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Park conservation or degradation? iCLUE modelling of land use change projections in the upper Manafwa watershed on Mount Elgon, Uganda

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ABSTRACT

Land use changes result from interactions between different factors over time. Land use models support natural resource conservation by helping stakeholders to understand and predict these changes. Through such model-based projections, governments and conservationists can identify hotspots of encroachment and formulate informed decisions for sustainable conservation. Land use on Mount Elgon has undergone rapid changes in the conservation area and community land since the 1970s. Park encroachment has threatened natural cover due to population pressure and increasing demand for agricultural land. To support conservation efforts, this study conducted near-future potential land use change projections using historical land use change and iCLUE model simulations. This study established hotspots of land use conversion, locations of park encroachment and the extent of land use intensification in the upper Manafwa watershed of Mount Elgon. The study applied remote sensing, a geographic information system, and a land use change model (iCLUE), while considering nine land use classes to project land use change for 2030, 2040 and 2050 using a "business-as-usual" scenario. Stakeholder verification of the model output was conducted in a dedicated workshop. The results showed that in 2050, agriculture (44.24%) and low-stocked tropical high forest (22.56%) will be the largest land cover classes with bushland and shrubs as the smallest land cover classes (~0.5%). Most of the land use conversion in the park is projected to occur along the boundary of the conservation area by agriculture and built-up areas. This study will guide stakeholders and decision makers in planning future sustainable management strategies to conserve and enhance remaining forest tracts in Mount Elgon.

1. Introduction

Land use and land cover (LULC) changes stand as a pivotal concern in the realm of environmental dynamics. These transformations have yielded far-reaching consequences, including ecosystem instability, habitat degradation and the heightened frequency of natural disasters, notably landslides (Nakileza & Nedala, 2020; Waiyasusri et al., 2016). While some shifts in LULC can arise from natural processes, the prevailing trajectories of change predominantly arise from the nexus of socio-economic development and population expansion (Qasim et al., 2013; Ramankutty et al., 2006). Regions of natural forest cover and diverse vegetation types in numerous instances contract due to conversion for human utilisation (Shao et al., 2020; Turner II et al., 2021). The imperative for spatial–temporal monitoring of LULC alterations is underscored by the critical insights it offers, especially in identifying areas necessitating urgent intervention (Prestele et al., 2016; Skole et al., 2012). Furthermore, this monitoring approach enables the formulation of knowledgeable projections and probable scenarios, boosting their plausibility through the integration of additional data gathered from routine LULC observation (Gomes et al., 2020).

The exploration of future scenarios regarding LULC changes and their consequential impacts on conservation has been significantly advanced through modelling techniques (Ramankutty et al., 2006; Turner II et al., 2021). Various classes of models have been employed in studies concerning land use change, including; process-based, empirical-statistical, stochastic and agent-based models (Verburg et al., 2004; Verweij et al., 2018). Particularly, empirical-statistical models have gained prominence in LULC research within subtropical and temperate

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regions due to their ability to provide reliable results (Liu et al., 2017; Verweij et al., 2018). The forces driving LULC change can be categorised into proximate and underlying factors (Qasim et al., 2013). Proximate factors encompass immediate human actions and activities stemming from intended land use, which directly impact natural forest cover. In contrast, underlying driving forces represent overarching social processes that amplify the proximate causes, exerting an indirect influence at the national or regional levels (Qasim et al., 2013; Tuffour-Mills et al., 2020). The inclusion of these factors in modelling serves a dual purpose: understanding their role in observed changes and predicting potential outcomes (Kariuki et al., 2021; Kolb et al., 2013). For instance, the important factors associated to deforestation processes in Mexico were; distance to pasture, climate, and landscape geomorphology while distance to secondary forests and climate were important factors for vegetation regeneration (Kolb et al., 2013).

The acceptability and successful implementation of modelling outcomes within the realm of nature conservation have posed a notable challenge. The limited uptake of these outcomes often originates from a deficiency in adequately involving and integrating stakeholders' perspectives into the modelling process (Volkery et al., 2008). The roles played by experts and stakeholders in land use change modelling as a participatory endeavour are distinct yet complementary (Hewitt et al., 2014; Meyer et al., 2014). Limited studies have ventured into engaging both experts and stakeholders across various stages of predicting land use change using diverse models, most notably; during scenario formulation, the validation process, and the verification of outputs (Celio et al., 2014; Hewitt et al., 2014). Integrating stakeholder experiences and localized knowledge regarding conservation practices notably augments the credibility of model outputs, forging vital connections between scientific insights and on-the-ground wisdom, thus enhancing the precision of the models (Castella & Verburg, 2007; Kariuki et al., 2021). Collectively, this amalgamation facilitates the validation of model results through the lens of stakeholders (Malek & Boerboom, 2015; Meyer et al., 2014).

Mount Elgon National Park (MENP) is a high altitude transboundary nature conservation area straddling the Uganda-Kenya border (Nakakaawa et al., 2015). Recent studies show a decline in area coverage of natural land cover types between 1960 to 2020. Mugagga et al., (2012) documented a decrease of woodland by 58% and forest by 34%, accompanied by a substantial upsurge in agricultural areas with a 241% increase from 1996 to 2006. Recent studies by Opedes et al., (2022) underscore a noteworthy shift in land cover between 1978 and 2020, revealing percentage increases in planted forest (3966%), built-up area (890%) and agriculture (186%) contrasted with percentage decrease cover in shrubs (-81%), bushland (-68%) and tropical high forest well-stocked (-50%). Worth noting, these changes are not exclusively covering the entire conservation area and a lot of local variations exist. Other studies on Mount Elgon have focused specifically on conservation efforts and implications (Himmelfarb & Cavanagh, 2018; Sassen et al., 2015), carbon stocks (Mugagga et al., 2015), landslides and coping strategies (Nakileza & Nedala, 2020). Natural vegetation is under threat due to encroachment by an ever increasing population and associated expansion of arable land. The future land cover situation and likely implications on conservation have not been investigated in Mount Elgon.

This study aimed at investigating near-future scenarios of LULC and implications on conservation area of the upper Manafwa watershed on Mount Elgon, Uganda using iCLUE model and participatory stakeholder engagement. This work is embedded within the context of the Manafwa watershed project that focusses on sustainable watershed management with local communities through the integrated farm planning (PIP) approach (Kessler et al., 2021; Misanya et al., 2023). The study offers valuable insights into the impending impacts on areas designated for conservation purposes by analysing the factors behind LULC changes and spatially simulating plausible future transformations with the engagement of stakeholders. The specific objectives of this study were to; identify hotspots, extent of encroachment in the conservation area and the most likely affected land use classes within the study area. This study further predicts the likely state of land use/cover between 2030 and 2050 and determines the contributions of the different factors to the projected changes. The projections are based on "business-as-usual" (BAU) scenario with limited monitoring, control and management of the conservation area. This projection was achieved by fitting a linear trend for all the land use classes based on historical data from 1978 to 2020 (Opedes et al., 2022). The iCLUE model projections were validated in a one day workshop with 17 Manafwa watershed stakeholder representatives and their feedback was used to interpret the land use change modelling results. The incorporation of stakeholders enhanced applicability and implementation of the study findings. The results help inform both conservation policy makers and conservation practitioners about the impacts of natural vegetation depletion, thus indicating potential areas of restoration.

2. Methods and materials

2.1. Description of the study area

The study was conducted on the upper Manafwa watershed of Mount Elgon conservation area in Eastern Uganda. The study area lies between 34°15.40′E, 01°06.92′N and 34°31.87′E, 00°56.22′N and covers an area of about 320 km^2 (Fig. 1). The altitude of the study area ranges between 1190 and 4306 m above sea level. The slope gradient is generally steep with many slopes having a gradient of 15° to 35° with some exceeding 70° (Opedes et al., 2022). Lixic ferralsols and nitisols are predominant soil types in the study area, while acric ferralsols and gleysols occupy limited areas. These fertile soils, characterized by clay and clay-loam textures make the area ideal for farming (Bamutaze et al., 2021).

Mount Elgon experiences a tropical montane climate with a bi-modal rainfall pattern of 1500 mm to 2000 mm per annum (Mugagga et al., 2015). The vegetation of the study area follows altitudinal montane vegetation zonation in the conservation area whereas planted trees, and perennial crops dominate the lower altitudes (below 2000 m) where settlement also exist (Mugagga et al., 2015; Opedes et al., 2022). Fig. 2 shows vegetation cover and land utilization within the study area.

Subsistence agriculture is the main economic activity and forms the livelihood for 69% of the households (Uganda National Bureau of Statistics, 2017). Bananas and Arabica coffee are intercropped with beans and maize, representing the primary crops cultivated here (Fig. 2). The study area exhibits significant land fragmentation, marked by a dense population of up to 850 inhabitants/km^2 in specific regions, coupled with an annual population growth rate of 3.6%, exceeding the national average of 3% (Bamutaze et al., 2021).

2.2. iCLUE model

This study used the iCLUE (Conversion to Land Use and its Effects) model (Verweij et al., 2018) to predict the future LULC change in the upper Manafwa watershed in 2030, 2040 and 2050. iCLUE is the latest software implementation of the CLUE model family, originally developed at Wageningen University in 1996 (Veldkamp & Fresco, 1996; Verweij et al., 2018). iCLUE spatially allocates land use classes based on provided areal land use demands (Huber García et al., 2018; Verweij et al., 2018). In the last 25 years, numerous CLUE applications have been implemented for diverse regions across the globe, spanning a wide spectrum of scales (local, regional, global) and spatial resolutions (Huber García et al., 2018; Tizora et al., 2018; Verburg & Overmars, 2009; Wu et al., 2015). In addition to enhancing the overall operational applicability, iCLUE introduced more model transparency to enhance the understanding of modelled land use change processes and solve operational hurdles experienced when using previous CLUE versions (Verweij et al., 2018). Nevertheless, the fundamental principles of the previous CLUE versions are maintained: simulated land use change are

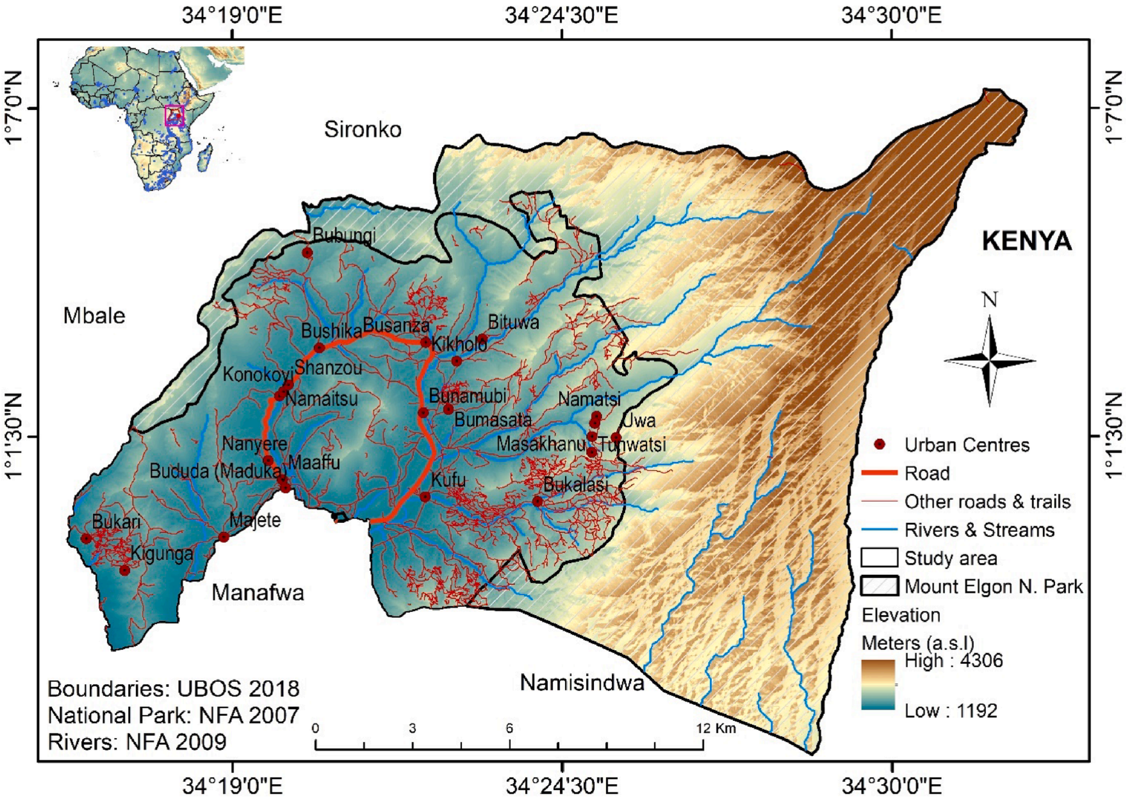

Fig. 1. The location of the study area and the extent of the upper Manafwa watershed with its drainage system in Mount Elgon, Uganda.

Fig. 2. Photographic depiction of the geophysical environment and land utilization in the study area; (a) land use and land cover in the community land, (b) agriculture and settlements at the fringes of the conservation area, (c) encroachment by agriculture (area without homesteads) with a landslide scar on steep slopes of the conservation area and (d) intact conservation area close to the water pumping station near the community separated by a "live" park boundary (planted eucalyptus and bamboo).

an outcome of the future demands in land cover, and interactions between the biophysical and human driving factors through time and space (Verweij et al., 2018). The major land use change factors considered in this study include: historical land use, rainfall, soil, topography and socio-economic data including: conservation status, population density, infrastructure developments and economic conditions.

Verweij et al., (2018) provide a comprehensive description of the specific iCLUE model operation and Fig. 3 illustrates the four steps followed by iCLUE for spatial allocation of land use classes. Land use suitability in iCLUE is defined as the appropriateness of a land use class at a specific location, based on the statistically derived characteristics and features of that area, especially soil, climate, accessibility, and terrain (Cormont et al., 2017). Subsequently, the iCLUE model proceeds to spatially allocate the projected scenario land use demands, obtained from trends on the historical land use of the upper Manafwa watershed. This allocation process is guided by the model's derived suitability criteria, and accounts for the allowed transitions between different land use types.

For step I, the iCLUE model uses stepwise regression to derive the importance of each driving factor variable based on previous land use change and associated biophysical factors / human drivers (see Fig. 3). Ranking of the variables / factors used in this study was undertaken to obtain detailed insights in the model results and indicate a general level of significance over all land use classes. This was achieved via a two-fold process: (a) the number of times a variable is removed from a model, so finally being not significant as a driving factor in one of the regression models for each land use class, and (b) the total sum of all P-values of the final models, with higher values having relatively smaller (but still significant) impacts on each of the models (see Appendix A: Table 3).

For step II, the projected land-use demands for the years 2030, 2040, and 2050, which represent the concluding years of the modelling timeframe within this study, were extracted using historical linear extrapolations dating back to 1978 for each respective land-use category. For step III and IV, the conversion information on land use allocations by the iCLUE model and all other the model settings are presented in supplement 1. To establish the impact of conversion on land use intensification and the conservation of the national park, we compared the percentage LULC extent in the community land and conservation area. The comparison was made using the MENP as demarcation line (National Forestry Authority (NFA), 2007).

2.3. Data acquisition and analysis

The study used a historical time-series of Landsat satellite images and geospatial datasets to analyse and predict future LULC changes in the upper Manafwa watershed of Mount Elgon. We used the historical land cover changes from 1978 to 2020 as derived in our previous study (Opedes et al., 2022) in the same study area. Table 1 details the LULC classification scheme that was used. These data were used to represent the state of LULC in the study area and as an input for future projections using a spatial resolution of 30x30m.

Data were acquired for biophysical and socio-economic factors as potential drivers of LULC changes. In order to ultimately derive insights from the model outcomes regarding the driving factors that dictate the land use change dynamics for individual land use categories, an

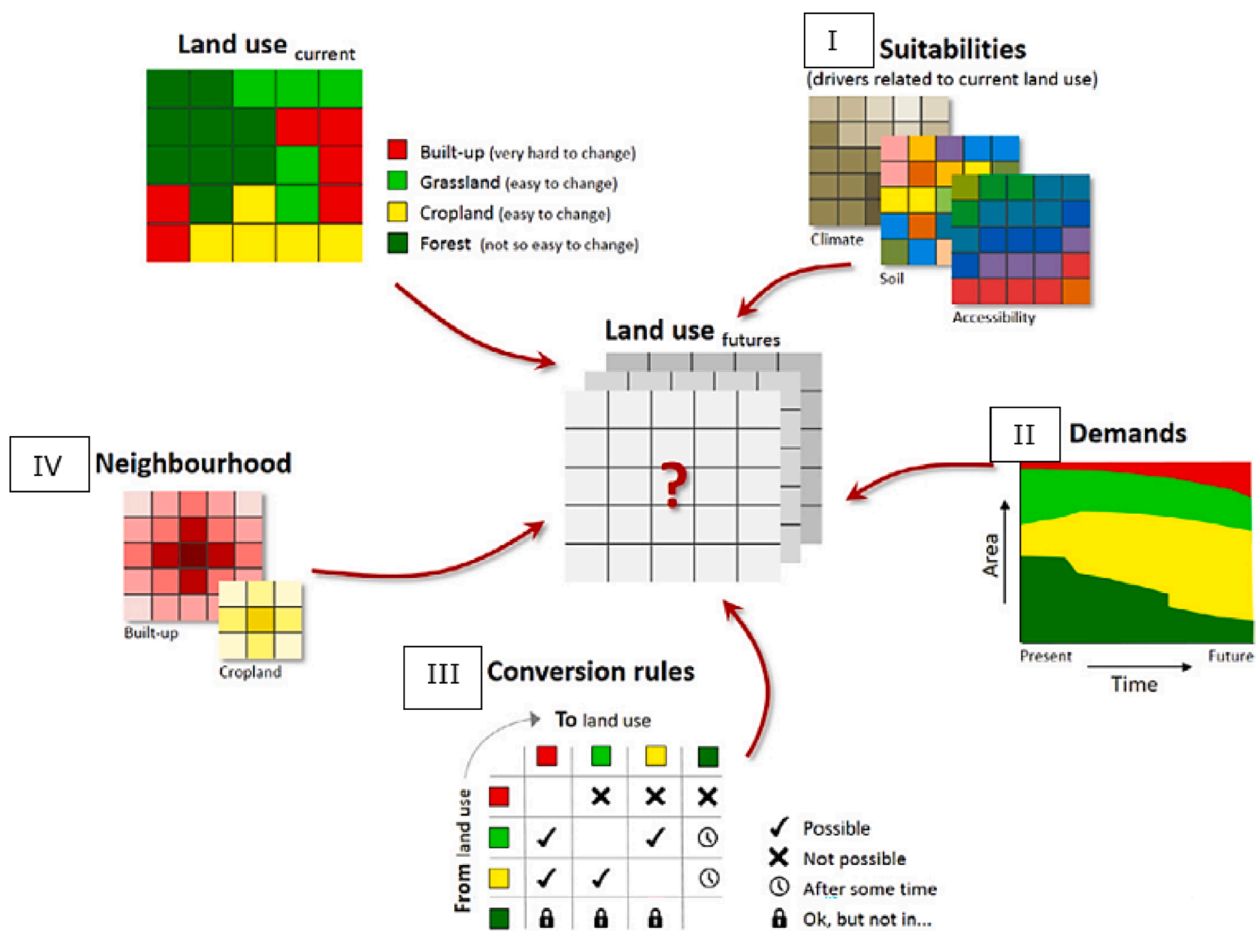

Fig. 3. The land-use projections with iCLUE model: (I) the land suitability, (II) the areal demands for every land-use class are the components that determine the future land-use allocation, (III) conversion rules and (IV) neighbouring land uses.
adapted from Verweij et al., (2018)

Table 1
The land use and land cover (LULC) classes for upper Manafwa watershed.

Land cover class	Description
Built-up	Artificially paved surfaces and built areas, including rural and urban residential & service areas, industrial & commercial areas, transportation & communication routes, construction sites, and green urban / mixed urban
Agriculture	Land area under perennial and annual food and / or cash crop cultivations; mixed farms of bananas, coffee, maize, beans, cabbages, and any other vegetables.
Planted forest	Manmade forests of planted broad leaved woody trees and / or evergreen needle-shaped leaved trees with top layer trees < 65% cover and second layer mixed with coffee and banana plants. Undergrowth of small trees, shrubs and grasslands with Closed to Open cover of 40–100-40% respectively.
Bushland	Natural and / or human-planted vegetation dominated by undergrowth of thickets intermixed with a bunch of grasses growing together as an entity but not exceeding an average height of 4 m.
Grassland	Extensively used grasslands with or without the presence of farm structures, such as fences, shelters, enclosures, watering places.
Bare & sparsely vegetated surfaces	Lands with exposed soil and sand, the vegetation cover never exceeds 10% during anytime of the year and stony (5% – 40%). Includes rock outcrops, bedrock exposures and accumulation of rock without vegetation, cliffs and active erosion surfaces.
Shrubs	Mixture of perennial woody shrubs and dotted trees without any defined main stem <5 m tall. The shrub foliage can be either evergreen or deciduous with or without grass species.
Tropical high forest low-stocked	Degraded or encroached part of the mixed natural forest with indigenous trees, top layer trees < 20%, and second layer mixed with shrubs and bush consist of seasonal broadleaf tree communities with an annual cycle of leaf-on and leaf-off periods.
Tropical high forest well-stocked	Primary mixed natural forest with tree canopy > 70%, almost all broadleaf trees remain green all year around. Well-stocked and canopy is never without green foliage.

adopted from Opedes et al., (2022)

extensive array of biophysical and socioeconomic variables were taken into account within this study, guided by the availability of data. An overview and description of data used is given in the Appendix A (Table 1). A total number of 38 factor variables were used in this study and ranked according to their contributions to observed projections as driving factors (see Appendix A: Table 3). The biophysical datasets used in this study included elevation, soil, rainfall, land use, and the tree cover status. Elevation data were acquired from ALOS PALSAR 12.5 m resolution Digital Elevation Model (DEM). The slope data were extracted from the elevation using ArcGIS Pro (version 2.5.1). The soil characteristic datasets used in this study were acquired from the International Soil Reference and Information Centre (ISRIC) data hub (https://data.isric.org last access: 15 November 2022) with resolution of 250 m. Other biophysical drivers used include average annual rainfall, land use, location of rivers and streams, soil type, tree gain and tree cover loss (Hansen et al., 2013; National Forestry Authority (NFA), 2007); Opedes et al., 2022). The socio-economic drivers considered include population density, road infrastructure and distance to town, health facilities, and education institutions. Note that highly correlated variables were automatically eliminated by the model (Huber García et al., 2018). All modelled future land use maps were produced at a spatial resolution of 30 m, consistent with the extent and resolution of the initial input land use map. Within the modelling process, all mentioned input variables are automatically resampled and reprojected by the model, as detailed by Verweij et al., (2018).

2.4. Stakeholder involvement and output verification

Stakeholders were selected from the Manafwa Watershed Restoration and Conservation Platform (MWARECoP), including; representatives from Bududa district, Uganda Wildlife Authority, Sub County and Natural Resource Committees, Community Based Organizations, and the Manafwa Watershed restoration project staff. A one-day workshop involving 17 stakeholders was conducted. Details of the participants are presented in Appendix A (Table 2). Stakeholders were briefed on workshop aims, research ethics, and confidentiality. They provided verbal consent for participation, knowing their input might be used anonymously in reports and publications. The workshop began with a presentation of our previous study findings (Opedes et al., 2022) on the historical LULC change in the study area. Afterwards, near-future projections were explained, including the iCLUE model and output statistics. Stakeholders then answered a questionnaire about their agreement with these projections, affected land use types, top drivers, and conservation implications. The session ended with a discussion, letting stakeholders share observations and giving feedback.

3. Results

3.1. Contribution of factor variables

The variables employed in the modelling process of this study were ranked based on the overview of use and relative importance of each variable to the final output, as outlined in Appendix A (Table 3). The table shows that 36 out of 38 drivers were demonstrated within the regression model by the stepwise regression as a relevant driver to be included in the model. Only two drivers (tree cover loss and sodic soil grade) were removed by the model and excluded as influential drivers in the variable list. This table does not depict the local spatial variation of all variables for each raster pixel.

Among these variables, land cover and soil pH emerged as the most influential, closely followed by absolute depth to bedrock. Stream location, soil organic carbon content, and distance to pathways were also among the major important spatial factors. Additionally, the extent of the MENP was a significant factor, securing a place within the top 10 contributing variables for the land use change projections. Predominantly, soil-related factors showcased substantial influence on the projected LULC changes, with factors such as Euclidean distance to secondary schools, population density, and Euclidean distance to health centres emerging among the top 20 contributors as socio-economic influences. Interestingly, tree cover loss and sodic soil grade variables were excluded by the model due to their non-contributory nature to the projections as shown in Appendix A (Table 3).

3.2. Historical and projected land use land cover change

Fig. 4 presents the historical LULC situation in 1978–2020 and projected changes for the near-future (2030, 2040, and 2050) using the iCLUE model. Man-made categories encompass built-up areas, agriculture, and planted forest, while the remainder fall under natural classes (Table 1). In 2020, dominant cover classes (>20%) included, agriculture (30%), tropical high forest well-stocked (22%), and tropical high forest low-stocked (19%), with shrubs and bushland constituting the smallest (<10 km^2) cover classes at 1.5% and 2.0% respectively (Fig. 4). A similar trend was observed from the historical decades.

Near-future projections show area coverage of man-made categories expanding steadily, leading to a decline in natural vegetation cover. By 2050, agriculture alone is predicted to cover approximately 45% of the study area (Fig. 4). Correspondingly, natural LULC classes are anticipated to decrease decade by decade. The tropical high forest well-stocked land use category is projected to diminish fourfold from its 2020 extent, primarily converting into tropical high forest low-stocked by 2050. Grassland and sparsely vegetated surfaces are anticipated to remain relatively constant due to terrain and distance from built-up areas. Notably, shrubs and bushland are projected to nearly vanish (~0.5%) and could disappear post-2050. Built-up areas is projected to

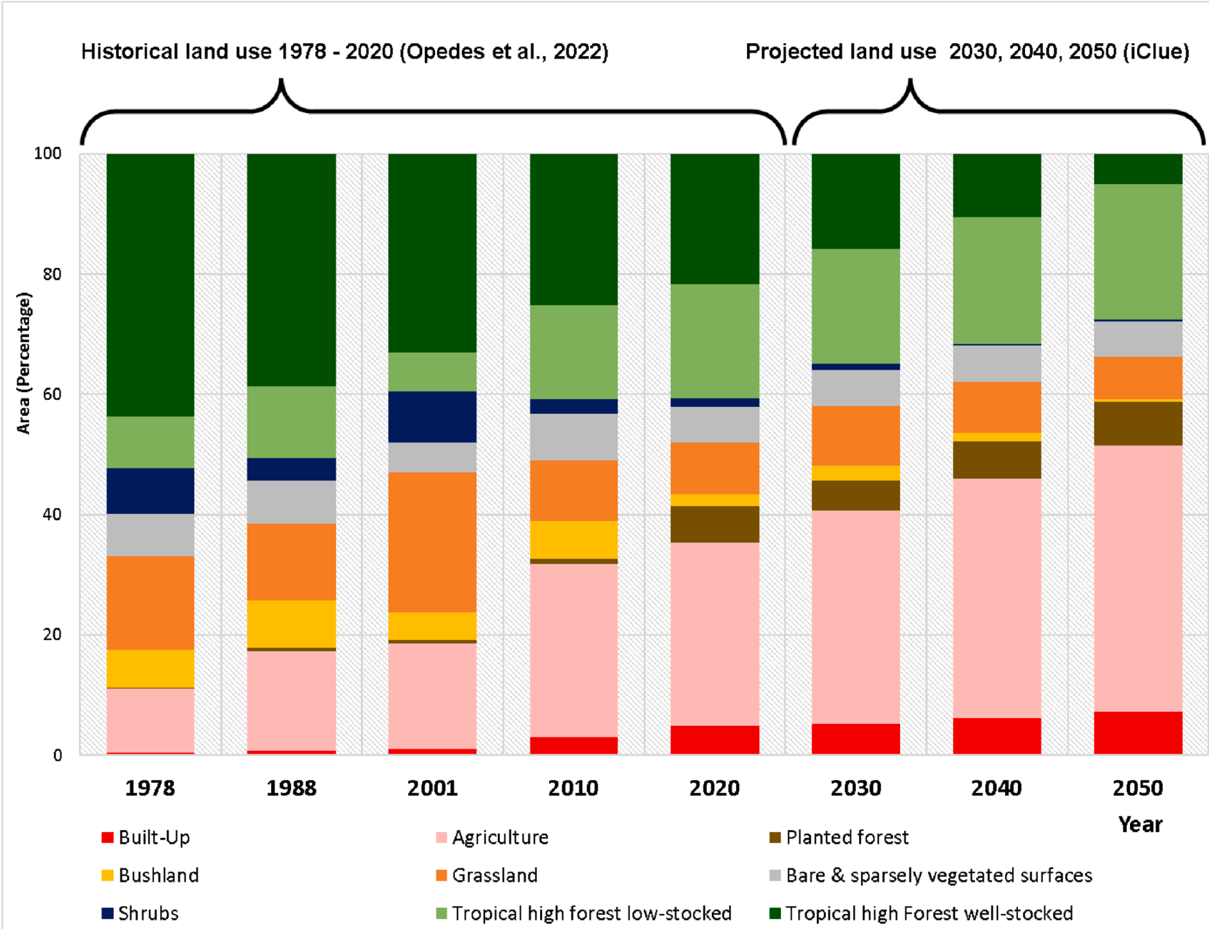

Fig. 4. Historical land use 1978–2020 taken from Opedes et al., (2022), and iCLUE Projections for 2030–2050 in the upper Manafwa Watershed. The area coverage for 1978–2020 is the actual historical LULC change. The starting point for the modelling with iCLUE was 2020, whereas 2030 – 2050 are results of projections from iCLUE Model.

progressively grow at a gradual pace (~1% per decade), constrained by challenging terrain and steep slopes that limit expansion.

Spatial and temporal LULC for 2020 and projections for 2030–2050 are depicted in Fig. 5 (a-d), while 5e shows location of changes only from 2020 to 2050. These conversions are predicted to largely occur at the conservation area's boundary, primarily transforming into agriculture, built-up areas, and planted forest (Fig. 5b and d). The conversion of tropical high forest well-stocked to tropical high forest low-stocked is expected to be dominant in 2040 and 2050 (Fig. 5c and 5d).

Conversions in the park and intensified land use in community areas are projected to persist. The Northern, Eastern, and Western parts of the study area are predicted to experience conversions from bushland, grassland, and shrubs into agriculture, built-up areas, and planted forests (Fig. 5b-d). Natural cover in the conservation area is expected to transform outwards over time, with most fringes likely to be converted into agriculture, planted forests, and built-up areas by 2050. Fig. 5e further illustrates a very large part of the study area (locations without LULC colours) as stable. However, the largest predicted conversions were, into agriculture, observed along the fringes of the conservation area and community land between 2020 and 2050. This is expected to be followed by tropical high forest low-stocked as seen on the Eastern part of the study area (Fig. 5e). The lowest conversions were predicted in bushland, grassland, bare & sparsely vegetated surfaces, and tropical high forest well-stocked.

3.3. Land use intensification and park conservation 2020 – 2050

Fig. 6 illustrates the proportional distribution of LULC within both the conservation area and community land for 2020 and projections of 2030 to 2050. In community land, agriculture covered 32% of the area in 2020, while the smallest coverage (<1%) included tropical high forest well-stocked, tropical high forest low-stocked, and shrubs. Conversely, in the conservation area (MENP), tropical high forest well-stocked dominated with 20% coverage, closely followed by tropical high forest low-stocked at 17% while built-up and planted forest had the lowest cover (<1%). Predictions indicate a dominant agricultural cover approximating to 35% of the community land by 2030, followed by built-up areas and planted forest, each at 5%. Projecting to 2050, agricultural coverage within the community is likely to expand to 38%, progressively encroaching upon bushland, grassland, and shrubs. Simultaneously, shrubs and bushland coverage in the community is expected to exhibit a consistent decline, dropping from over 0.5% in 2030 to over 0.3% in 2050.

A shift in dominant cover types within the conservation area is expected. Tropical high forest low-stocked (secondary forest) is projected to claim 18% coverage by 2030, ascending to 21% by 2050. Conversely, tropical high forest well-stocked (primary forest) is expected to undergo a swift decrease from 15% in 2030 to 5% by 2050 within the conservation area (Fig. 6). Furthermore, the coverage of shrubs and bushland is predicted to experience sustained reduction, dwindling from 0.77% and 1.9% in 2030 to 0.24% and 0.37%, respectively by 2050. The extent of

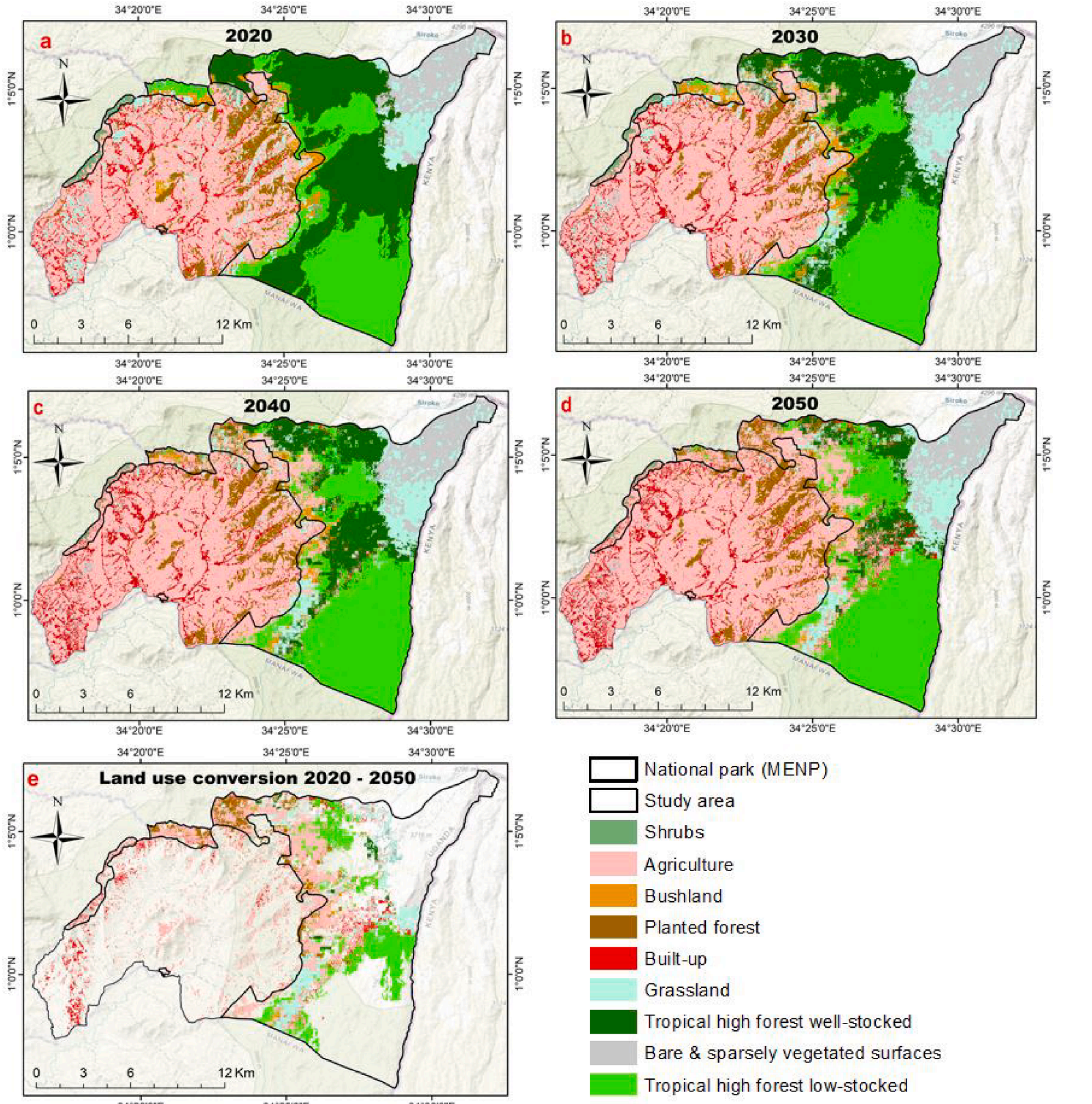

Fig. 5. The LULC for 2020 a), and projections for b) 2030, c) 2040, d) 2050 and e) land use conversion 2020–2050 in the upper Manafwa watershed. Note that Fig. 5e shows only the changes with into classes (2050). The national park (thick black line) shows the extent of projected conversion by the man made classes inside and outside the conservation area.

grassland and bare & sparsely vegetated surfaces in the conservation area is projected to remain relatively stable.

3.4. Stakeholder verification of land use projections

The participatory workshop involving MWARECoP stakeholders yielded a consistent consensus with the model projections. All stakeholders concurred that the iCLUE model effectively projected spatially-explicit land use change from 2030 to 2050. Stakeholders' perceptions of anticipated land use change in the upper Manafwa watershed by 2050 are depicted in Fig. 7. Under a business-as-usual scenario, the majority of stakeholders anticipated substantial encroachment into the conservation area through agriculture and settlements. Notably, tropical high forest well-stocked is projected to be the most impacted, facing conversion due to frequent resource extraction. The stakeholders pinpointed changes to predominantly occur in frequently accessed locations adjacent to the conservation area, flat and gentle slopes, and near emerging towns. Sub Counties and villages near the conservation area emerged as focal points for conversion. Primary drivers of these changes were identified as rapid population growth, escalating demand for agricultural land, and prevailing poverty. Supplementary factors notably MENP boundary, law enforcement, and limited education and awareness levels were acknowledged to play contributing roles.

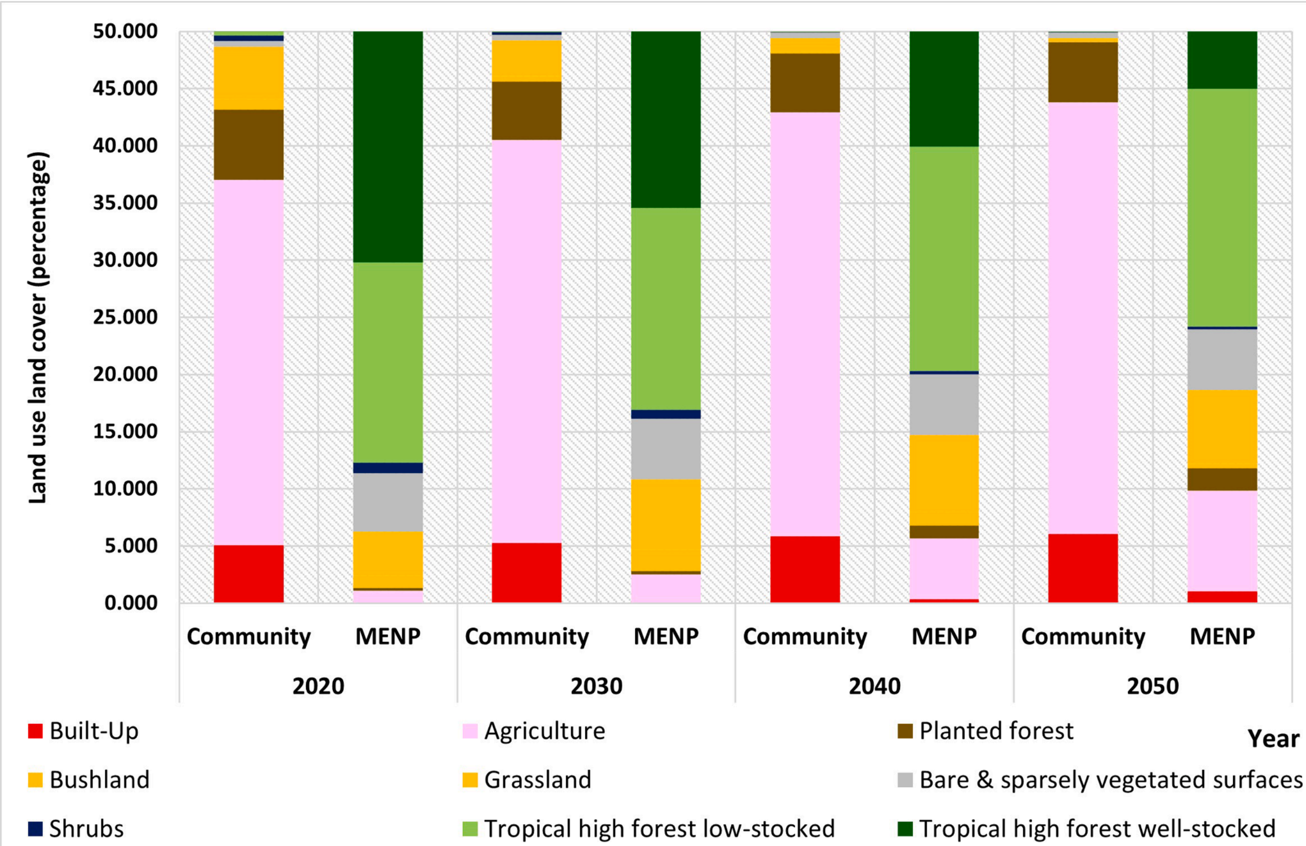

Fig. 6. The comparison of percentage LULC classes in the community land and the conservation area (MENP) for 2020 and the projections for 2030–2050. The park boundary was used as the line of separation between the community and the conservation area.

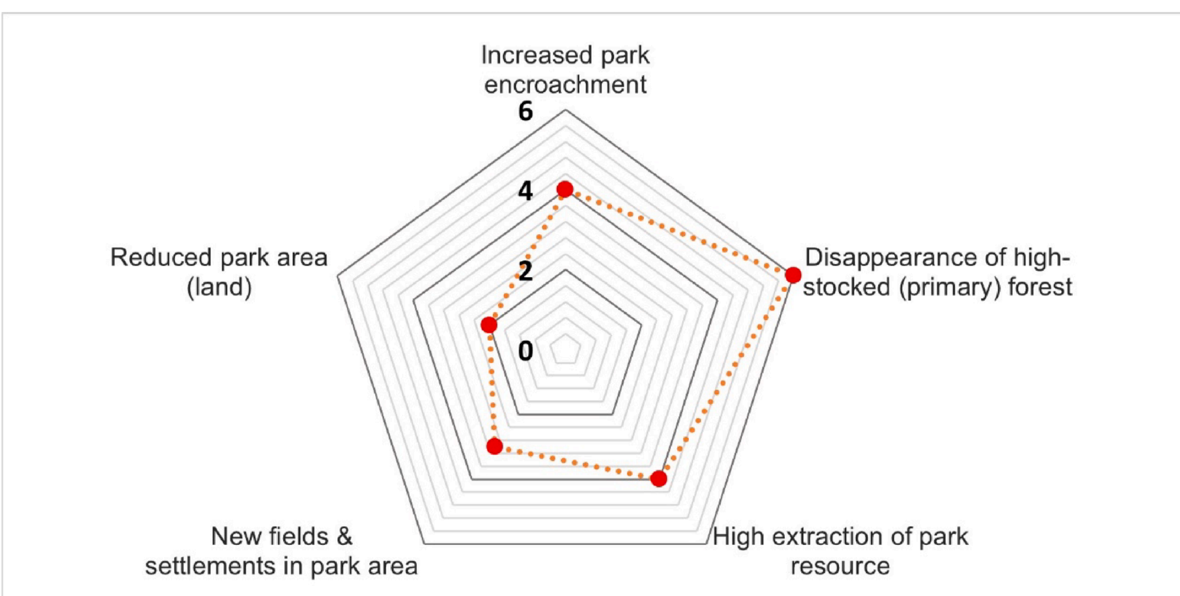

Fig. 7. Stakeholders' perspectives on expected changes within Mount Elgon conservation area by 2050 during the verification workshop. The numbers show the frequency of the responses to expected changes from the stakeholders.

4. Discussion

4.1. Contribution of factor variables

The variables identified as influential, including land cover, bedrock depth, stream locations, distance to pathways, and the extent of the conservation area, are pivotal determinants in shaping land use choices among local communities, significantly impacting decisions related to agriculture and built-up areas (Hoyer & Chang, 2014; Malek & Boerboom, 2015). This forecasted trend aligns with the continuing reduction in natural cover within the conservation area, reflecting the interconnected challenges posed by high population and arable land demands (Malek & Boerboom, 2015; Waiyasusri et al., 2016). Concurrently, the rapid population growth, coupled with weak law enforcement, and persistent conflicts have been previously reported as complex contributors to forest cover decline (FAO & UNEP, 2020; Himmelfarb & Cavanagh, 2018). Additionally, the study highlights the substantial influence of soil characteristics in driving projected land use change. Farmers in Mount Elgon region usually apply fertilizers and organic manure to enhance soil fertility especially in areas experiencing soil erosion (Oyana et al., 2015).

Simultaneously, the absence of certain variables notably tree cover loss and sodic soil grade in the model draws attention to their minimal contribution to the projected outcomes. This exclusion implies that, within the specific context of this study area, these factors have limited significance in shaping land use dynamics. The model elimination of non-contributing factors was similarly reported by Huber García et al., (2018). Nevertheless, the study findings indicate that a combination of biophysical and socio-economic factors underscores the intricate balance between human activities and ecological conservation in the study region.

4.2. Land use land cover 2020 and near-future projections (2030–2050)

The rapid depletion of natural forest cover and intensified land use stem from the surging demands of population growth and the need for arable land to feed the subsistence farmers and their families as evidenced in the Northern, Eastern, and Western parts of the study area. These are locations where sub counties with the highest human population (>200,000 people) was recorded in Bududa district (Uganda National Bureau of Statistics, 2017). According to the National Planning Authority, (2020), a significant 68.9% of households in Uganda rely on rainfed subsistence agriculture. These figures provide a reliable justification of the projections. High population leads to continued land fragmentation, driving the expansion of arable land through deforestation, human-induced fires, and unsustainable forest resource exploitation within the conservation area (Opedes et al., 2022; Sassen et al., 2013). The reduction in forest cover is further attributed to limited monitoring and dealing with encroachment within the conservation area (Sassen et al., 2015). Unsustainable exploitation of forest resources, coupled with settlement demands stemming from historically mismanaged resettlement schemes, has significantly impacted forest cover in the Mount Elgon conservation area (National Planning Authority, 2020; Petursson et al., 2013). As Uganda's population is projected to grow from 34.6 million in 2014 to 89 million by 2050 (United Nations, 2019), it is arguable that pressure on forest land acreage will intensify (FAO & UNEP, 2020).

Conversely, the rate and nature of transitions are intrinsically tied to conservation efforts and the degree of enforcement. Notably, the expanding area of planted forest can be attributed to regreening initiatives implemented by multiple stakeholders and partners within the study area (Misanya et al., 2023; Opedes et al., 2022). The government's ambitious goals to increase forest cover to 24% by 2040 through reforestation, afforestation, and fostering private commercial plantations (National Planning Authority, 2013) can potentially boost forested areas. Additionally, government strategies aim to reduce the percentage of households reliant on subsistence farming from 69% in 2020 to 55% by 2025 (National Planning Authority, 2020) by promoting livelihood diversification programs such as agro-industrialization and capitalizing on tourism potential (National Planning Authority, 2020). Effective implementation of government environmental related programs, along with enhanced law enforcement, is expected to result in increased planted forest cover within the study area.

4.3. Land use intensification and park conservation 2030 – 2050

The study findings illuminate a complex landscape of changes within the study area, marked by intensified land use, particularly within the fringe of the conservation area. This phenomenon is partly explained by the relative proximity of settlements to the park, which exacerbates land use alterations. The observed pattern underscores a dynamic interplay between different land cover categories. While the decline in tropical high forest well-stocked, shrubs, and bushland coverage is evident, this reduction is compensated by increases in tropical high forest low-stocked, agriculture, planted forest, and built-up areas. Indeed, previous research has accentuated the vulnerability of natural vegetation to the encroachment through agriculture and urbanization (Kariuki et al., 2021). Further, in relation to similar previous studies, areas situated closer to the conservation area are more susceptible to encroachment due to higher accessibility, in comparison to more remote regions (Hoyer & Chang, 2014; Malek & Boerboom, 2015). The projected land use transitions documented in this study within the conservation area, specifically the expansion of built-up areas and agriculture, primarily occur in regions featuring gentle slopes and developed soil profiles, which are conducive to settlements and cultivation (Tuffour-Mills et al., 2020).

4.4. Stakeholder verification of land use projections

The stakeholder workshop validated the projected land use change and this strengthens the link between scientific knowledge and indigenous perspectives (Castella & Verburg, 2007; Volkery et al., 2008). The collaboration enhanced result credibility and acceptance, facilitating actionable strategies by involved stakeholders as reported previously (Hewitt et al., 2014; Meyer et al., 2014). The shared insights of this study empowered MWARECoP stakeholders to specifically devise targeted measures for sustainable land use and reduced encroachment (Fig. 8). Holistic conservation management necessitates collective efforts from researchers and practitioners. To mitigate encroachment, community members should adopt sustainable farming practices, implement soil conservation measures, and diversify livelihoods (Sassen et al., 2015; Shaban et al., 2016). Projects like the Manafwa watershed restoration initiative and collaborations with Uganda Wildlife Authority have introduced sustainable farming and beekeeping practices within the park (Nakakaawa et al., 2015). Effective encroachment reduction require cohesive action plans, coordinated governmental and non-governmental initiatives, and community participation.

This study considered pertinent factors aligned with iCLUE modelling environment, based on data availability and compatibility. However, just like other studies, intricate, hard-to-quantify factors like political influence and dynamic government policies were not integrated (Han et al., 2015). Kucsicsa et al., (2019) highlighted that limited data availability and specifications can constrain model parameters and outcomes. Park trails and paths not factored in this study may for instance, inadvertently exacerbate resource exploitation and encroachment as that has occurred previously (Himmelfarb & Cavanagh, 2018; Malek & Boerboom, 2015). Such limitations may impact projection accuracy. Additional unforeseen events including natural disasters, resettlement initiatives, changes in administrative boundaries and conservation zones could similarly shape distinct outcomes. To illustrate, the historical boundary shifts on Mount Elgon have spurred encroachment (Ditiro et al., 2008; Himmelfarb, 2006). Nonetheless, this

Fig. 8. Stakeholder validation of the study findings on the near future projections of land use change (a) in the upper Manafwa watershed of Mount Elgon Uganda triggered MWARECoP members to develop informed work plan (b) for implementation.

study identified encroachment hotspots, impacted land use classes underscored by intensification effects, particularly in the study's Northern and Eastern regions and along the MENP boundary. These findings serve as an alert to policymakers about imminent LULC shifts and the enduring consequences of conservation area encroachment. Future studies should encompass these insights and consider various models and locally relevant drivers to enhance projection accuracy.

5. Conclusions

This study utilized the iCLUE model to predict land use and land cover changes (2030–2050) within the study area, adopting a business-as-usual scenario. By incorporating historical data with pivotal factors influencing LULC alterations, we evaluated the anticipated shifts between the conservation area and community land, delineated by the MENP boundary. The results highlight a surge in agricultural activities within the community land and a transition towards tropical high forest low-stocked cover within the conservation area.

These findings not only offer a glimpse into the impending landscape transformations but also underscore their implications on tropical conservation areas. Most notably, the cherished natural cover of Mount Elgon forest faces an escalating threat from expanding rainfed agriculture, which the projections suggest will intensify over time. These insights empower conservationists and stakeholders to devise precision strategies in countering encroachment on park lands as already evidenced with MWARECoP stakeholders. For enhanced precision, the combination of spatial modelling, stakeholder input, and high-resolution datasets is recommended. Furthermore, future investigations should explore diverse scenarios (specifically; impact of policy, climate change and community-driven planning) to model comprehensive land cover transitions, enhancing our comprehension of potential future trajectories.

CRediT authorship contribution statement

Hosea Opedes: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Michiel van Eupen:** Methodology, Software, Formal analysis, Validation, Resources, Data curation, Writing – review & editing, Visualization. **Caspar A. Mücher:** Conceptualization, Methodology, Software, Formal analysis, Validation, Resources, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Jantiene E.M. Baartman:** Validation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Frank Mugagga:** Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jnc.2023.126493.

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