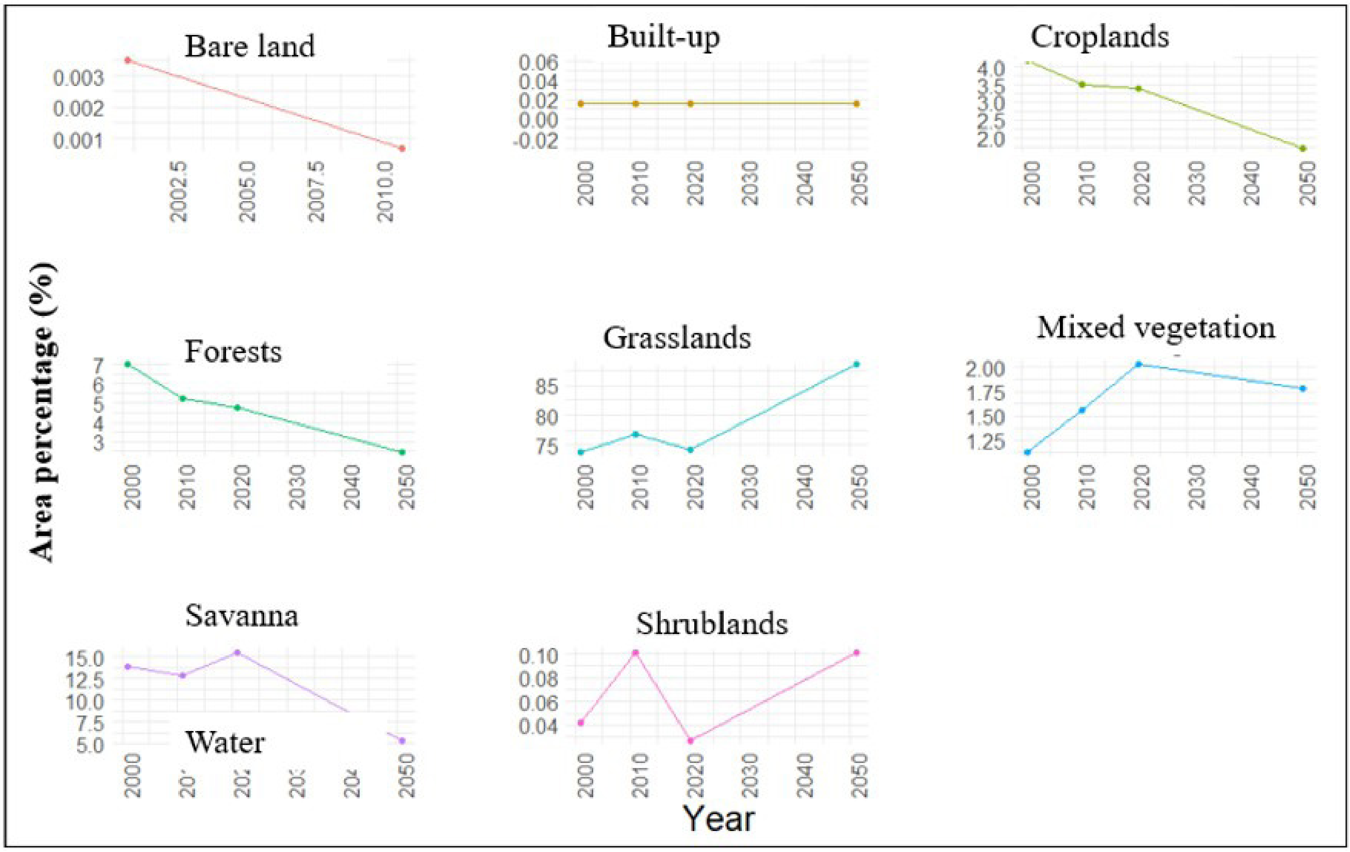
Note: scenario 1: 2050 LULC projection if 10% tree cover is attained in 2021 and maintained; scenario 2: 2050 projection under forest-to-cropland conversion; scenario 3: 2050 projection if degraded lands are restored; and BAS scenario representing projected 2050 LULC under prevailing LULC trends.

Scenario 2 (forest-to-cropland conversion) and scenario 3 (restoration of degraded forests) show a minimal difference in changes to bare land, with both scenarios simulated to result in less than 10% bare land. The model however indicates that by 2050, the highest cropland proportion will be attained under scenario 1 rather than scenario 2. This implies that the conversion of forestland into croplands may not be sustainable in optimizing productivity, leading to food security in the future. There is a risk that cropland encroachment into forests could lead to the destruction of forests, which are crucial for absorbing greenhouse gases such as carbon dioxide, protecting soils from erosion, and creating a microclimate favourable to crop production. The UN Food and Agriculture Organization (FAO) report *The State of the World's Forests 2022* emphasized that maintaining healthy forest cover through a sustainable agrifood system is the most effective way to achieve food security and optimize securing the multiple benefits that forests provide to farming systems (FAO, 2022). Thus, maintaining a sustainable forest cover, especially within dryland areas, may be a promising entry point to promote food security.

4.2 Narok County

Based on the analysis of LULC changes between 2001 and 2021, and using the three scenarios, we project an expansion of grasslands and a reduction in forest cover (Figure 15).

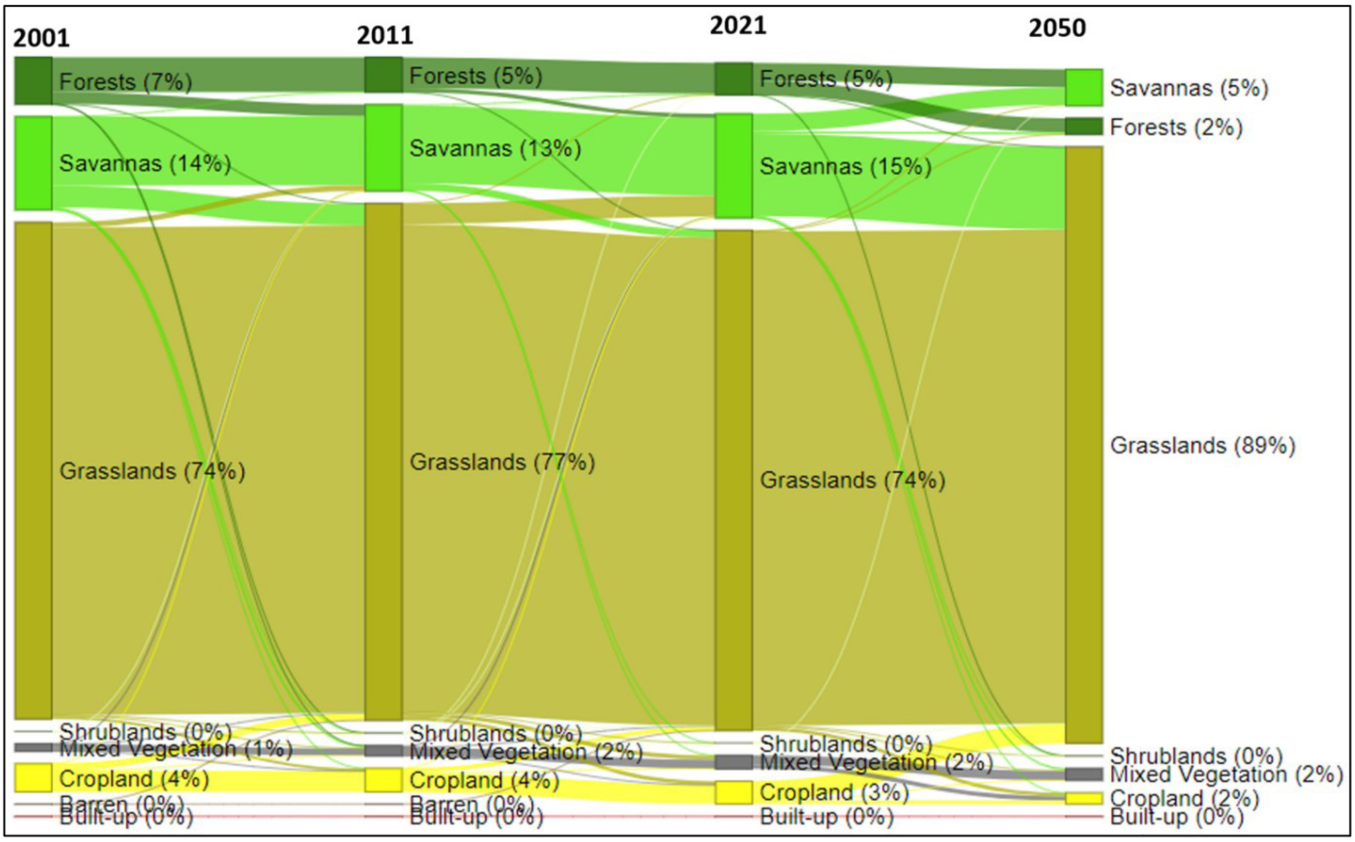
Figure 15. Temporal LULC change in Narok County between 2001 and 2050.



Source: Authors' own.

We observed that croplands have declined over the past two decades by 179 km^2, from 4% to 3%, with a projected decline trend to a further 2% by 2050 under the prevailing conditions (Figure 15). We observe that most of the losses in croplands are translated to grasslands, a trend we expect to continue (Figure 16). The last timeframe for this observation coincides with the Covid-19 pandemic, which affected transportation of farm inputs as well as the food-related markets and trades, leading to a decline in crop production (Government of Kenya, 2018).

Figure 16: Temporal transitions among LULC between 2001 to 2050.

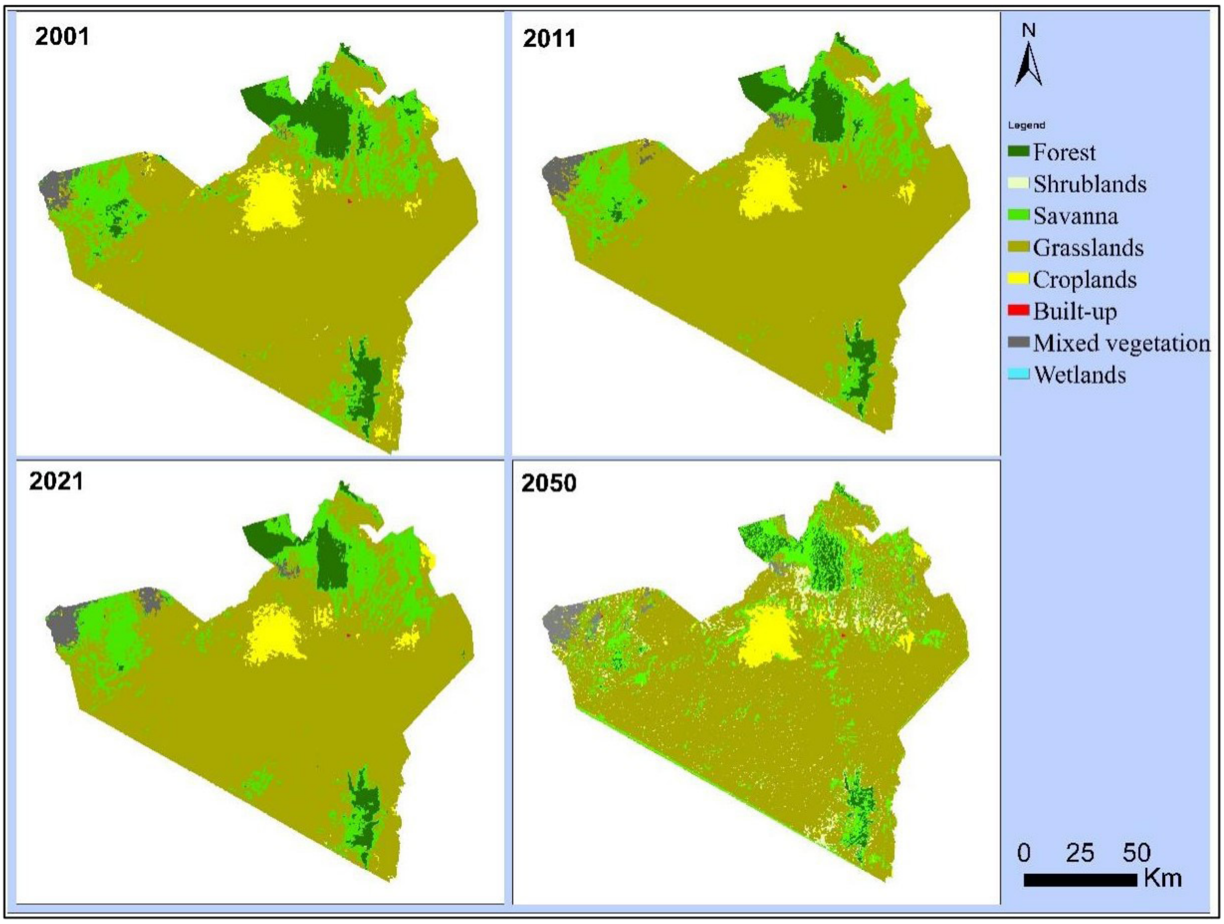


Source: Author's own.

Similar to croplands, our findings reveal a consistent decline in forest cover since 2001, a trend expected to be maintained by 2050 (Figure 17). However, unlike the sharp decline between 2001 and 2011, the rate of deforestation is observed to have slowed between 2011 and 2021 (Figure 17). This timeframe coincides with the period when the Kenyan government executed massive eviction of communities from the forests in a bid to establish the boundary of Mau Forest, to prevent further deforestation (Klopp & Sang, 2011). This points to the success of forest management interventions in slowing deforestation in the county.

Findings of this study reveal that losses in forest cover were attributed to shifts croplands, as losses in forest cover were transitioned to mixed vegetation, grasslands and savanna (Figure 16). However, the observed proximity of croplands at the edges of forests (Figure 17) implies a high probability of cropland expansion into the surrounding forests (Duku et al., 2021). The occurrence of farmlands at the edges of the forest covers Narok County, therefore, presents the possibility of future expansions of farmlands into the forest land.

Figure 17: LULC change in Narok County between 2001 and 2050.



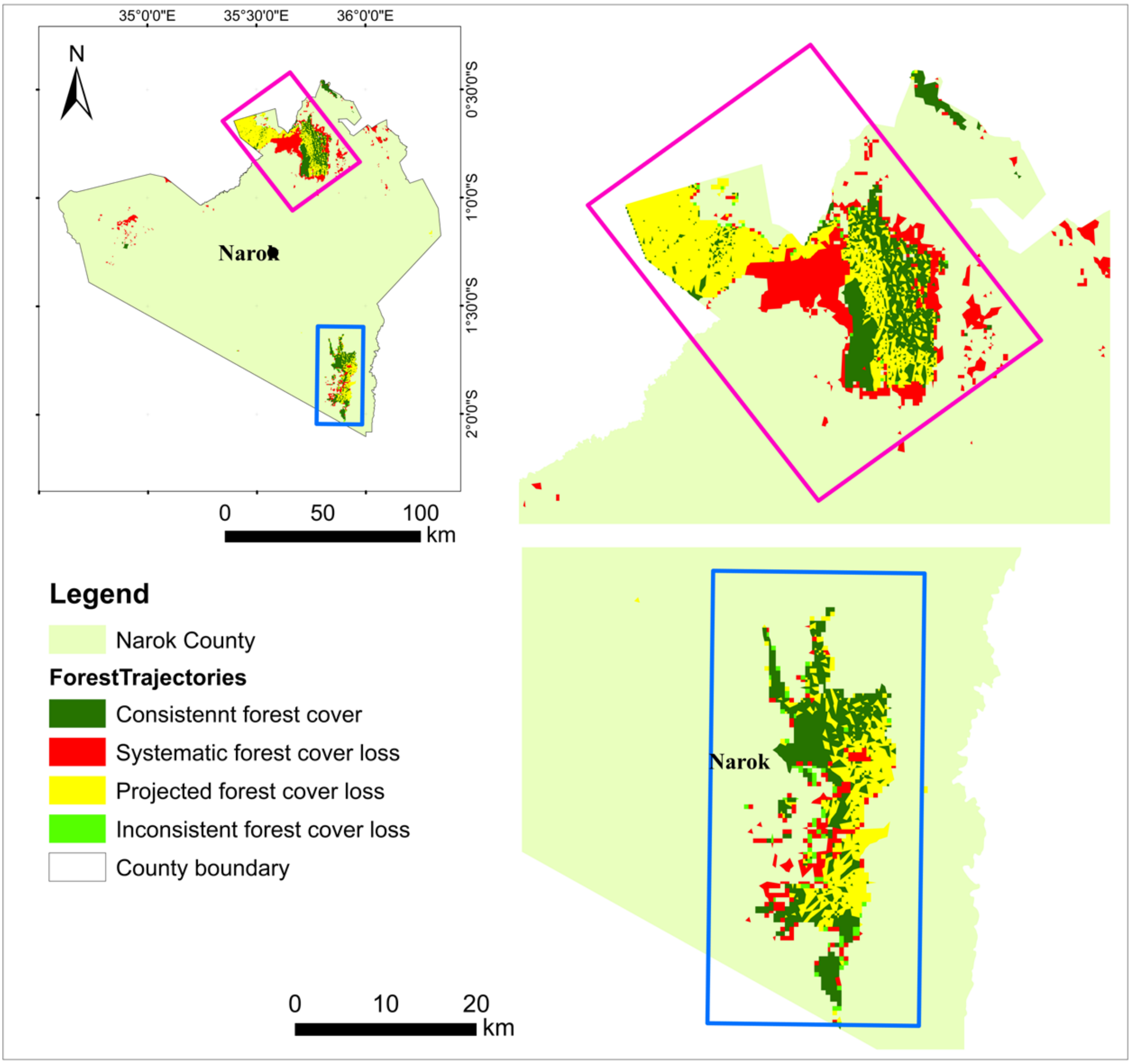
Source: Authors' own, adapted from MODIS LULC dataset.

In Narok County, the only LULC classes that have shown an increasing trend in the past two decades are grasslands, savannas and mixed vegetation. No significant changes have been observed in built-up areas, while a sharp decline in bare land was observed (Figure 16).

Despite the current decreasing rate of deforestation, the forest cover in Narok is expected to decline further by 2050, albeit at a slower rate according to the models results (Figure 12). This finding is consistent with the historical pressure experienced by the Mau Forest in previous decades. However, it also suggests that current management interventions, while effective at present, will be insufficient to sustainably halt the losses in the Mau Forest in future.

The analysis of forest cover trajectories in Narok indicates that the ongoing decline in forests has primarily affected the forest edges, while the projected decline in 2050 is observed to be concentrated in the central areas of the forest (Figure 18). Further, a huge portion of the forest is under threat of deforestation and should be prioritized for conservation (yellow patches in Figure 18).

Figure 18: Forest cover trajectories in Narok County.



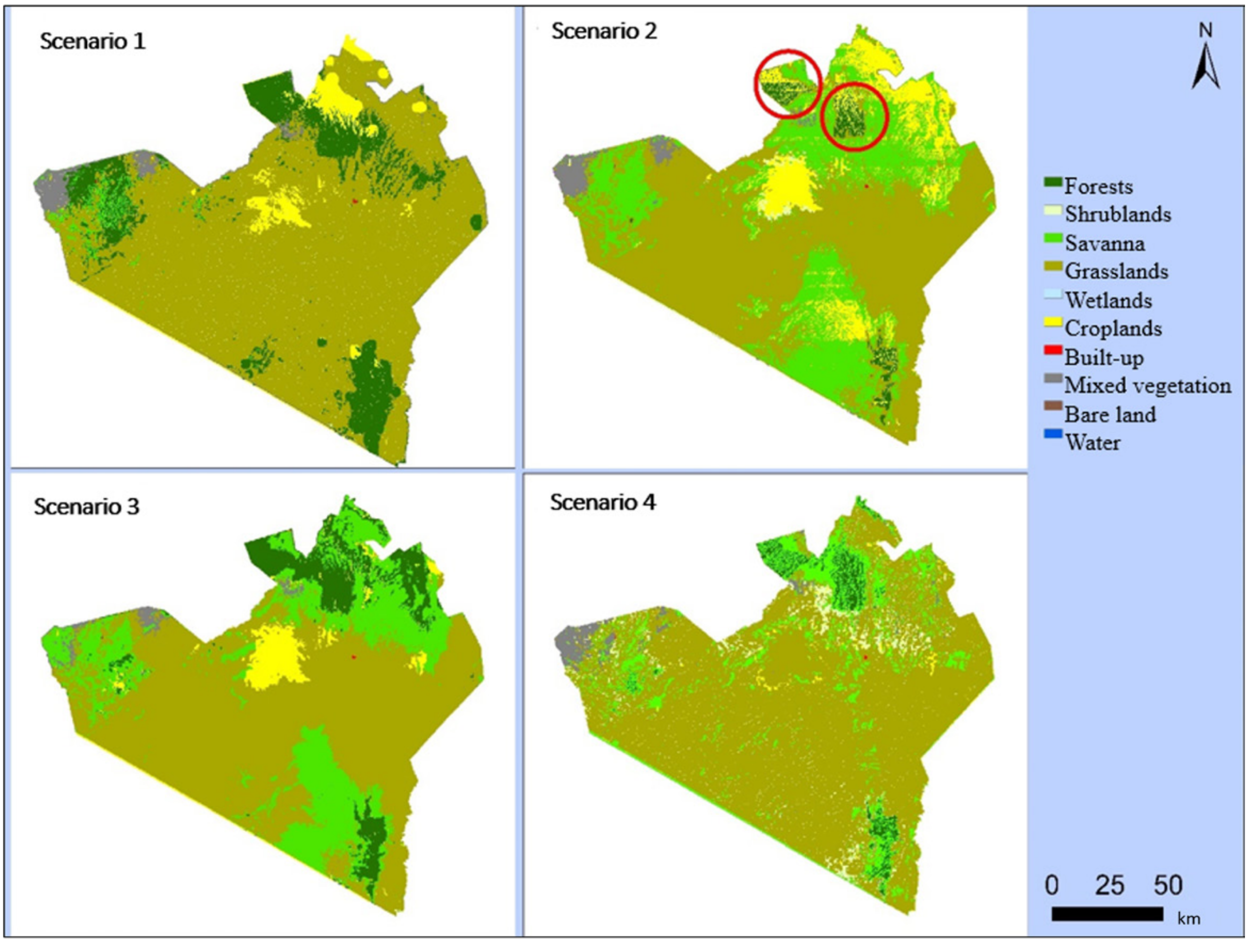
Source: Authors' own.

LULC scenarios

Transitions between and among land cover classes were found to significantly vary under different scenarios in Narok County in the long term. The most desirable outcome is expected to occur under scenario 1, where forest cover is expected to surpass the nationally targeted 10%. However, under this scenario, most of the restoration seems to occur in the southern and western parts of Narok, leaving the significant northern part of the forest vulnerable to encroachment (Figure 19).

As mentioned earlier, this scenario illustrates the limitation of focusing on new tree plantations while neglecting the established forest cover. To meet the national commitment of achieving 10% forest cover, the establishment of new tree plantations is widely acknowledged as a promising entry point. However, since existing forest cover indicates suitable areas for their establishment, it is imperative to prioritize the conservation of existing and restoring degraded forest cover alongside new plantations on new plots.

Figure 19: Projected LULC under different scenarios in Narok County.

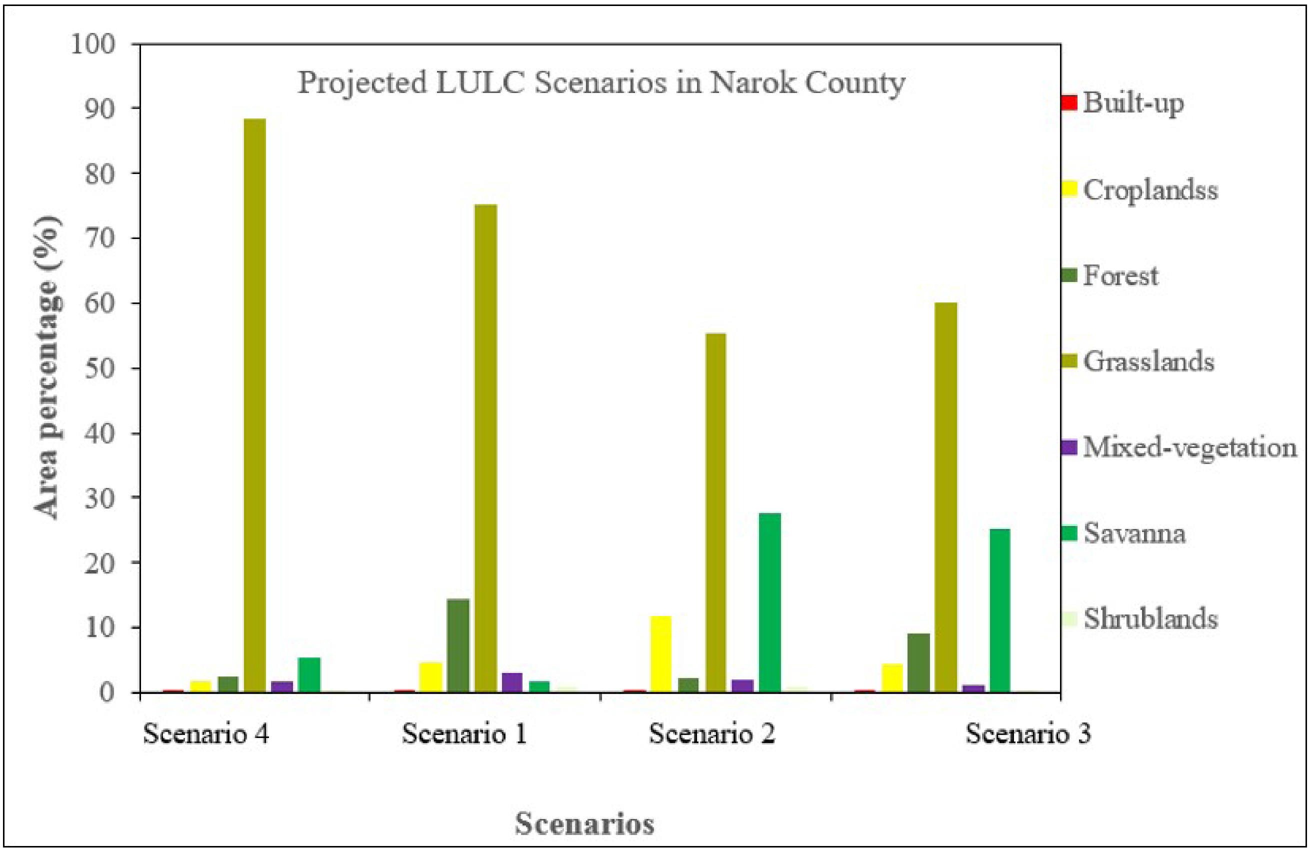


Source: Author's own, adapted from MODIS LULC dataset.

Note: scenario 1: current attainment of 10% tree cover; scenario 2: forest-to-cropland conversion; scenario 3: restoration of degraded lands; scenario 4: business-as-usual scenario.

Through the *Shamba* system, as represented in scenario 2, cultivated cropland would nearly triple in Narok County by 2050, from 4% to 11% (Figure 20). However, while this scenario represents an enhancement of food security, it could result in intense forest encroachment and degradation as farmers clear forested land to pave the way for cultivation. The output in Figure 20 (red circles) shows the projected conversion of forestland into farmlands, leading to more than 50% decline in forested land by 2050 (Figure 20).

Figure 20: Projected LULC under different scenarios in Narok County.



Source: Author's own, adapted from MODIS LULC dataset.

Note: scenario 1: current attainment of 10% tree cover; scenario 2: forest-to-cropland conversion; scenario 3: restoration of degraded lands; scenario 4: business-as-usual scenario.

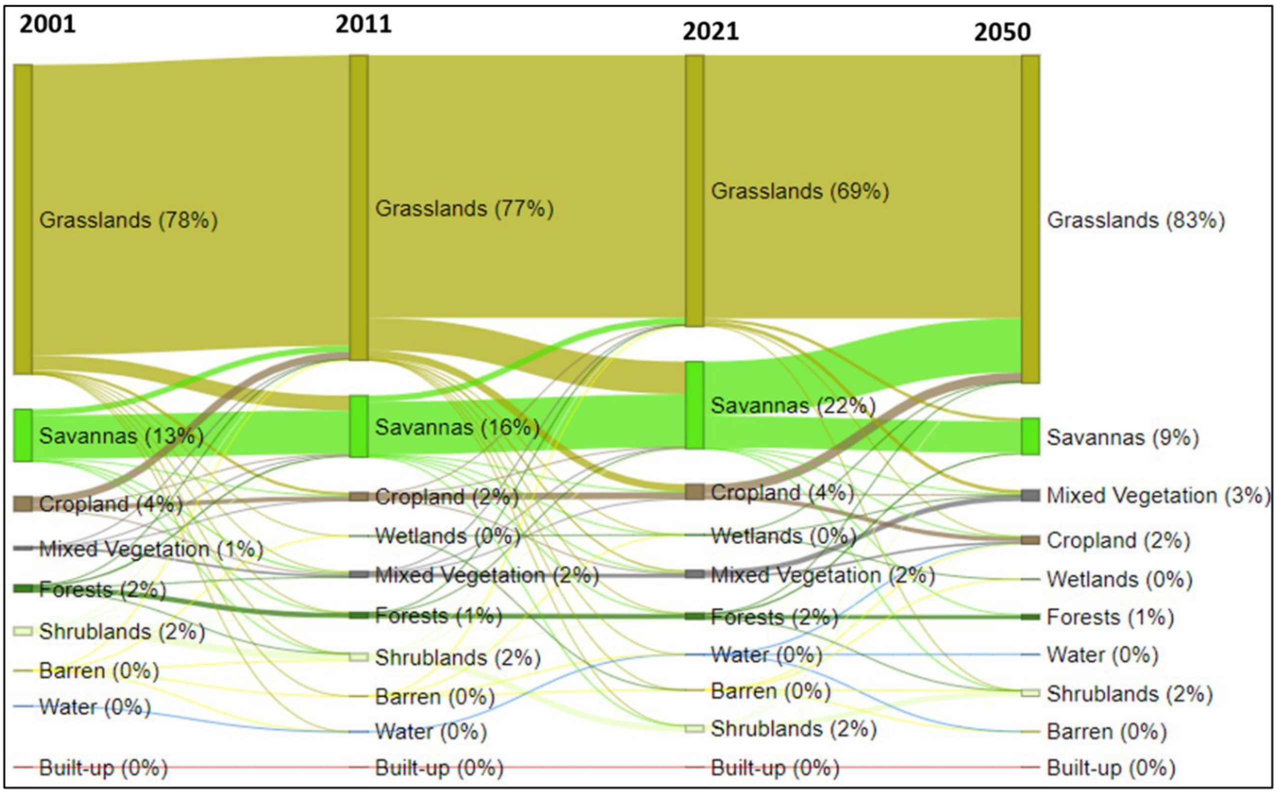
As noted above, the proximity of farmlands to forestlands, along with provisions allowing forest-to-cropland conversion, has historically led to deforestation. We propose that zoning lands to clearly delineate the best sites for forests and cultivation could substantially mitigate encroachment into forests and promote their sustainable conservation.

4.3 West Pokot

The findings of this study reveal a consistent dominance of grasslands throughout the considered period, and our models show an expected increase from 69% to 83% between 2021 and 2050 (Figure 21).

Compared to other counties, such as Turkana, the low proportion of bare land implies that West Pokot County is less vulnerable to land degradation through soil erosion. However, soil conservation measures should still be implemented to prevent the extension of bare land. Despite their low percentage, forests are projected to experience a sharp decline by 2050 (Figure 21).

Figure 21: The temporal transitions (gains and losses in LULC classes) between 2001 and 2021, with predictions for 2050 in West Pokot County.



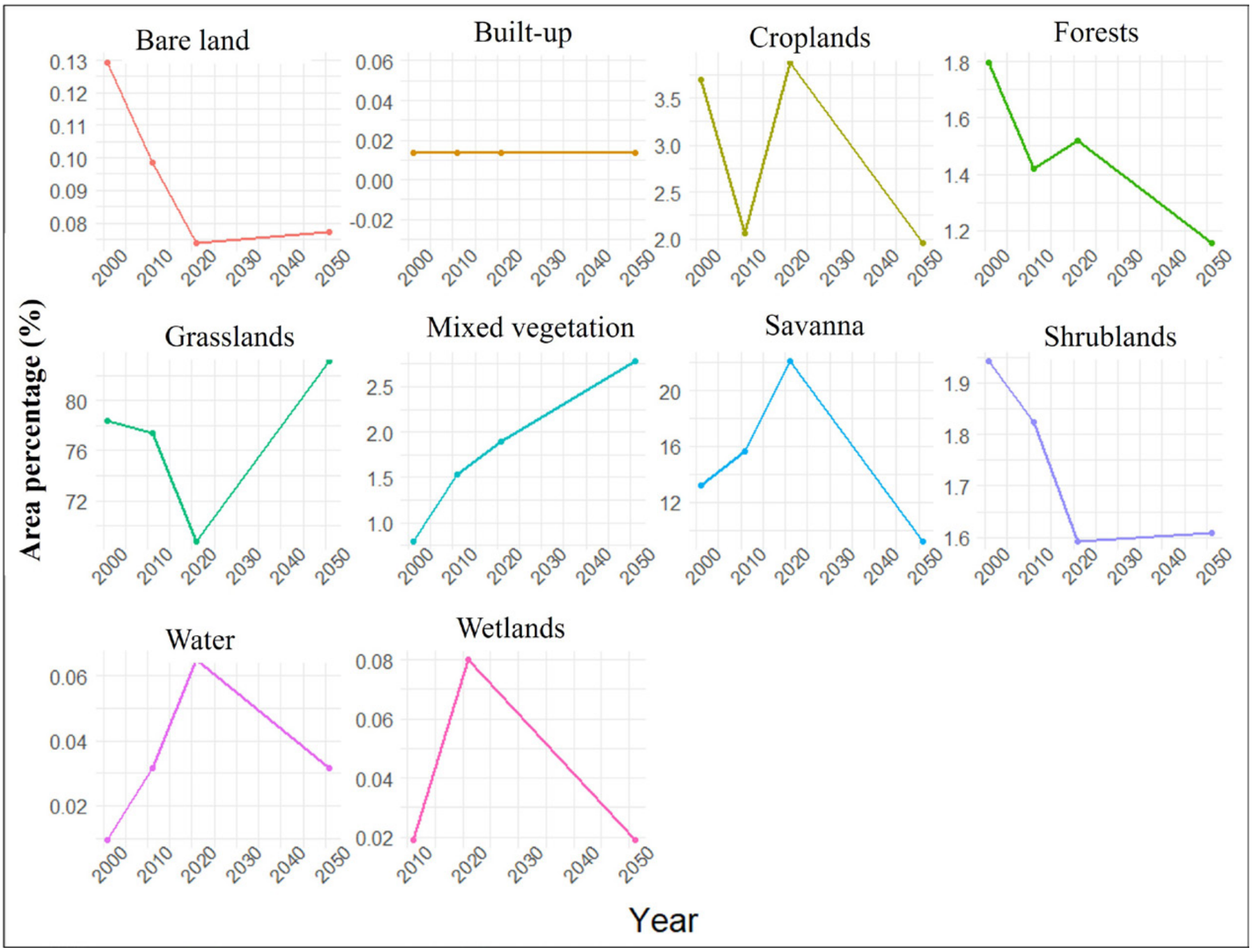
Source: Author's own, adapted from MODIS LULC dataset.

The conversion of areas adjacent to water bodies to forests or crops presents the possibility of wetland degradation through over-extraction and pollution of water resources. In essence, sustainable agricultural technologies should be employed to promote food security while protecting the natural resources on which agricultural activities rely.

The mutual occurrence of tree cover and croplands presents the possibility to consider agroforestry as a form of land management. This approach, however, requires precautions to ensure that the extension of agricultural lands does not lead to the degradation of forests.

A decline is projected for water bodies and wetlands by 2050. This might indicate predicted low precipitation in 2050, a condition that may also explain the projected decline in croplands during the same year. Despite their observed low cover, forestlands are expected to decline to 1.1% by 2050 (Figure 22).

Figure 22: West Pokot temporal LULC change between 2001 and 2050.

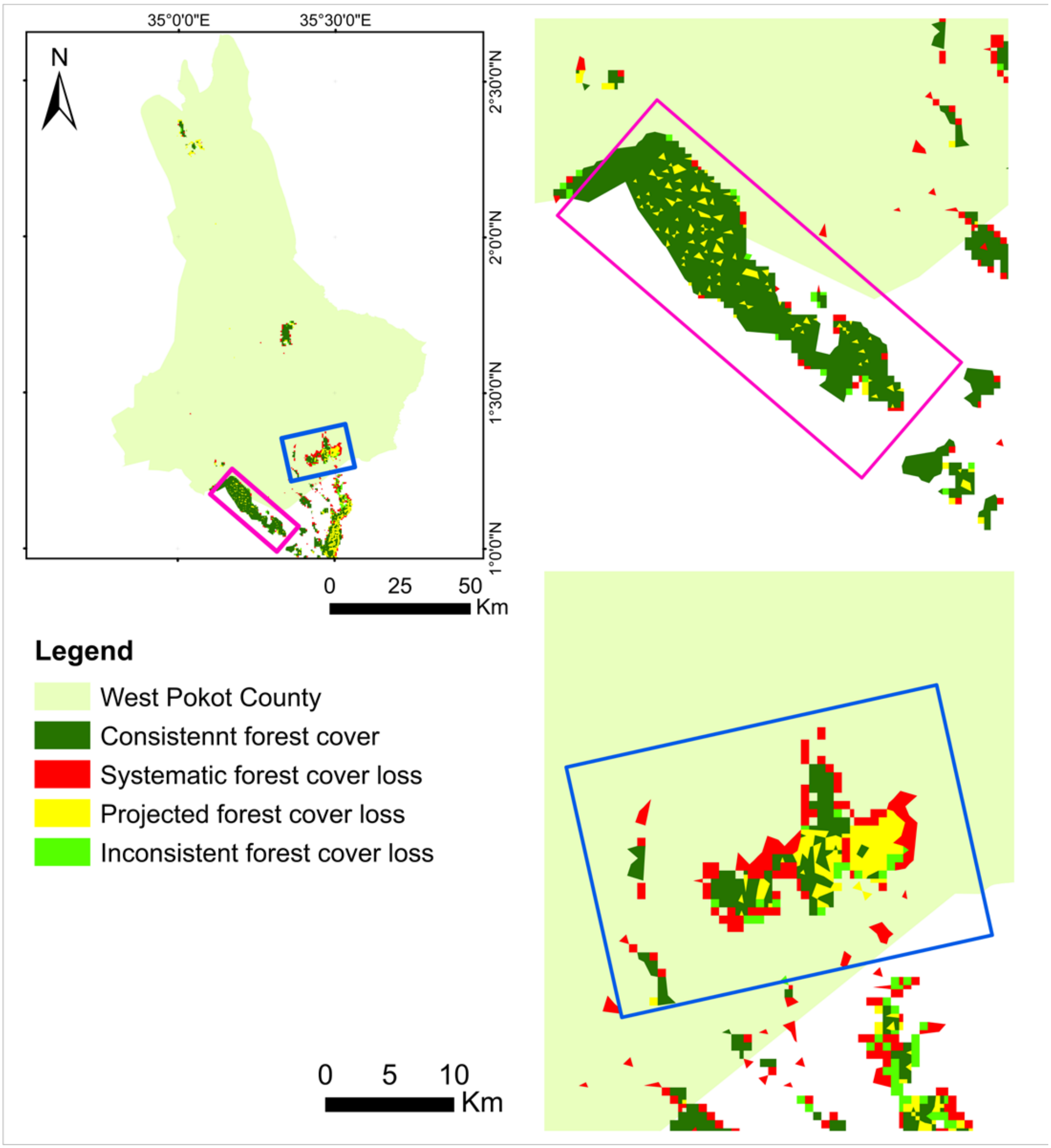


Source: Author's own.

Parcels that are projected to be under massive threat of deforestation lie between the border of West Pokot and Elgeyo Marakwet counties, while consistent deforestation may occur along the edges of the forest (Figure 23). Attaining the recommended 10% forest cover, therefore, requires deliberate and strategic measures in restoring forests and curtailing further degradation.

The county government, partnering with other institutions, has made such efforts by planting trees across the county. However, it should be noted that such initiatives have long-term impacts and that their benefits might not be realized immediately. Also, the management of existing trees should not be neglected at the expense of new seedling plantations.

Figure 23: Forest cover trajectories in West Pokot County, projected for 2050.

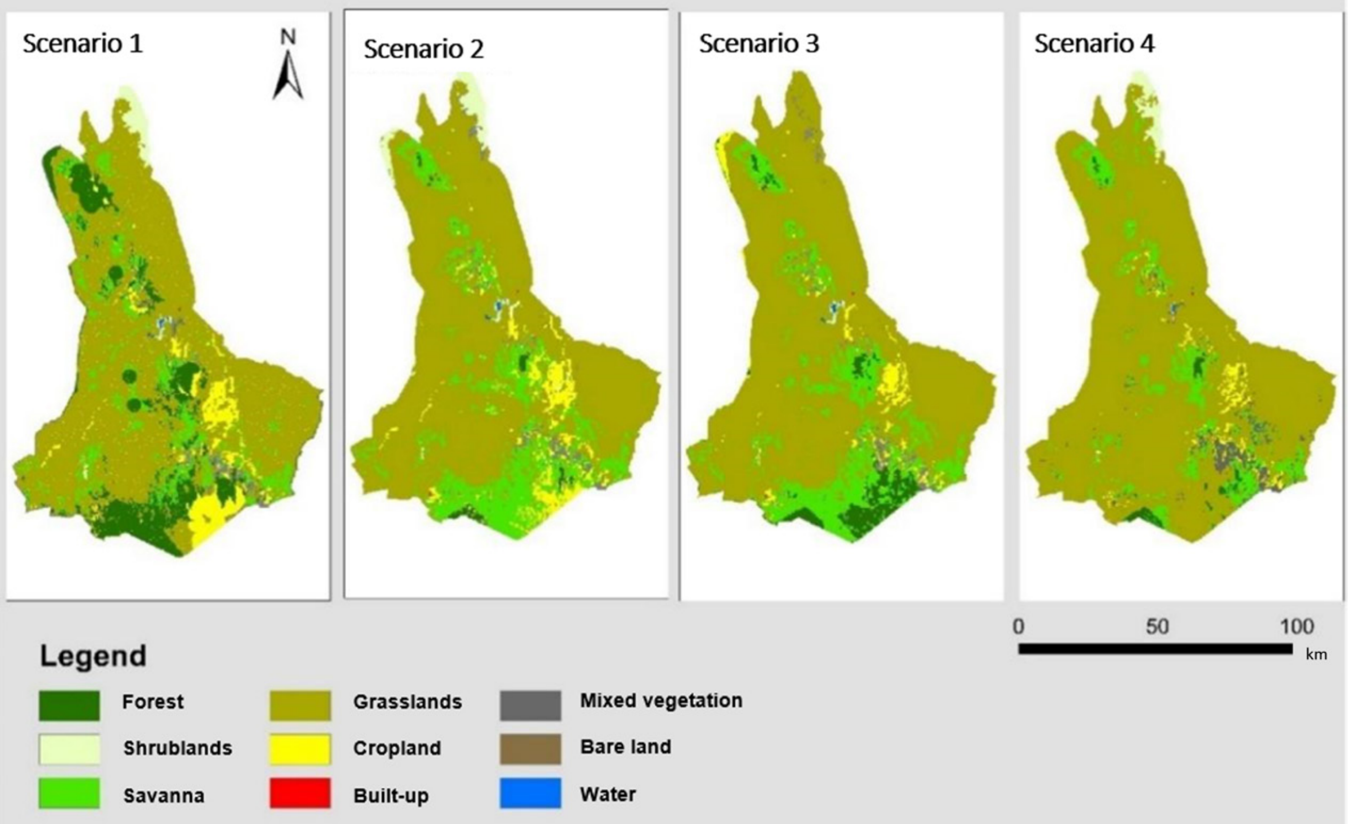


Source: Authors' own.

LULC scenarios

The 2050 projection of LULC under different scenarios in West Pokot is presented in Figure 24. Scenario 1 presents a desirable outcome that increases both the forest cover and croplands to enhance both food security and protect the environment. However, this scenario shows that following previous trends, croplands are likely to be located at the edges of forested lands. While the consequence of this proximity may not always pose a threat of forest encroachment and destruction, it is most likely to occur; measures to monitor and protect the forested parcels from encroachment should be maintained.

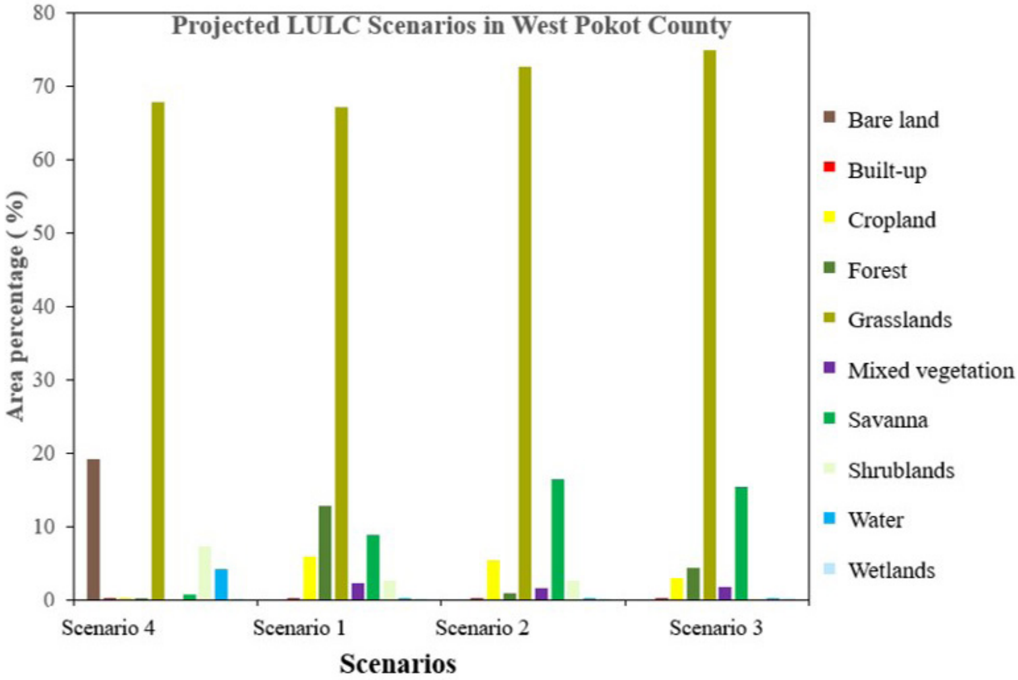
Figure 24: The LULC scenarios in West Pokot, with 2021 for comparison to current conditions.



Source: Author's own.

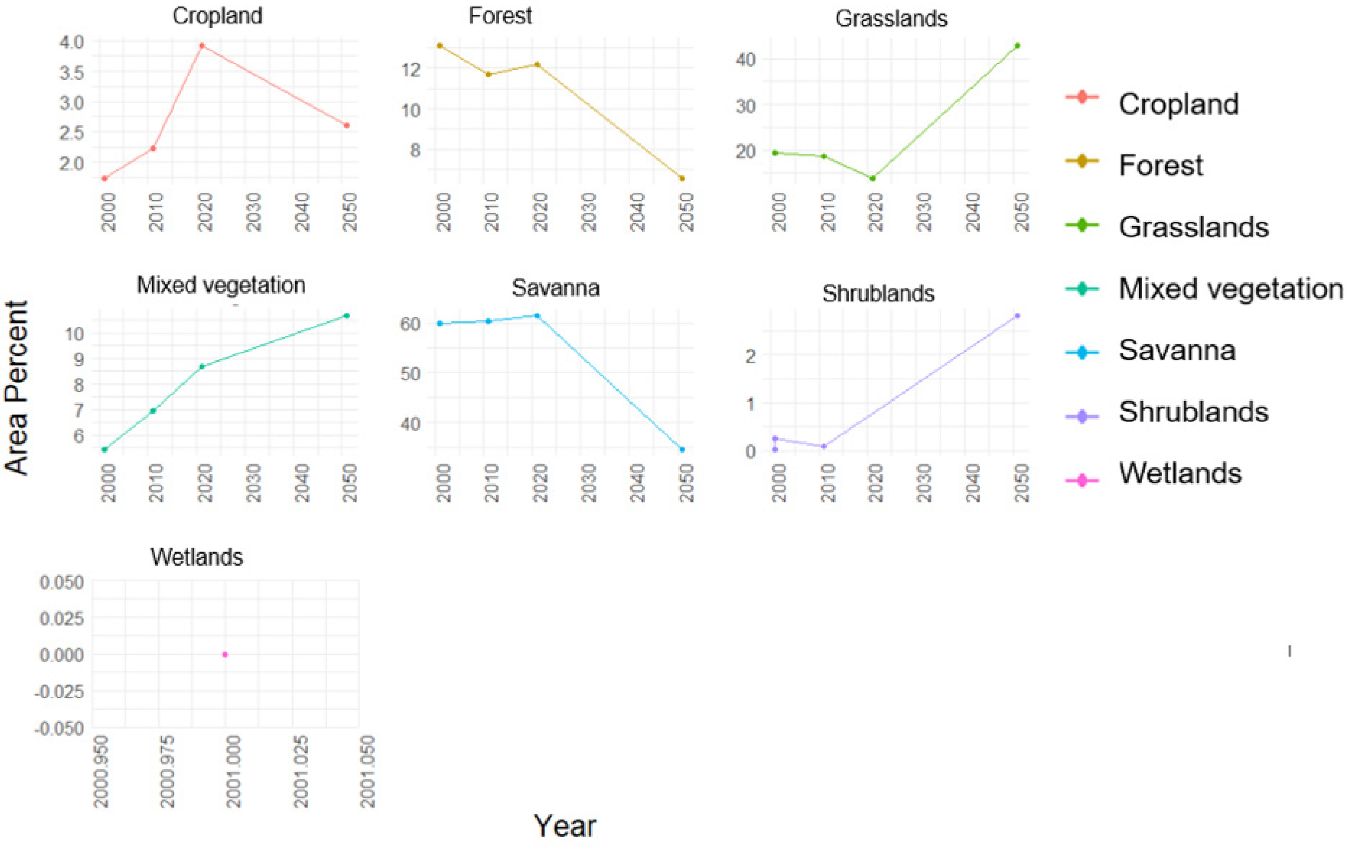
In all the considered scenarios, grasslands remain the most dominant LULC in West Pokot County. If interventions in the first scenario are maintained, the county will achieve 13% forest cover by 2050 (Figure 25). Compared to the restoration of degraded forests as outlined in the third scenario, which is projected to lead to 4% forest cover, this approach presents the most promising pathway towards sustainable forest cover (Figure 25).

Figure 25: Projected LULC under different scenarios in West Pokot County.



Source: Author's own, adapted from MODIS LULC dataset.

Figure 26: Temporal LULC change in Elgeyo Marakwet County between 2001 and 2021, with predictions for 2050



Source: Authors' own.

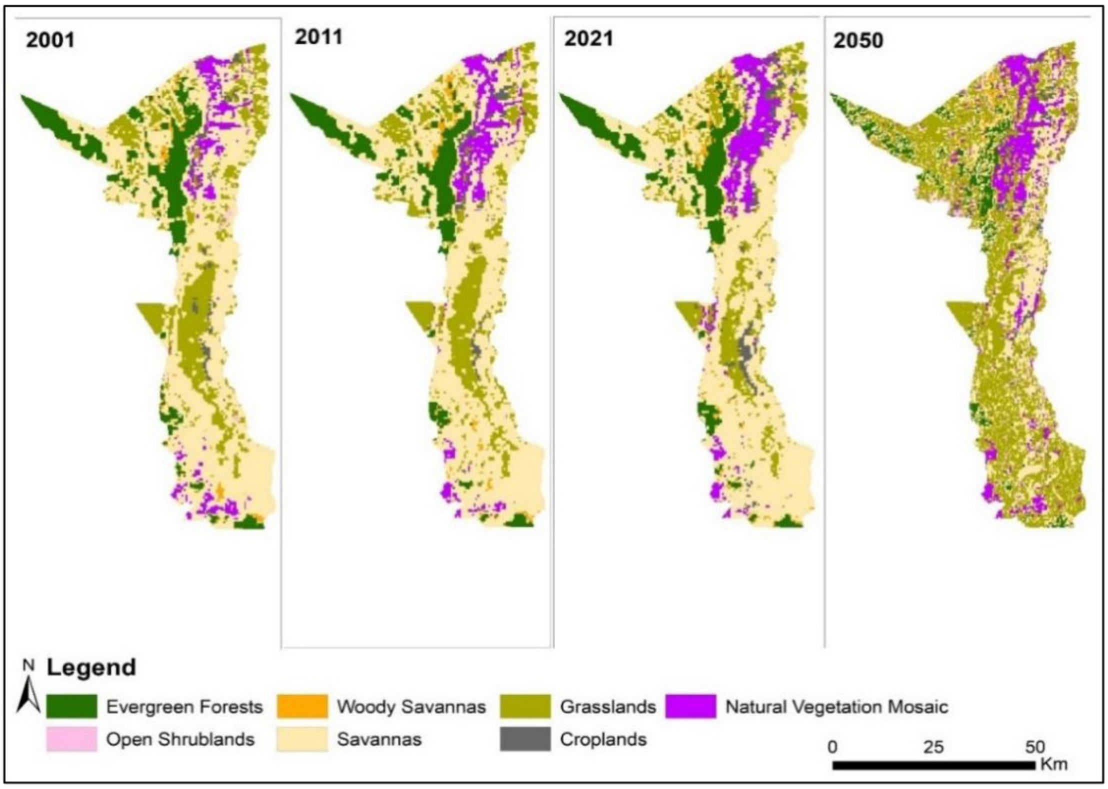
4.4 Elgeyo Marakwet County

Of all four counties analysed in this study, Elgeyo Marakwet presently has the highest proportion of forests, covering approximately 12% of its entire LULC. However, this is a decline in forested land from 13% in 2001, and it is projected to decline further by nearly 50% in 2050 (Figure 26). This finding indicates that despite the considerably high forest cover, prevailing forest management strategies are inadequate in maintaining or improving the forest cover.

Savannas are predicted to decrease to 30% by 2050 (Figure 26), and the analysis of LULC change predicts these shifts will be to grasslands by 2050 (Figure 27). While such changes may not have significant impacts due to the similarity of their ecological functions, the projected massive decline in all forest covers from 12% to 6% is a worrying trend (Figure 26) and an early warning sign which demands rapid response through adoption and implementation of sustainable forest management intervention.

Apart from forests, both croplands and savannas are expected to decline while mixed vegetation, grasslands, and shrublands are simulated to increase sharply by 2050 (Figure 26). Further, we observed that croplands are in highland regions at the edges of forests and are projected to shift inward towards the declining forest cover (Figure 27).

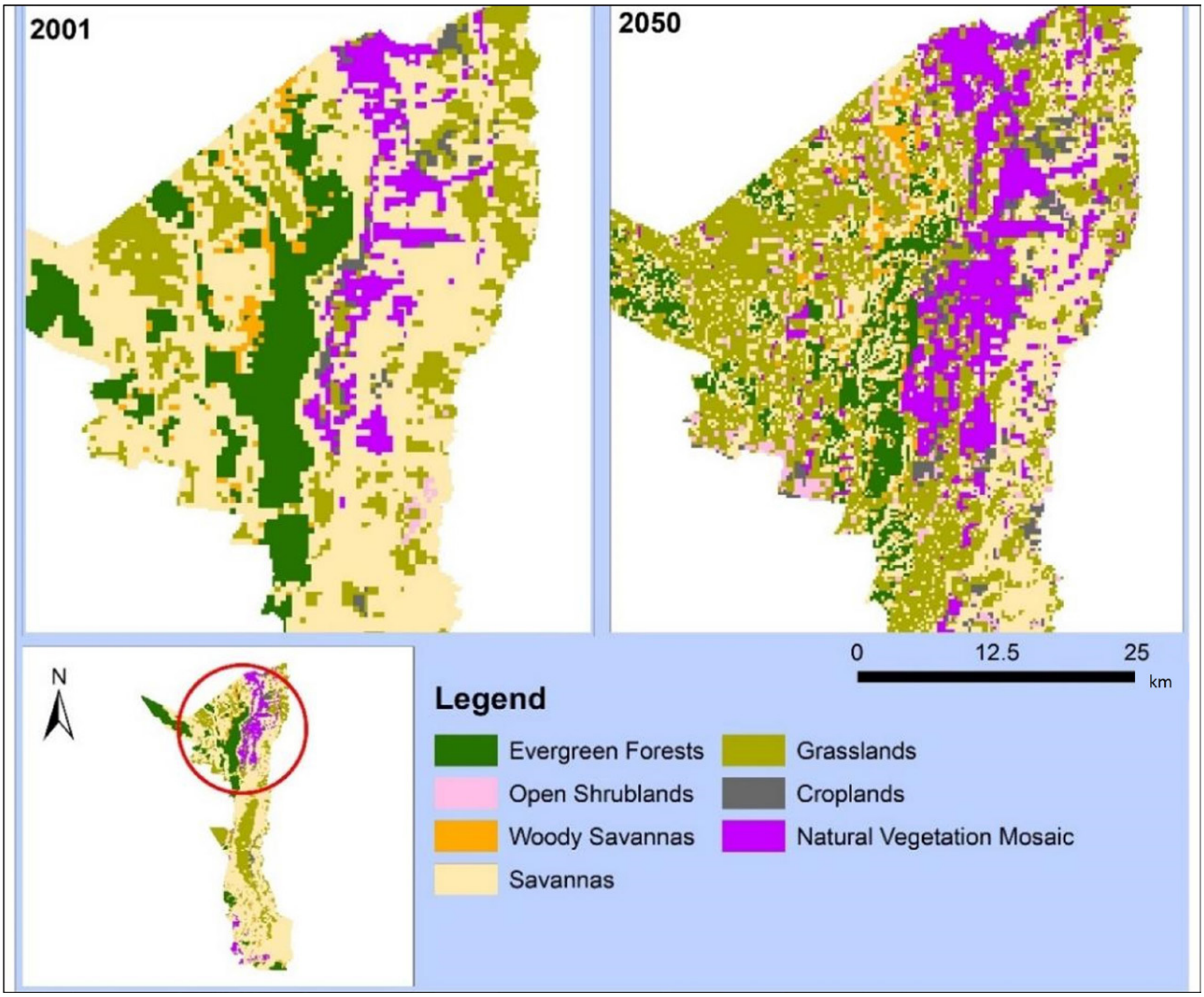
Figure 27: LULC between 2001 and 2021, with a projection for 2050 in Elgeyo Marakwet.



Source: Author's own, adapted from MODIS dataset.

Noting the projected coexistence of forests and cropland, it would be imperative to engage farmers in forest management decisions. Community members are agents of any transformative change, and their engagement in defining forest management priorities and strategies is vital in ensuring sustainability (Wiesmann et al., 2011).

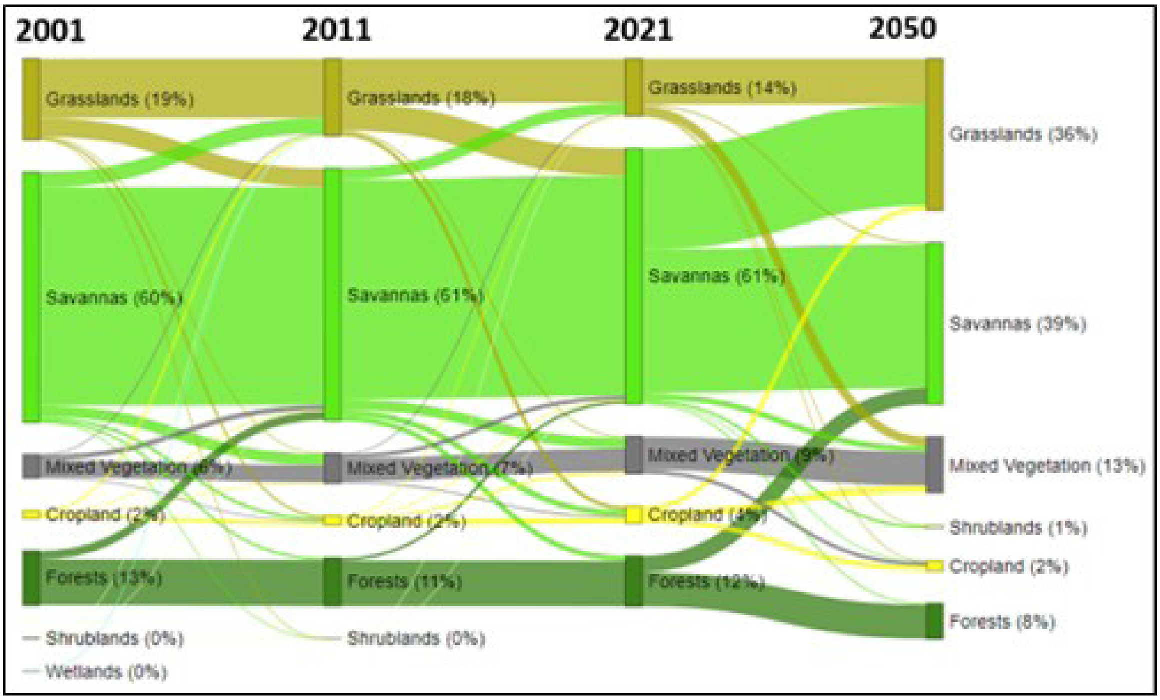
Figure 28: Shift of cultivation land towards declining forest land in Elgeyo Marakwet County.



Source: Authors' own.

An analysis of LULC trajectories confirms a 25% decline in forest cover (from 12% to 8%) by 2050, changed to savannas (Figure 29). Similarly, 20% of savannas are projected to change to croplands, shrublands and mixed vegetation. Additionally, a significant decline in croplands is projected, with these areas being reduced by half and transitioning to mixed vegetation.

Figure 29: LULC trajectories in Elgeyo Marakwet County between 2001 and 2050.

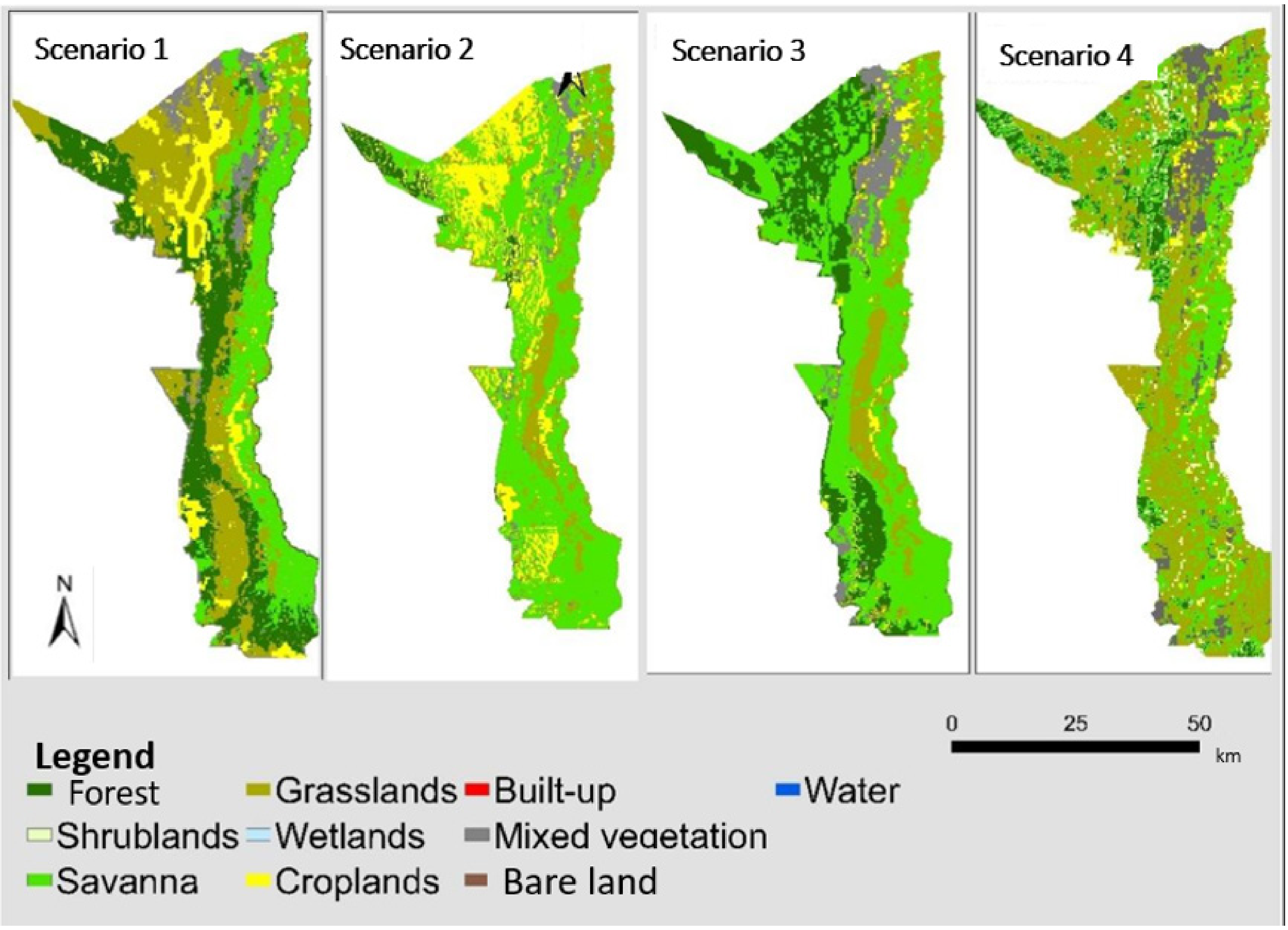


Source: Author's own, adapted from MODIS LULC dataset.

LULC scenarios

An analysis of LULC under different scenarios shows savannas and grasslands dominating in all four scenarios (Figure 30). However, forestland and croplands seem to be more dominant in scenarios 1 (attaining 10% forest cover) and 2 (forest-to-cropland conversion) respectively. While scenario 1 is projected to result in forest distribution along the western and southern parts of the county, restoration of degraded forests (scenario 3) will result in forest distribution in the northern and southern parts of the county, where forests have experienced consistent degradation (Figure 30). A combination of scenarios 1 and 3 would therefore result in a more widespread distribution of forest cover throughout the county.

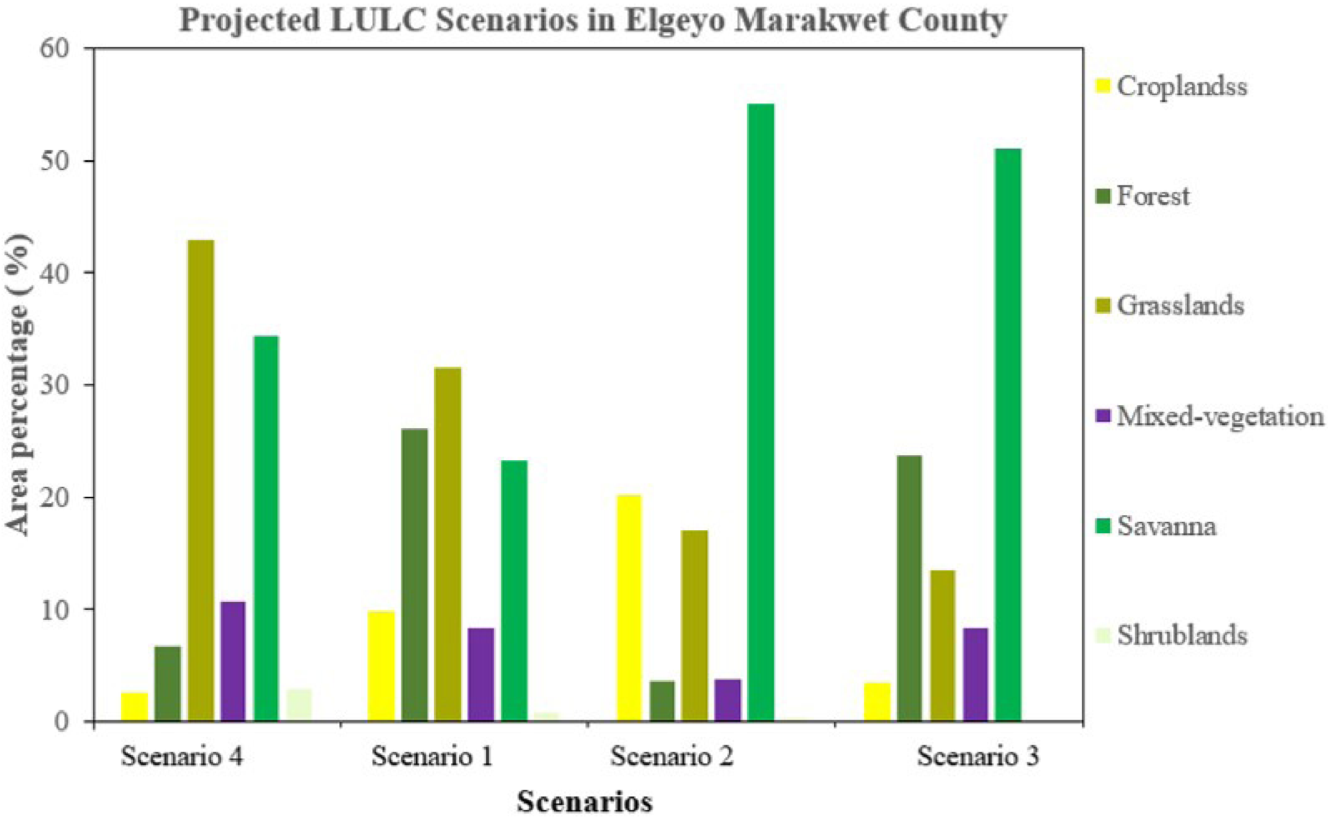
Figure 30: Projected LULC under different scenarios in Elgeyo Marakwer County.



Source: Author's own, adapted from MODIS LULC dataset.

A closer look reveals a very slight difference in forest cover under scenarios 1 and 3, which are expected to yield forest cover of 26% and 24% respectively by 2050. If the business-as-usual status is maintained (scenario 4), the forest cover is expected to decline to 7% of the total LULC by 2050. For forest cover under scenario 2, in which communities are permitted to cultivate within the forests, projections show the highest cropland cover of 20%, at the expense of forests, which are projected to fall to 4% by 2050 under the same scenario (Figure 31).

Figure 31: A graph of projected LULC under different scenarios in Elgeyo Marakwet County.



Source: Author's own, adapted from MODIS LULC dataset.

5. Discussion and key insights

Each county, while similar in some ways, has its own outcomes due to a variety of reasons. Below we list findings for each county individually, before concluding with overall insights for the region.

5.1 Key insights for Turkana County

A significant portion of land in Turkana County (15%) is categorized as bare land, indicating its susceptibility to soil erosion. Implementing an integrated soil management approach would be crucial for land management strategies within the county. Implementing forest management interventions that aim to achieve 10% forest cover, such as tree planting and conservation of existing forests, is projected to yield a 33% forest cover by 2050. Conversely, the business-as-usual scenario is projected to result in the highest proportion of bare land (19%).

The conversion of forestland into croplands may not be sustainable for promoting future food security. Conversely, the promotion of forest establishment in Turkana appears to create favourable conditions that may lead to increased crop yields by 2050.

Further studies should be conducted to ascertain the composition of tree cover within the county as well as the distribution of invasive species. Biological invasions are prominent along the edges of natural forests and where tree density is low (Khaniya & Shrestha, 2020), as visualized in Turkana County.

During the IMARA project's third quarterly meeting, feedback from local stakeholders on preliminary findings confirmed the tree cover along rivers in Turkana to be non-endemic ("invasive" or "alien") species. However, there was a general resistance against the control of invasive species in Turkana County owing to their perceived benefits.

According to the International Union for Conservation of Nature (IUCN), invasive alien species often pose a net negative impact as their cover increases. After habitat loss, they are the leading contributor to species endangerment and extinction and pose a worldwide economic loss exceeding USD 423 billion annually (IPBES, 2023). Invasive tree species can change habitat suitability for native plants, reduce grazing potential of land, and deplete groundwater TK(T. Linders et al., 2020; T. E. W. Linders et al., 2019). While beneficial at the initial stages of establishment, invasive species always pose a net negative impact as their cover increases (Wise et al., 2012). Research findings on management strategies for non-endemic species should be disseminated to inform local actors and to help to control their spread. Conflicts on non-endemic or "invasive" species management often arise due to their perceived short-term benefits. It is essential to educate communities on the nature and impacts of non-endemic species to encourage timely action in managing the species.

5.2 Key insights for Narok County

The analysis of LULC changes in Narok County from 2001 to 2021 suggests a projection for 2050 that includes an expansion of grasslands and a decline in forest cover. It is crucial to prioritize the conservation of existing forests and the restoration of degraded forest areas, alongside establishing new plantations on available plots.

The presence of farmland at the forest edges in Narok County indicates the potential for future expansion of farmlands into forested areas. Croplands are observed to have consistently declined over the past two decades, with a projected further decline. The increasing cost of production and unfavourable market conditions have previously contributed to the abandonment of wheat and maize farming, leading land users to shift towards agribusiness ventures with secured financial returns, such as hay cultivation.

5.3 Key insights for West Pokot County

In West Pokot County, tree cover occupies 11% of the total land area, of which only 2% constitutes forests necessitating the need for forest conservation and restoration of degraded forests. If interventions from the first scenario are maintained, a forest cover of 13% is projected by 2050.

Forest cover along county boundaries is particularly vulnerable to deforestation. Collaborations across borders are therefore crucial for ensuring sustainability in forest management.

Bare land makes up less than 1% of the total LULC, indicating a low susceptibility to severe soil erosion impacts based on soil cover. However, under the business-as-usual scenario, bare land is expected to increase significantly by 2050.

5.4 Key insights for Elgeyo Marakwet County

Elgeyo Marakwet County has a considerably high proportion of forest cover (12%). A very slight difference in forest cover is projected under scenarios 1 (attaining 10% forest cover) and 3 (restoring degraded forests), which are expected to yield forest cover of 26% and 24% respectively by 2050.

If the trends of the past two decades persist, forest cover could decline to 7% of the total LULC by 2050. Additionally, if communities are allowed to cultivate within forests (scenario 2), cropland cover could reach 20%, but this would come at the expense of forests, which are projected to drop to 4% by 2050 under this scenario.

The implementation of either scenario 1 or 3 could lead to a broader distribution of forest cover across the county. However, additional modeling is required to illustrate the potential interactions between these two scenarios.

Considering the anticipated coexistence of forests and cropland, it is crucial to involve farmers in forest management decisions. Community members play a pivotal role in driving transformative change, and their involvement in establishing forest management priorities and strategies is essential for ensuring sustainability.

6. Conclusions and recommendations

Based on the findings of this study, the spatiotemporal distribution of land cover significantly varies among the four counties. Decisions on the selection and implementation of sustainable land management interventions should, therefore, be contextualized based on the geographical location rather than through generalization.

Overall, the existing forest cover seems to be neglected and at threat of future degradation. Integrating management interventions that aim at achieving 10% forest cover while restoring degraded forest lands would yield the most desired environmental outcome by 2050.

The model indicates that by 2050, the cropland proportion attained under scenario 1 (achieving 10% forest cover) will not be significantly different from that under scenario 2 (forest-to-cropland conversion). This is because croplands are being abandoned due to rising production costs and unfavourable market conditions. Integrating a holistic approach, which simultaneously promotes economic benefits from farm produce while conserving the environment, may therefore offer promising solutions to achieving sustainable farming systems. The proximity of farmlands to forestlands presents the challenge of future forest-to-cropland conversion. Consistent degradation of forests is rampant at the edges of forests, with the central parts of the forests being vulnerable to future deforestation. Clear demarcation and zoning of lands to clearly distinguish between forest lands and cultivatable parcels would therefore be a vital step toward curtailing further deforestation.

The conversion of forestland into croplands may be unsustainable in promoting food security in the long term, a perspective affirmed by Padoch and Sunderland (2013). Maintaining healthy forest cover may facilitate the provision of favourable conditions to croplands through climate regulation (Madeira et al., 2009; Palmer, 2021), conservation of groundwater (Berrahmouni & Mansourian, 2021; Shah et al., 2022) and protection of soils from erosion (Elliot et al., 2018; Rodrigues et al., 2021; Teng et al., 2019). Maintaining a robust forest cover within a sustainable agrifood system is therefore expected to be an efficient approach in attaining food security and maximizing the diverse benefits that forests offer to farming systems. Our finding that forests and farming tend to cluster alongside water bodies underscores the possibility of wetland degradation through over-extraction and pollution of water resources. Sustainable agricultural practices and technologies should be adopted to protect wetlands from future degradation while ensuring food security.

Spatial mapping of LULC also reveals the linear distribution along water bodies of forest cover, which is composed mainly of the invasive species. Developing capacity-building programs aimed at building consensus on the definition, impacts and need to manage invasive species may be a useful tool for early detection and rapid response to invasion by alien species. This approach could assist authorities and local communities in learning about the costs of and adopting approaches to contain non-endemic species.

The analysis of LULC changes presented here can aid in identifying hotspot areas that require prioritized management interventions. Additionally, it highlights potential drivers of change which may guide strategies for sustainable ecosystem restoration. However, to enhance the effectiveness of LULC mapping, it is essential to integrate empirical field data gathered from land users with practical experience and knowledge of LULC changes and their underlying causes. Future work building on this analysis should incorporate the perceptions of local actors to derive insights into the drivers of LULC changes.

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