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Evaluating Land Degradation for Sustainable Silvopastoralism in Savanna Region: A Case Study in Matimba and Rwimiyaga sectors in Eastern Province of Rwanda

David Ukwishaka[1,2] Aime Tsinda[2], Emmanuel Muyombano[2], Josephine Malonza[3], Esther Ndacyayisenga[4]

[1]*Rwanda Environment Management Authority*
[2]*University of Rwanda College of Science and Technology, School of Architecture and Built Environment, Department of Spatial planning*
[3]*University of Rwanda, College of Science and Technology, School of Architecture and Built Environment, Department of Architecture and Design*
[4]*Ministry of Infrastructure*

Abstract

Land degradation significantly affects the quality and productivity of land resources. It is caused by activities such as deforestation, soil erosion, desertification, pollution, overgrazing, and unsustainable agriculture. This study assesses land degradation in the Matimba and Rwimiyaga sectors of Nyagatare District, focusing on whether areas where silvopastoralism has been implemented correspond to regions experiencing significant land degradation from 2000 to 2022. Using the Good Practice Guidance (GPG) methodology, the study assessed changes in land cover, land productivity, and Soil Organic Carbon (SOC) as indicators of land degradation. The findings show significant changes in land cover over 22 years, with a reduction of 26,933 hectares in grassland (mainly used as rangeland) due to conversion to cropland. Deforestation, overgrazing, and expansion of built-up areas contributed to land degradation of 5,637 hectares over 22 years. Changes in land productivity indicate early signs of decline in about 40% of cropland, while the SOC remained relatively stable during the study period. Overall, from 2000 to 2022, the Matimba and Rwimiyaga sectors experienced land degradation of 7,347.4 hectares. The study discussed silvopastoralism sustainability and found that 46.7% of paddocks with this practice are in areas experiencing land improvement, 48.9% in stable areas, and only 4% in degraded areas. This implies that silvopastoralism is a promising strategy for improving land health. Therefore, the study recommends expanding silvopastoralism to other pastures with land degradation status and integrating this practice into Rwanda's National Adaptation Plan (NAP) for sustainability.

Keywords: *Silvopastoralism, Land Degradation, Savanna, Rwanda*

@Corresponding author: davidukwi@gmail.com

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1. Introduction

1.1. Background

Land degradation is a critical environmental issue with far-reaching consequences that affects ecosystems, food security, and human well-being (AbdelRahman & Arafat, 2020; Kawy & Darwish, 2019). The United Nations Convention to Combat Desertification (UNCCD) recognizes land degradation as one of the most noticeable environmental concerns of recent times (UNCCD, 2018). The UNCCD define land degradation as ‘the reduction or loss of the biological or economic productivity and complexity of rain fed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from a combination of pressures, including land use and management practices (UN, 2022). It was reported that more than 75% of Earth’s land areas are substantially degraded, affecting the well-being of 3.2 billion people, and if this trend continues, 95% of Earth’s land areas could become degraded by 2050 (IPBES, 2018; Leahy, 2018). Generally, rapid expansion and unsustainable management of croplands and grazing lands is the main driver of land degradation, causing significant loss of biodiversity and ecosystem services, including food security, water purification, the provision of energy, while climate change has exacerbated these issues globally (IPBES, 2018; Vassen, 2018). It is in this line, that the urgent actions are needed to achieve the land degradation neutrality and restore the natural environment.

Savanna regions are one of the fragile and vulnerable ecosystems, when it comes to land degradation due to the unstainable grazing and other crop practices (Dudley et al., 2020). Firstly, savanna experience prolonged dry season with limited rainfall concentration, which make this ecosystem more susceptible to drought and desertification (Falkenmark & Rockström, 2008; Incoom et al., 2020). This is worsening by its fragile soil structure that are easily disturbed by overgrazing, deforestation, and unstainable agriculture practices, that are prominent in the such ecosystems (Olson, 2004). The situation in land degradation can be hard if nothing done, by considering the human population that are increasing in savanna regions which put pressure on natural resource (IPBES, 2018), where for example, it is estimated that Africa host over 300 million people who lives in the tropical savanna regions. In these regions, there are several main activities practiced by the local populations. These activities are often centered around the utilization of natural resources available in the savanna ecosystem, this include agriculture by supporting variety of crops, and pastoralism whereby many people engage in herding cattle, sheep, and goats, often moving their herds in search of pasture and water (Reid, 2012). Most importantly, many savanna areas are home to protected areas and reserves focused on conserving wildlife and habitats. Furthermore, savanna woodlands provide resources for firewood and charcoal production, which are important sources of energy in many areas. These activities are interconnected and can impact each other in savanna ecosystem (Chidumayo & Gumbo, 2010). Therefore, sustainable practices in these activities are essential to maintain the ecological balance and support the well-being of the local populations.

In terms of reducing the land degradation and restore the natural environment in savanna region, there are various environmental restoration activities that can be applied. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Service (IPBES), recommended that integrated crop, livestock and forestry systems is one of the solutions for avoiding or reversing land degradation (IPBES, 2018). In this respect, silvopastoralism which is an integrated land-use system that combines trees or shrubs with livestock grazing suit in savanna region (Jose & Dollinger, 2019; REMA, 2021b). It involves strategically planting trees or shrubs in pastures or rangelands to enhance ecosystem services. In this regard, tree provide habitat for birds, insects, and other wildlife, enhancing overall biodiversity, while tree roots stabilize soil, prevent erosion, and improve forage (Jose & Dollinger, 2019). Additionally, tree offer shade, reducing heat stress for livestock, while leaf litter from trees enriches soil nutrients (Casanova-Lugo et al., 2022; Peri et al., 2016).

The overgrazing in the African savanna ecosystem affects its overall balance (Kgosikoma et al., 2015). In tropical areas, livestock production is challenging due to drought, which reduces plant growth and, consequently, animal growth as well, because dry plants have low nutritional value, and is harder to digest and less appetizing to livestock, resulting in reduced food intake and decreased productivity (Outlaw et al., 2022). To address these challenges, silvopastoralism has been implemented as a solution in tropical and sub-tropical areas, particularly in savanna ecosystems (Outlaw et al., 2022). Silvopasture is effective in these locations as it aims to sustain the environment while increasing outputs. It is suitable for both smallholders and large commercial farms (Peri et al., 2016). Silvopasture not only offers economic benefits but also helps restore savanna ecosystems, enhancing their resilience to climate change impacts such as drought. It generates livelihood benefits for the community and improves their resilience to drought (Pezo et al., 2018).

This is the case in the savannas of the Nyagatare District and other parts of the Eastern Province of Rwanda. Specifically, in the Matimba and Rwimiyaga sectors, the savanna is primarily used for livestock grazing and crop cultivation (REMA, 2021a). However, the combination of grazing, deforestation, inadequate mining systems or quarries extraction, overgrazing, drought, and wind erosion has resulted in severe degradation of the lowlands and savannas (NLA, 2023; REMA, 2021a; RWFA, 2018). Herds of cattle concentrated in relatively small areas lead to erosion around their paths, and to compaction and other forms of soil degradation in the grazing areas (Olson, 2004). As a result, forage availability for livestock was limited, and there was large-scale soil loss, reducing the land's productive potential. Historically, the pastures were in savanna ecosystem and possessed the indigenous trees (Olson, 2004). Afterward, the land had been increasingly being the cattle ranches, since the resettlement program after 1994. This led to the clearing of trees in favoring of forage growing for cattle. As the results, the areas experienced the reduction of land productivity because of deforestation.

In response, Rwanda Environment Management Authority (REMA) has implemented the silvopastoralism approach in Nyagatare, covering an area of 915.3 ha of pasture (REMA, 2022) to restore the land by using indigenous trees. The method for selecting the locations where the silvopastoralism were implemented was involving the pastoralists, where they voluntarily choose to benefit from this practice. The introduction of silvopastoralism is not unique to Rwanda, it was also implemented in the Gishwati-Mukura forest reserve in 2020 (Godfrey Mwesigye, 2022). REMA, through its project on Forest Landscape Restoration in Gishwati-Mukura, has established silvopastoral techniques using native species. However, only one study has been conducted to analyze the adoption of silvopastoral systems and the perceptions of pastoralists in the Gishwati-Mukura landscape, mainly in areas with abundant rainfall (REMA, 2021c). Therefore, there is a need to evaluate the land degradation status in the savanna region where the drought affects plants.

The overarching aim of this study is to assess land degradation in the Matimba and Rwimiyaga sectors, which have been significantly impacted by drought, and evaluate the role of silvopastoral practices in mitigating this issue. The study seeks to provide insights into the effectiveness of these practices and their potential applicability in other degraded areas. Specifically, this paper aims to:

- Map and estimate the extent of land degradation from 2000 to 2022.
- Assess the impact of silvopastoral practices on land improvement.
- Compare degradation trends in areas with and without silvopastoral practices.
- Identify opportunities for scaling silvopastoral systems in degraded regions.
- Propose strategies for enhancing land resilience and sustainability.

2. Materials and Methods

2.1. Study Area

The research focuses on the eastern savanna region of Rwanda, specifically the Matimba and Rwimiyaga sectors of Nyagatare District. These two sectors have experienced degradation over time due to overgrazing and deforestation (REMA, 2021a). The impact of climate change, such as drought, has further worsened the situation. Therefore, these sectors were chosen as the study area because silvopastoralism has been implemented in this location as a means of increasing resilience to climate change and restore the degraded land (REMA, 2021a), However, no previous studies have focused in the areas to understand whether this practice have improved the areas that marked the land degradation over the years. Figure 1 provides a location map of the study area.

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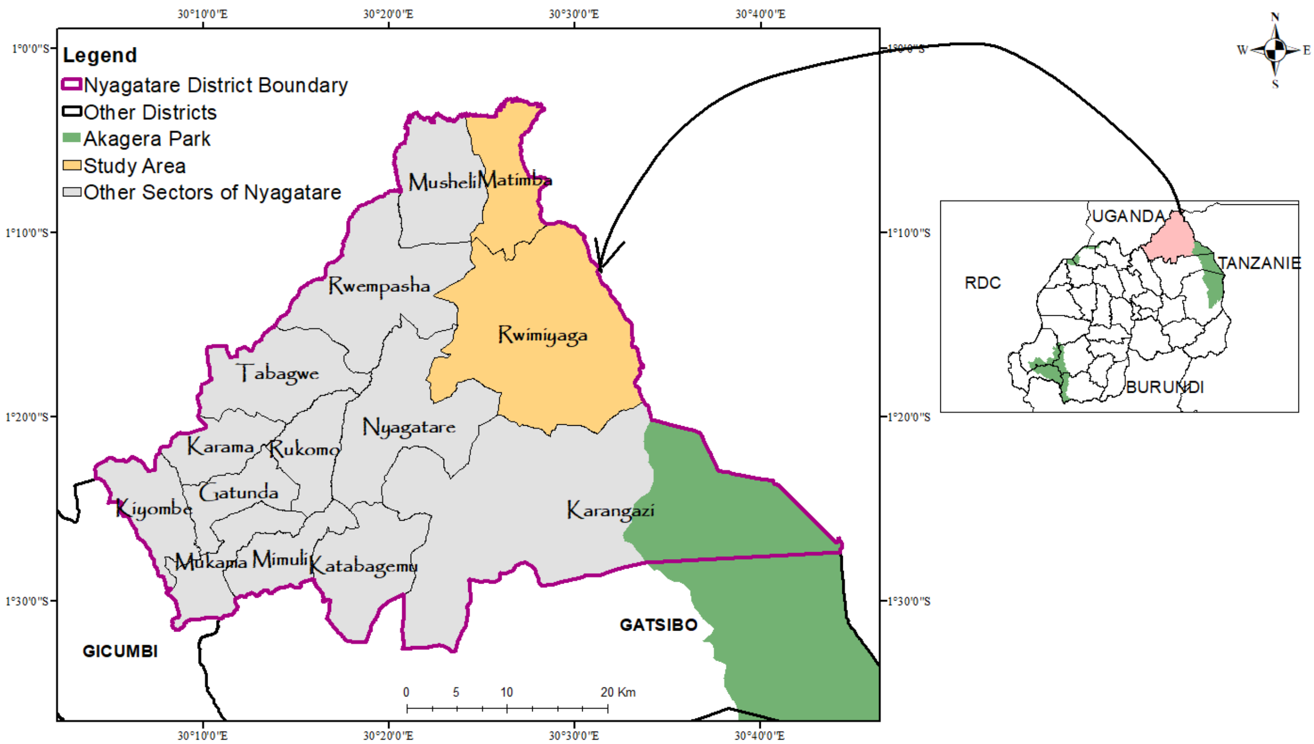

Figure 1: *The map of Nyagatare District showing the study areas (Rwimiyaga and Matimba sectors)*

Data sources: *National Boundaries Shapefiles from National Institute of Statistics of Rwanda (NISR)/National Parks shapefile from Centre for GIS and Remote Sensing (CGIS), University of Rwanda. The map was developed using ArcGIS 10.8/ Coordinate System: WGS 84*

2.1.1. Climate and Hydrology

The Nyagatare savanna, located in the Rwimiyaga Sector, experiences a mean annual precipitation ranging from 740 to 1000 mm (REMA, 2021a). There are two rainy seasons: one from March to May, receiving 310 mm of rainfall, and another from September to December, receiving 354 mm of rainfall. From 1981 to 2017, there has been a decreasing trend in rainfall amounts during the first wet season and an increasing trend during the second wet season (Meteo Rwanda, 2023). The period from 1991 to 2000 has been identified as the driest phase based on annual rainfall data between 1961 and 2018. Notable rainfall deficits occurred in 1992, 1993, 1996, 1999, and 2000, with contrasting rainfall excesses in 1998 and 2001. The first dry season typically lasts from late May to early September, while the long dry season extends from late May into the early months (Meteo Rwanda, 2023).

The eastern savannas are situated in the Nile Basin, with the Akagera River serving as the border with Tanzania. It is worth noting that the Karangazi River is also present, although it is unreliable and sporadic. Regrettably, this limited river network severely hampers water availability for both humans and animals in the area (Green, 2019).

2.2. Data Collection

2.2.1. Satellite-Based Data

The data used were selected based on its capacity to allow the accurate analysis of land cover, productivity, soil organic and land degradation patterns over 22 years. Thus, satellite images provided a comprehensive, spatially explicit view of the study area and cover large scale. The Satellite imageries used are Landsat 7 and 8. The Landsat 7 (launched in 1999) and Landsat 8 (launched in 2013) were selected given their extensive time coverage allowing for a 22-year assessment (2000-2022) of land degradation and sourced from the United State Geological Survey (USGS) Earth Explorer platform. Sentinel 2 was also used to assess the land cover in recent years, as it covers the images from 2016. While the MODIS was used in the assessment of the land productivity, to monitor changes in Net Primary Productivity (NPP) of vegetation.

Table 1: *Satellite Technical Specifications for Sourced Imagery*

Satellite	**Description**
Landsat 7	Spatial resolution (Multispectral Bands): 30 meters (m) resolution. Temporal resolution: 16 days Spectral Bands: 8 Temporal Coverage: 1999
Landsat 8	Spatial Resolution (Multispectral Bands): 30 meters (m) resolution for multispectral bands (visible, near-infrared, and shortwave infrared). Temporal Resolution: 16 days. Spectral Bands: 11 spectral bands, including 2 thermal bands. • Bands 1-7 (VNIR and SWIR): 30 m. • Band 8 (Panchromatic): 15 m. • Bands 10 and 11 (Thermal Infrared): 100 m, resampled to 30 m. Temporal Coverage: From 2013 onwards.
MODIS	Spatial Resolution (Multispectral Bands): • 250 meters (m) for Red and Near-Infrared bands. • 500 meters (m) for Shortwave Infrared (SWIR) and other multispectral bands. • 1,000 meters (m) for thermal infrared and other atmospheric bands. Temporal Resolution: 1-2 days (frequent revisit time). Spectral Bands: 36 spectral bands, ranging from visible to thermal infrared. Temporal Coverage: From 1999 onwards (Terra satellite) and 2002 onwards (Aqua satellite).
Sentinel-2	Spatial Resolution (Multispectral Bands): • 10 meters (m) for visible (Red, Green, Blue) and Near-Infrared (NIR) bands. • 20 meters (m) for Red-Edge and Shortwave Infrared (SWIR) bands. • 60 meters (m) for atmospheric correction bands.

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	Temporal Resolution: 5 days (at the equator with both Sentinel-2A and Sentinel-2B). Spectral Bands: 13 spectral bands, including visible, near-infrared, red-edge, and SWIR bands. Temporal Coverage: From 2015 (Sentinel-2A) and 2017 (Sentinel-2B).

2.2.2. Ground based observations

The results derived from satellite images were validated using ground-based observations from field visits that were conducted in April 2024. Field observation involved recording the data by capturing the photos where the analysis indicated that there is land degradation and other areas where the land recorded to be improving. The shapefile of paddocks where the silvopastoralism have been implemented was shared from Rwanda Environment Management Authority (REMA). Furthemore, other research papers and reports were used to supplement the findings.

2.3. Data Analysis

The image processing was conducted using GIS software (ArcGIS, QGIS and Google Earth Engine). Statistical analysis and visualization were performed using Excel. The table 2 present the tools used.

Table 2: *Tools and their applications*

Tool	Application
ArcGIS	Supported to do the imagery analysis for mapping the land cover change as one indicator for assessing the land degradation. The tool was also used to make final map of land degradation. The tool was selected as it has robust capabilities in imagery analysis.
Trend.Earth (QGIS)	The Trend.Earth is the QGIS extension that was used to map the Soil Organic Carbon as one indicator for the land degradation. Trend.Earth offers specialized tools for such environmental assessments and integrates well with QGIS for geospatial analysis.
Google Earth Engine	The tool was used to analyze the land productivity by adopting the analysis done by FAO. Google Earth Engine was chosen for its ability to handle large-scale geospatial data analysis.
Excel	Excel was used to make graphs and statistical analysis, as it is a valuable tool for analyzing and presenting data in a structured format.

2.3.1. Assess the extent of land degradation

To calculate the extent of land degradation over total area, the Good Practice Guidance (GPG) that have been developed to support countries for reporting on United Nations (UN) Sustainable Development Goals (SDGs)'s indicator 15.3.1 on the proportion of land that is degraded over total land area, have been used. This guidance supports the development of analytical methods for measuring its three sub-indicators, which are; the trends in land cover, trends in land productivity, and the trends in carbon stocks (above and below ground), which is currently represented by SOC stocks (Sims et al., 2021). The figure below presents the steps of calculating the extent of land degradation, by using three sub-indicators.

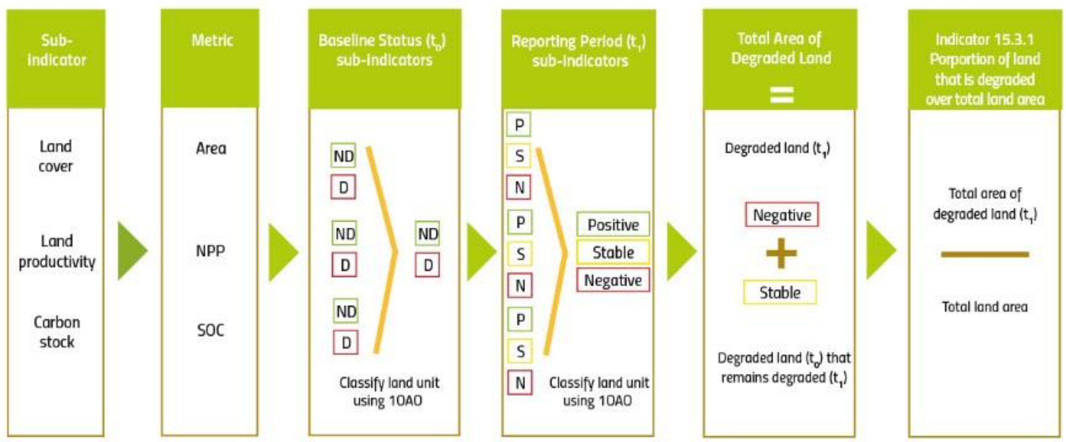

***Figure 2**: Steps to derive the indicator from the sub-indicators where ND is "not degraded" and D is "**degraded**"*
Source: (Sims et al., 2021)

Sims et al., (2021) have noted the difficulty of relying on a single indicator to accurately assess the state or condition of the land. Therefore, the study considered three sub-indicators as proxies to monitor the essential variables that reflect the land's capacity to provide ecosystem services. In practical terms, for the purposes of calculating the land degradation (indicator), tracking change in the extent of degraded land is a three-step process:

- Calculate the extent of degradation in the baseline period (t_0) which is 2000.
- Calculate the extent of degradation in the reporting period (t_n) 2022, which indicates the recent extent of degraded land.
- Calculate the change in extent of degradation between the baseline and reporting period.

2.3.2. Land Cover Sub-indicator

This sub-indicator reports degradation in land cover change based on assessment of the positive or negative aspects of transitions from one land cover type to another. The first task, was to consider the main drivers of land cover change, and then to determine which transitions to identify as "degraded" or "not degraded". Referring to the Good Practice Guidance (GPG), land degradation is defined based on land use transitions. For example, when land cover transitions from any class to trees (forestland), it was defined as an improvement in terms of land productivity. Conversely, when land transitions from trees to any other class, it was defined as degradation, as deforestation is one of the causes of land degradation. Further, if cropland or grassland is converted into built-up areas, it was also defined as degradation. According to the transition of the land cover, the following matrix was used to indicate the status for each transition to the land.

		Land Cover type 2022					
Land Cover type 2000		**Cropland**	**Grassland**	**Otherland**	**Trees (Forest)**	**Settlement**	**Water**
	Cropland	Stable	Withdrawal of Agriculture	No transition	Afforestation	No transition	No transition
	Grassland	Agricultural expansion	Stable	Vegetation loss	Afforestation	Urban expansion	Encroachment of river bank
	Otherland	Agricultural expansion	Vegetation establishment	No Change	Afforestation	Urban expansion	No transition
	Trees (Forest)	Deforestation	Vegetation loss	Deforestation	Stable	Urban expansion	Encroachment of river bank

Table 3: *Land cover transition Matrix*

Land cover maps for 2000 and 2022 were generated using Landsat 7, Landsat 8, and Sentinel-2 satellite imagery, along with classification techniques. Each map was categorized into (trees) forestland, cropland, other land, grassland, and built-up areas. To analyze changes between these two periods, a transition matrix was employed. Land degradation was identified as transitions indicating a decline in land quality, improvement was associated with transitions reflecting land restoration, and stability was defined as areas where no changes occurred in land cover class. Consequently, areas of degradation, improvement, and stability were mapped based on the transition matrix analysis.

The total area was calculated for each transition type (degraded, improved, stable). While, the proportion of degraded, stable and improved land was calculated relative to the total area of each land cover class and the total land area, using the following formulas.

$$A(Transition)_i = \Sigma A(Transition)_i j$$ *Equation 1*

Where:

- $A(Transition)_i$ is the total area of transition (degraded, improved, or stable) for land cover class i;
- $A(Transition)_{ij}$ is the area of transition from class i to class j.

$$P(Degraded)_i = (A(Degraded)_i / A(Total)_i) * 100$$ *Equation 2*

Where:

- $P(Degraded)_i$, is proportion of degraded land for land cover class *i* (%);
- $A(Degraded)i$ is the total degraded area for land cover class *i* (ha);
- $A(Total)_i$ is the total area of land cover class *i* (ha);

$$P(Improved)_i = (A(Improved)_i / A(Total)_i) * 100$$ *Equation 3*

Where:

- $P(Improved)_i$ is proportion of improved land for land cover class i (%);
- $A(Improved)_i$ is the total improved area for land cover class i (ha);
- $A(total)_i$ is the total area of land cover class i (ha).

$$P(Degraded) = (A(Degraded) / A(Total)) * 100$$ *Equation 4*

Where:

- $P(Degraded)$ is the proportion of total degraded land for the entire region (%);
- $A(degraded)$ is the total degraded area across all land cover classes (ha);
- A (total) is the total area of land cover class (ha).

2.3.3. The Land Productivity sub-indicator

The land productivity is one the sub-indicator that determine the land degradation by indicating the changes in the health and productive capacity of the land. The Land Productivity sub-indicator reported productivity degradation using Earth Observation (EO) data to monitor changes in Net Primary Productivity (NPP) of vegetation. This assessment was based on three metrics, calculated from a time series of annual NPP observations, that are designed to identify changes in the trajectory and level of productivity. The three metrics are as follow:

- Trend, which measures the trajectory of productivity change over the long term,
- State, which compares the current productivity level in a given area to recent historical observations of productivity in that same area, and
- Performance, which indicates the level of local productivity compared with other areas with a similar land productivity potential regionally.

In combination, these three metrics identified the degradation in land units where land productivity is: i) exhibiting a significant negative trend over the longer term ii) exhibiting a recent change in trajectory compared to the long-term trend iii) substantially lower than 'normal' for a given location over time iv) substantially lower than other similar land capability units within a given region v) increasing but remains lower than 'normal'.

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The land productivity was sourced from the system developed by the FAO. The system is based on cloud computing which is the Google Earth Engine (GEE) application. The land productivity mapping from FAO, was based on participatory assessments, and satellite-derived data.

2.3.4. Soil organic carbon (SOC)

The third sub-indicator for assessing land degradation evaluates changes in soil organic carbon (SOC) from 2001 to 2022. This assessment is complex due to several factors, including the high spatial variability of soil properties, the time and cost involved in conducting representative soil surveys, and the limited availability of time-series SOC data for many regions worldwide. The Trends.Earth tool was utilized to estimate SOC changes and identify potentially degraded areas by combining land cover data with SOC estimates (CI, 2024).

The first step was to determine the SOC reference values. Trend.Earth uses Soil Grids 250m carbon stocks for the first 30 cm of the soil profile as the reference values for calculation. It's important to note that Soil Grids compiles data from various sources over many years.

To estimate the changes in Carbon stocks for the reporting period, Carbon conversion coefficients for changes in land use, management and inputs are recommended by the Intergovernmental Panel on Climate Change (IPCC) and the UNCCD. However, spatially explicit information on management and Carbon inputs is not available for most regions. As such, only land use conversion coefficient was applied for estimating changes in C stocks (using land cover as a proxy for land use). The coefficients used were the result of a literature review performed by the UNCCD. Those coefficients represent the proportional in Carbon stocks after 20 years of land cover change.

Changes in SOC were studied for land cover transitions involving agriculture, and for that reason there is a different set of coefficients for each of the main global climatic regions. According to the location of Rwanda, the coefficient for tropical montane (f = 0.64) climate was considered (CI, 2024). In addition, the relative different in SOC between the baseline (2001) and the target (2022) period was computed. The areas which experienced a loss in SOC of 10% of more from 2001-2022 was considered potentially degraded, and areas experiencing a gain of 10% or more as potentially improved.

3. Results

To fully comprehend the initial state prior to implementing the silvopastoralism, it was crucial to evaluate the level of land degradation in the area. As land degradation can lead to decreased soil fertility, diminished biodiversity, reduced agricultural productivity, the loss of ecosystem services, and worsened environmental issues such as erosion, flooding, and desertification. The results focused on the land degradation that was assessed based on sub-indicators which are the land cover, land productivity and soil organic carbon as well as considering the areas where silvopastoralism.

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3.1. Land Cover

The process of finding the extent of land degradation involved mapping the land cover between two periods (2000 – 2022), as shown in Figure 3.

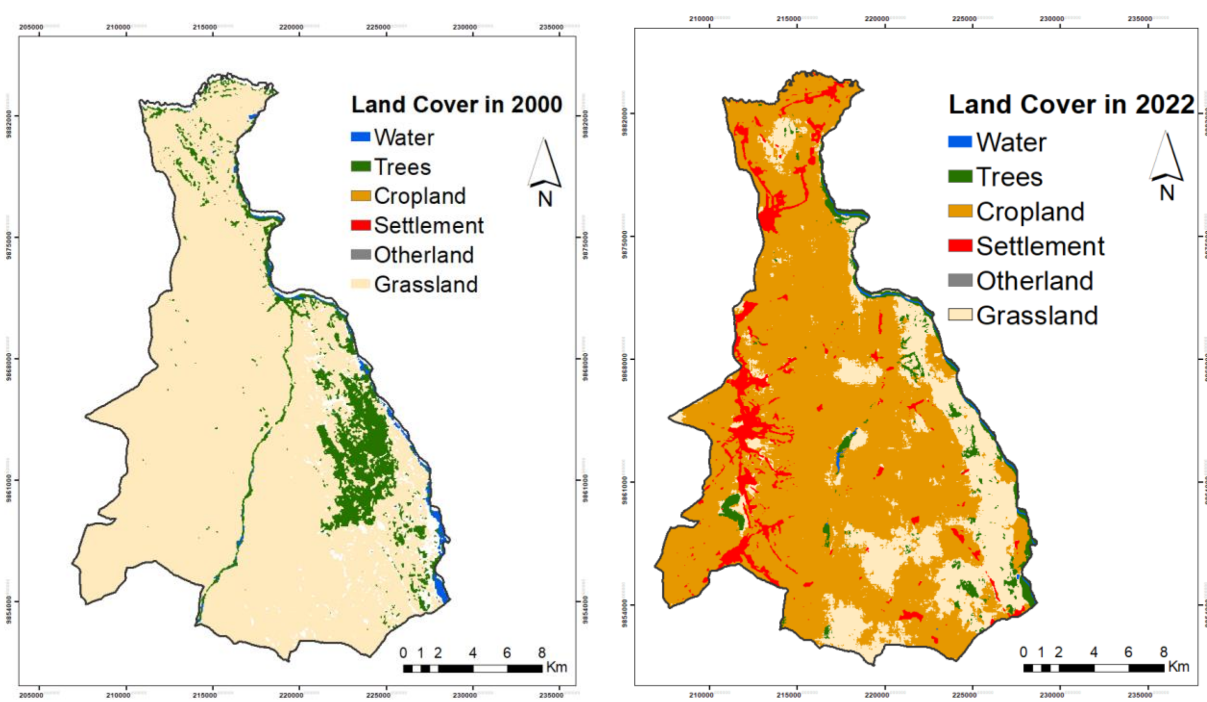

Figure 3: *Land Cover for the Study Area (Matimba and Rwimiyaga) for the period 2000 (left) and 2022 (Right)*
Data Source: 2000 classified Landsat images by Regional Center for Mapping of Resources for Development (RCMRD), and 2022 Sentinel images classified by Environmental Systems Research Institute (ESRI)

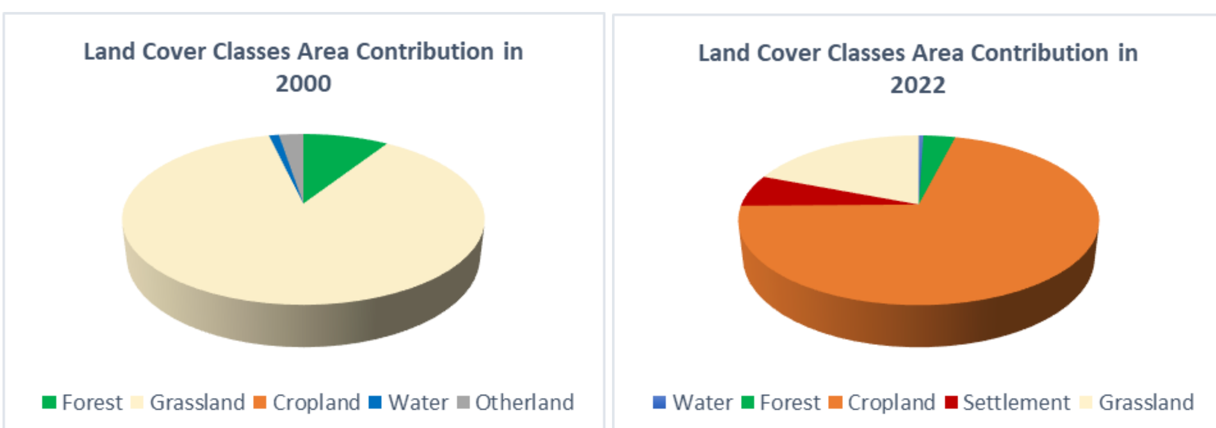

Figure 4*: Area contribution per Land Cover Classes for 2000 and 2022*

Figures 3 and 4 show the distribution of land cover classes and their respective areas. In the year 2000, grassland was the dominant land cover, occupying 32,629 hectares, which is equivalent to 87% of the total area. However, over time, the proportion of cropland has been increasing steadily, reaching 42% of the total area in 2022. The grassland occupies 33% of the landscape and primarily used for livestock grazing. The areas designated for settlement also experienced growth, accounting for 11% of the total area in 2022. Furthermore, deforestation was observed in areas of the eastward marked by the clearing of trees.

Land Cover Transition

Land cover transition is the change in the type of land cover, and was described by a change in the classification of land cover elements. A transition that reduces the biological or economic productivity and complexity of the land was considered as degradation. By comparing the land cover maps, for 2000 and 2022 period, the land cover transition maps have been produced to indicate the land cover and their associated loss of land, as presented in Figure 5.

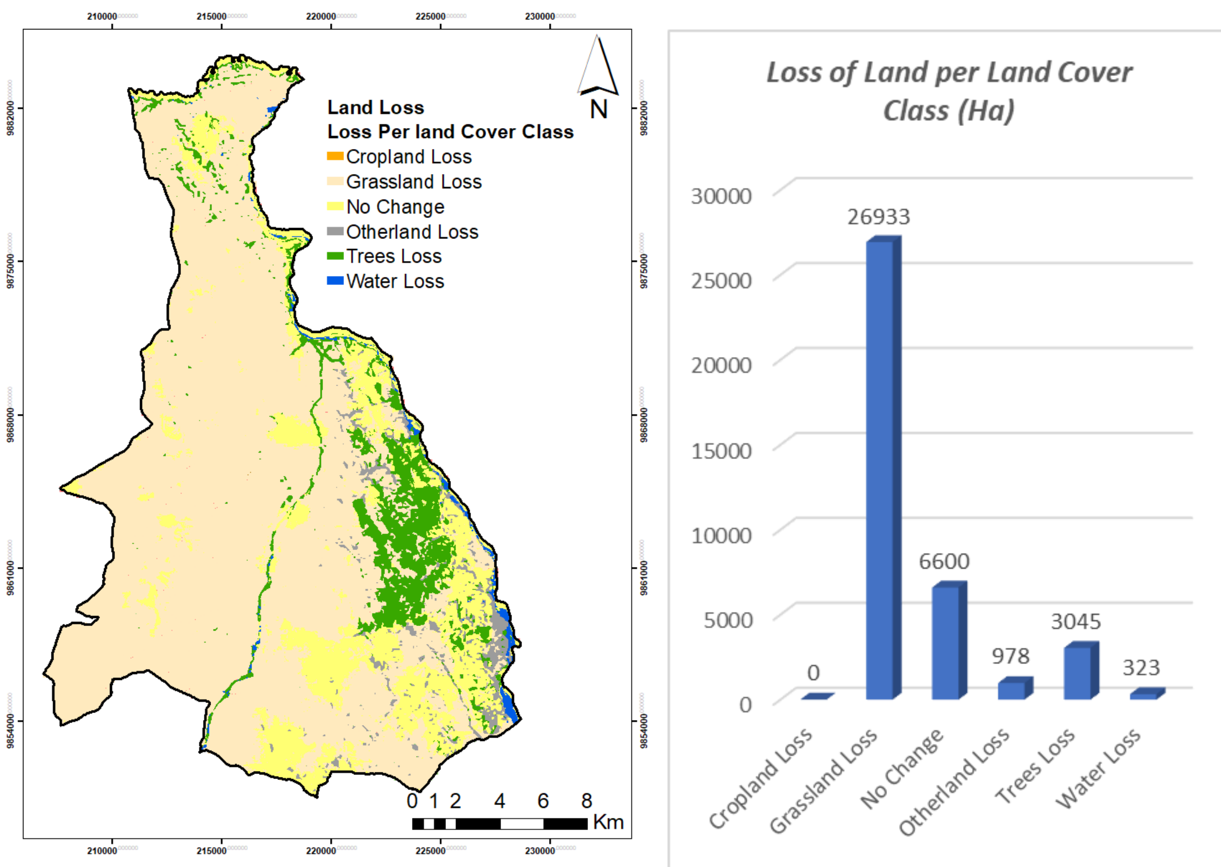

Figure 5: *Land Loss per land cover classes*
Data sources: *2000 classified Landsat images by Regional Centre for Mapping of Resources for Development (RCMRD), and 2022 Sentinel images classified by Environmental Systems Research Institute (ESRI)*

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The research findings revealed significant changes in land cover dynamics between 2000 and 2022. The area of grassland experienced a notable decline, decreasing by 26,933 hectares from its initial extent of 32,629 hectares in 2000. On the other hand, approximately 6,600 hectares showed no change in land cover over the same period. Additionally, the area dedicated to tree cover eastward experienced a substantial reduction of 3,045 hectares. This represents a stark decrease of 38% compared to the tree cover area in 2000. These findings highlight the dynamic nature of land cover changes within the study area during the examined period.

Land degradation per land cover

The Good Practice Guidance (GPG) for mapping land degradation involved using land cover to assess changes in land cover patterns and identify areas experiencing degradation. The table 4 provides a summary of the land use change matrix and the corresponding land degradation status.

Table 4: *Land Use Change Matrix (2000 and 2022)*

		Land Cover type 2022					
Land Cover type 2000		**Cropland**	**Grassland**	**Other land**	**Trees**	**Settlement**	**Water**
	Cropland	1	0.369121	0	0.371212	0	0
	Grassland	24204	5684	7.919959	496	2225	7
	Other land	432	420	0	83	37	6
	Trees	1914	1080	0.527422	373	27	23
	Water	93	40		190	0	67

Based on Table 4, which presents the land use change matrix for land cover classes in 2000 and 2022, the land cover degradation status table was produced. Table 5 displays the status for each land use transition.

Table 5: *Land productivity status*

		Land Cover Classes 2022					
Land Cover Classes 2000		**Cropland**	**Grassland**	**Other land**	**Trees**	**Settlement**	**Water**
	Cropland	Stable	Degradation	0	Improvement	0	0
	Grassland	Improvement	Stable	Degradation	Improvement	Degradation	Degradation
	Other land	Improvement	Improvement	0	Improvement	Improvement	0
	Trees	Degradation	Degradation	Degradation	Stable	Degradation	Degradation
	Note: Where there is 0, it means that there is no land use transition from 2000-2022						

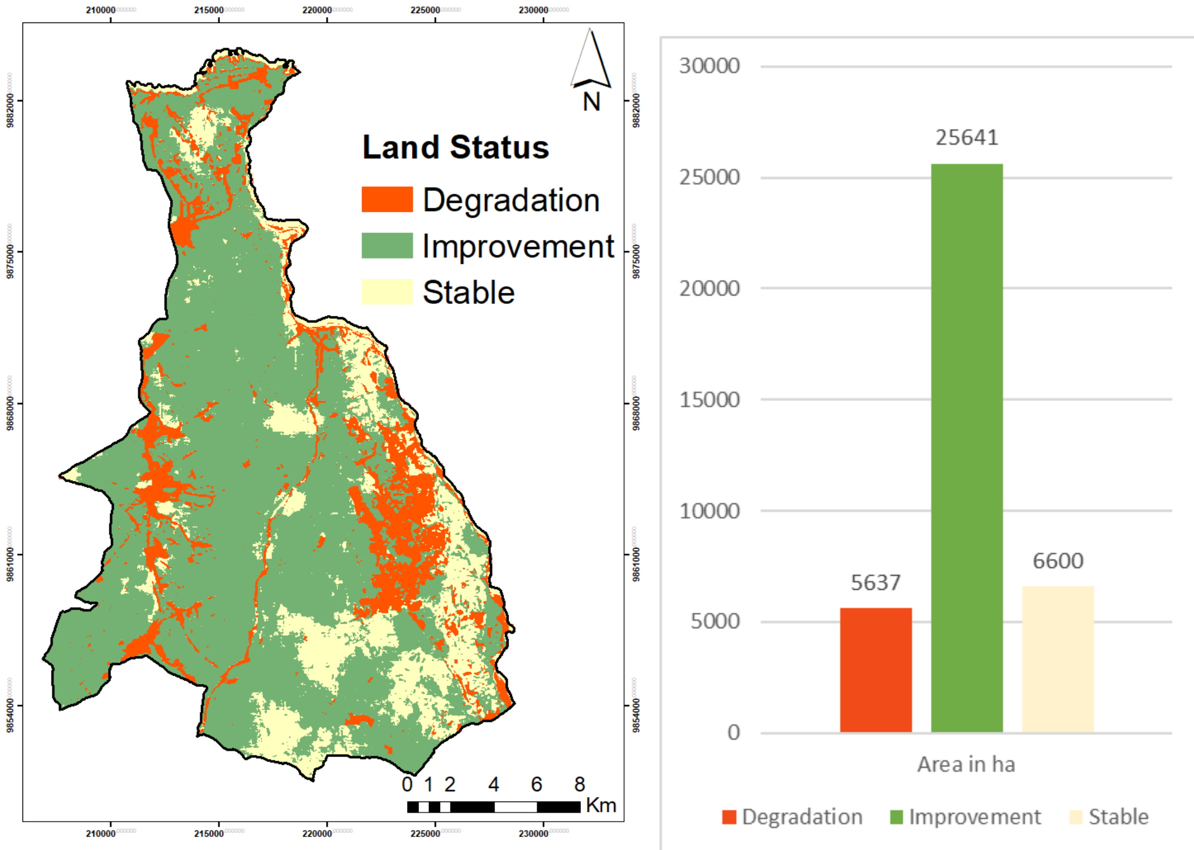

***Figure 6:** Land degradation map based on land cover change (Right) and the histogram (left) for comparison on degradation status*

<u>*Data Source:*</u> *2000 classified Landsat images by Regional Centre for Mapping of Resources for Development (RCMRD), and 2022 Sentinel images classified by Environmental Systems Research Institute (ESRI)*

According to the land status definition, 25,641 hectares showed improvement due to the expansion of cropland, resulting in increased land productivity. The study also found that 6,600 hectares remained stable, with no changes, mainly consisting of grassland still being used as rangeland. However, activities such as deforestation, overgrazing, and the increase in built-up areas caused degradation of 5,637 hectares over the 22-year period.

3.2. Land Productivity Dynamics (2001-2022)

For this study, Land productivity dynamics (LPD) was typically measured using satellite-derived data, such as Normalized Difference Vegetation Index (NDVI) that track changes in vegetation cover and health. The figure below presents the Land Productivity Dynamics from 2001-2022 in the study area.

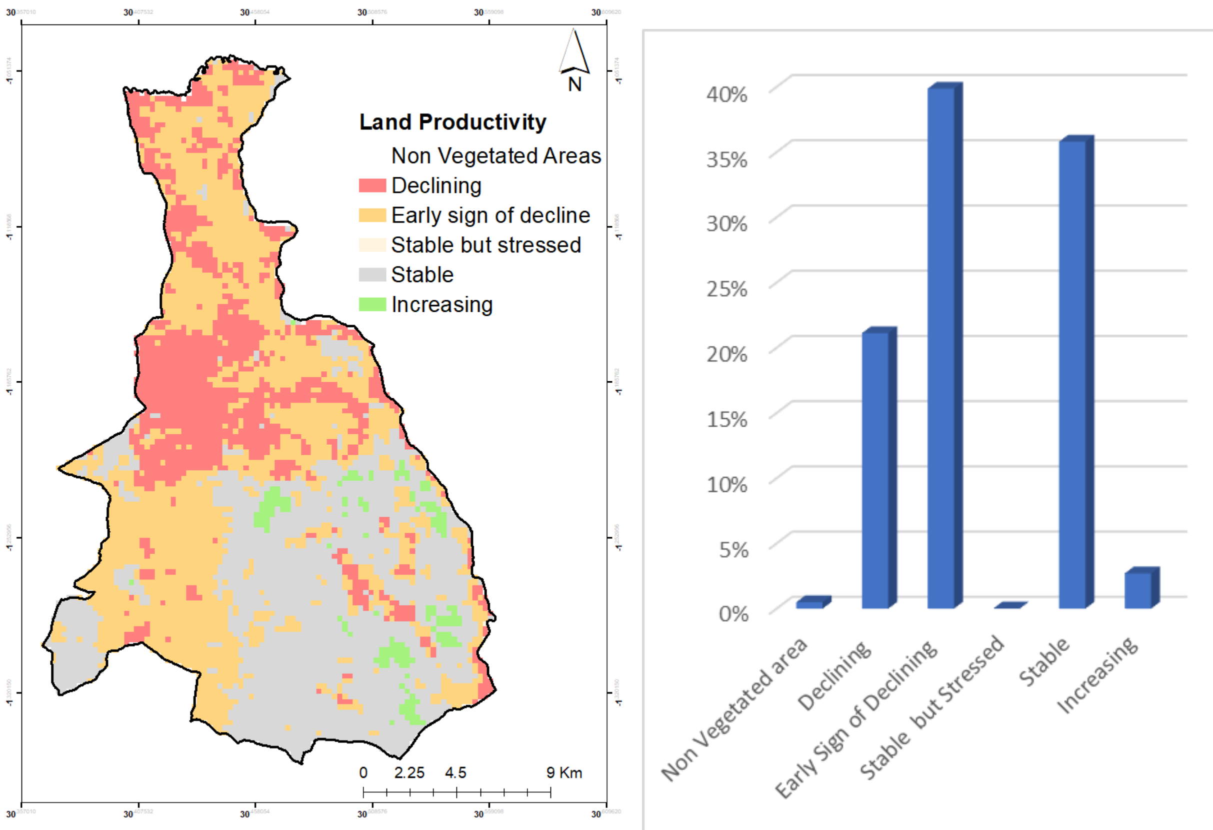

Figure 7: Land Productivity Dynamic from 2001-2022.
Data Source: MODIS imageries

The results indicated that in the study area, 40% of the land showed early signs of declining land productivity, while 48% demonstrated stable productivity, mainly in areas with persistent grassland. Signs of decline were prominent in areas with cropland. Further, 21% of land productivity has already declined, mostly in areas with settlements. Images taken revealed differences in land productivity capacity, as the planted trees did not grow to the same height across the study area. In lowland areas near the Karangazi River, the trees thrived, and the grasses were healthier than in highland pastures.

***Figure 8**: Well grown trees in pastures located in lowlands in Rwimiyaga Sector near Karangazi River where the land productivity is high demonstrated by healthy forage*

Data Source: Ukwishaka David, 2024

***Figure 9:** The silvopastoral trees in highland areas pasture in Rwimiyaga Sector where the land productivity is low with dry forage*
Data Source: Ukwishaka David, 2024

3.3. Soil Organic Carbon (SOC)

The soil organic carbon stock, a key indicator for land degradation assessment, was analysed using the Trends.Earth tool to track changes between 2001 and 2020. SOC mapping utilized MODIS imagery, highlighting spatial variations to inform conservation strategies. Figure 10 presents the SOC distribution: Left: 2001 SOC stock and Right: 2020 SOC stock. The analysis reveals significant temporal changes, identifying areas requiring targeted interventions to mitigate degradation and promote sustainable soil management. These insights emphasize the role of SOC in land health monitoring and restoration planning.

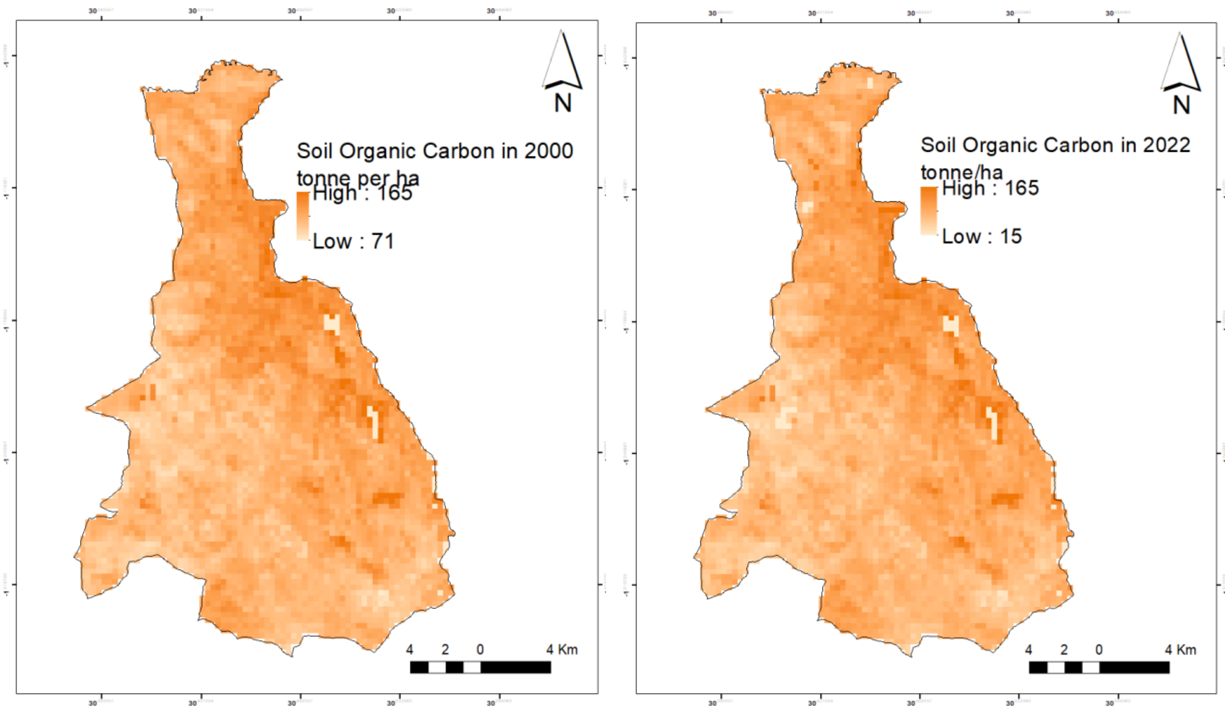

***Figure 10**: Soil Organic Carbon Stock (Left: 2001 and Right: 2020)*
Data Source: *MODIS Imageries*

The Soil Organic Carbon (SOC) ranged from 15 to 165 tons per hectare. Between 2001 and 2022, SOC levels showed minimal variation overall. While some areas experienced localized degradation or improvement, most of the study area recorded no significant change in SOC stock.

Figure 11 illustrates the changes in SOC stock over 22 years, categorized by land degradation status. This analysis provides valuable insights into the spatial dynamics of soil health and highlights the stability of SOC in most areas.

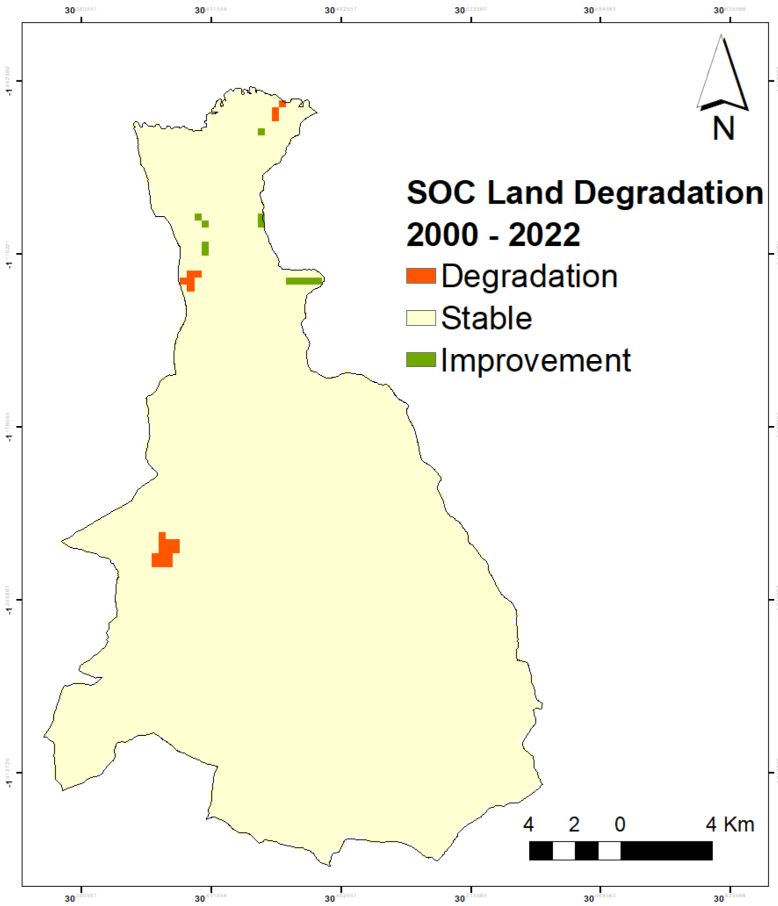

Figure 11: Land Degradation based on Soil Organic Carbon Stock Change from 2001 to 2022
Data Source: *MODIS Imageries*

3.4. **Combined Land degradation**

The final land degradation map was created by combining three key sub-indicators: land cover, land productivity, and soil organic carbon (SOC). Figure 12 illustrates the overall land degradation across the study area from 2000 to 2022.

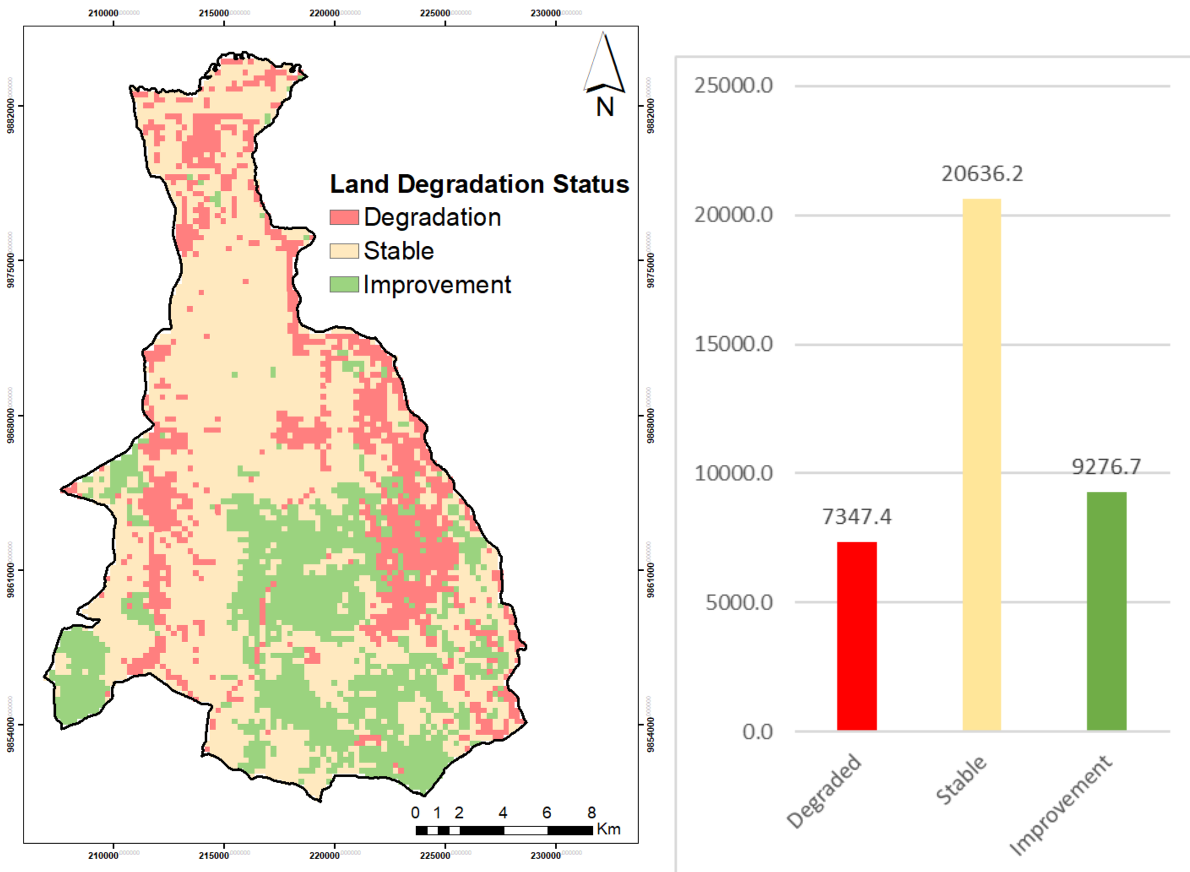

Figure 12: Overall land degradation map for the study area (2000-2022)

Overall, over 22 years (2000-2022), the Matimba and Rwimiyaga sectors have experienced land degradation of 7,347.4 hectares. The majority, 20,636.2 hectares, remained stable, with no significant changes in degradation or improvement. However, this stability does not necessarily indicate good land condition; it simply means that the land has not changed. Areas totalling 9,276.7 hectares have shown improvement, indicating an increase in land quality.

3.5. Silvopastoralism

As a solution to land degradation and drought, silvopastoralism has been implemented to protect exposed soils from erosion, prevent overgrazing during pasture regeneration, provide additional fodder and shade for livestock, generate wood for communities, and promote water infiltration. Figure 13 displays the locations of paddocks where silvopastoralism has been implemented, including a sample plot within the frame.

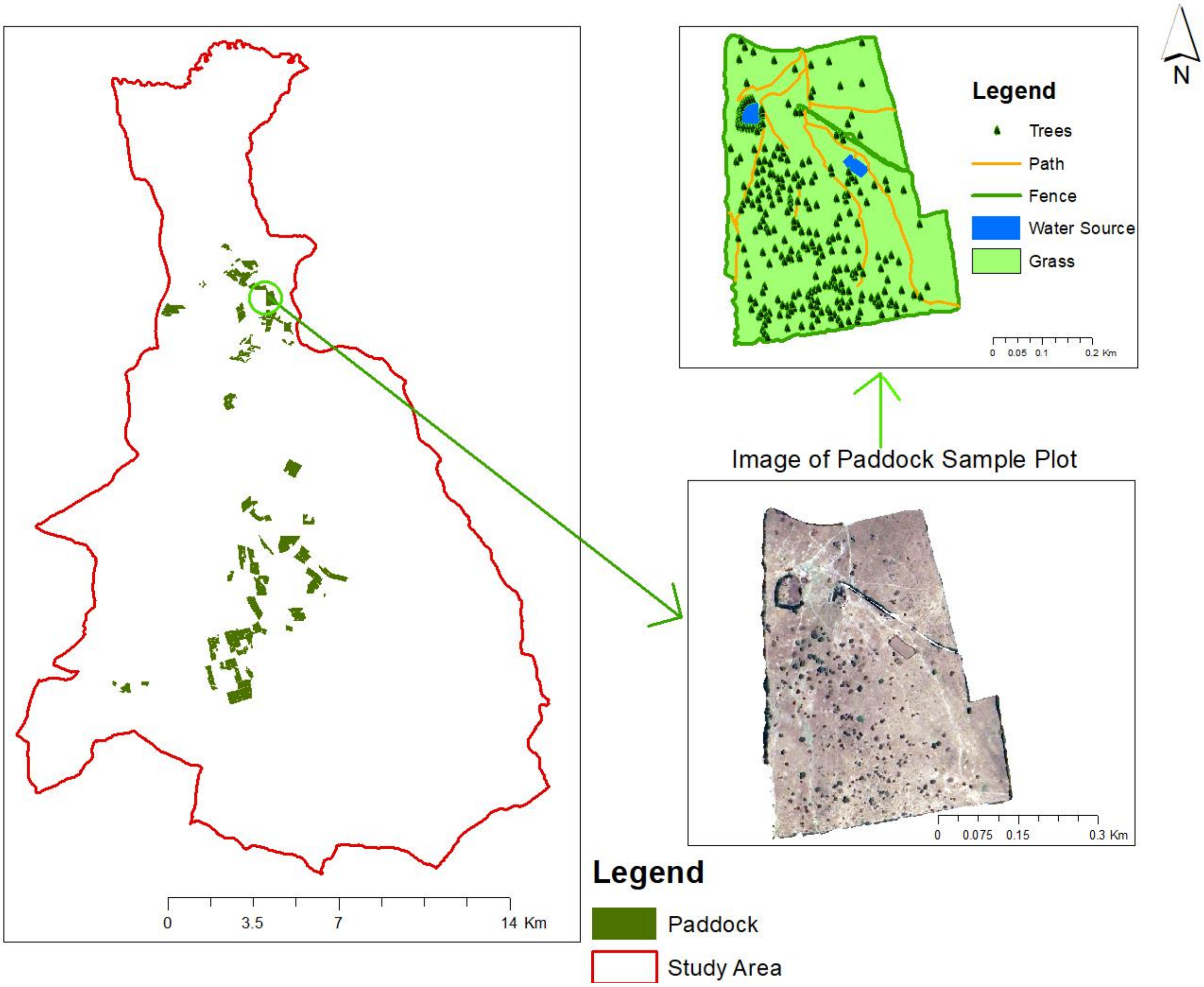

Figure 13: Location of Paddock in which the silvopastoralism have been implemented
Data Source: *Paddock Shapefile provided by Rwanda Environment Management Authority (REMA)*

Silvopastoralism has been implemented in 95 paddocks, covering 915.3 hectares of pasture, with an average of 44 trees per hectare. The distance between trees is 15m within paddocks and 6m along the paddock. The project provided 132 dam sheets, with 99 allocated to Matimba and Rwimiyaga cattle keepers, addressing the issue of cattle traveling long distances to access water. Figure 14 presents the key features of the paddock with a silvopastoral design, including fencing, trees, and dam sheets for livestock water access.

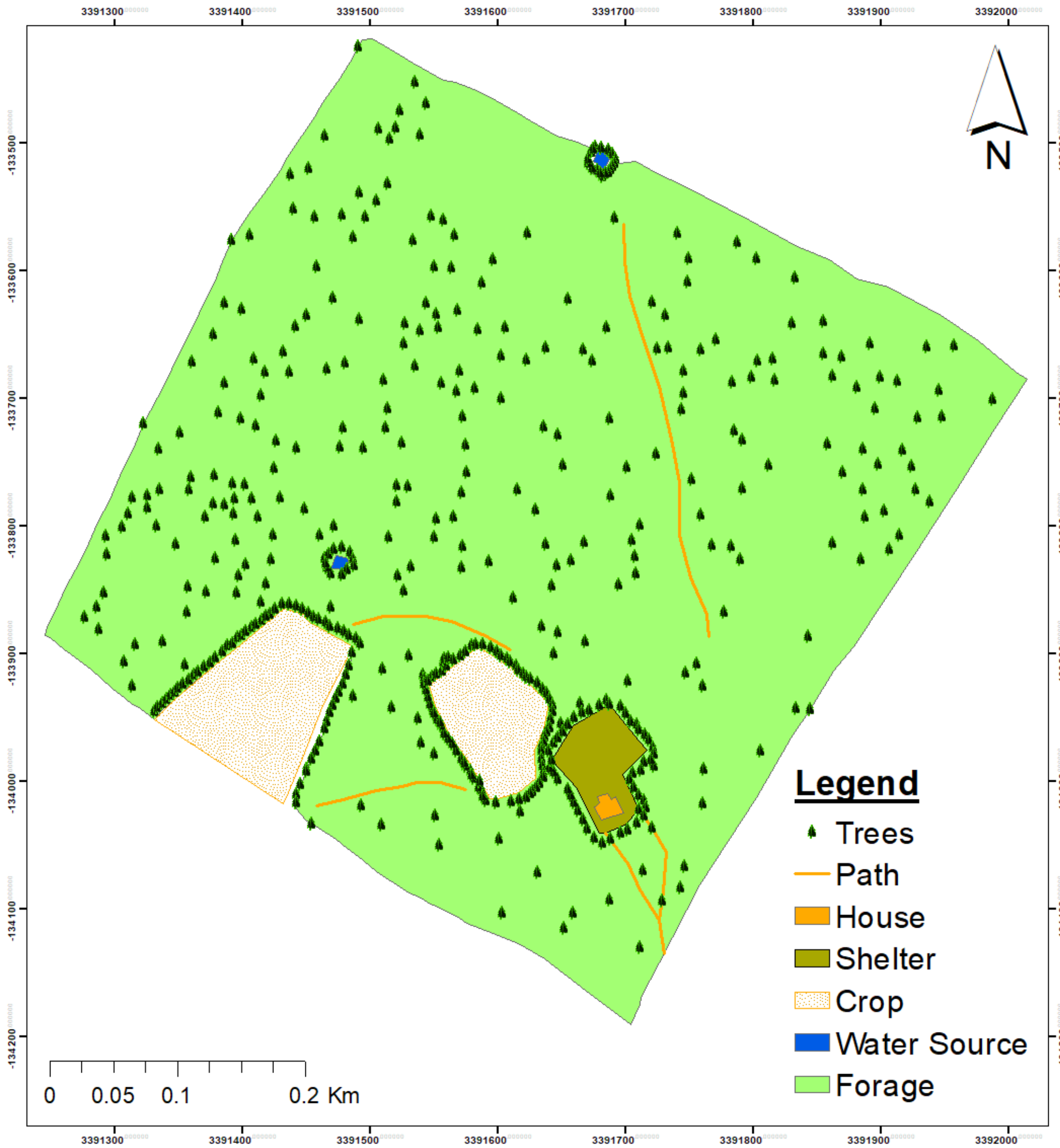

Figure 14: Sample paddock in Rwimiyaga Sector
<u>Data Source:</u> *Paddock Shapefile provided by Rwanda Environment Management Authority (REMA)*

In the study areas, only 4% of the paddocks are located in the areas where there is land degradation status, 48.9% is stable, while 46.7% are in the areas where there is the improvement. Figure 15 present the location paddock with silvopastoralism with the land status.

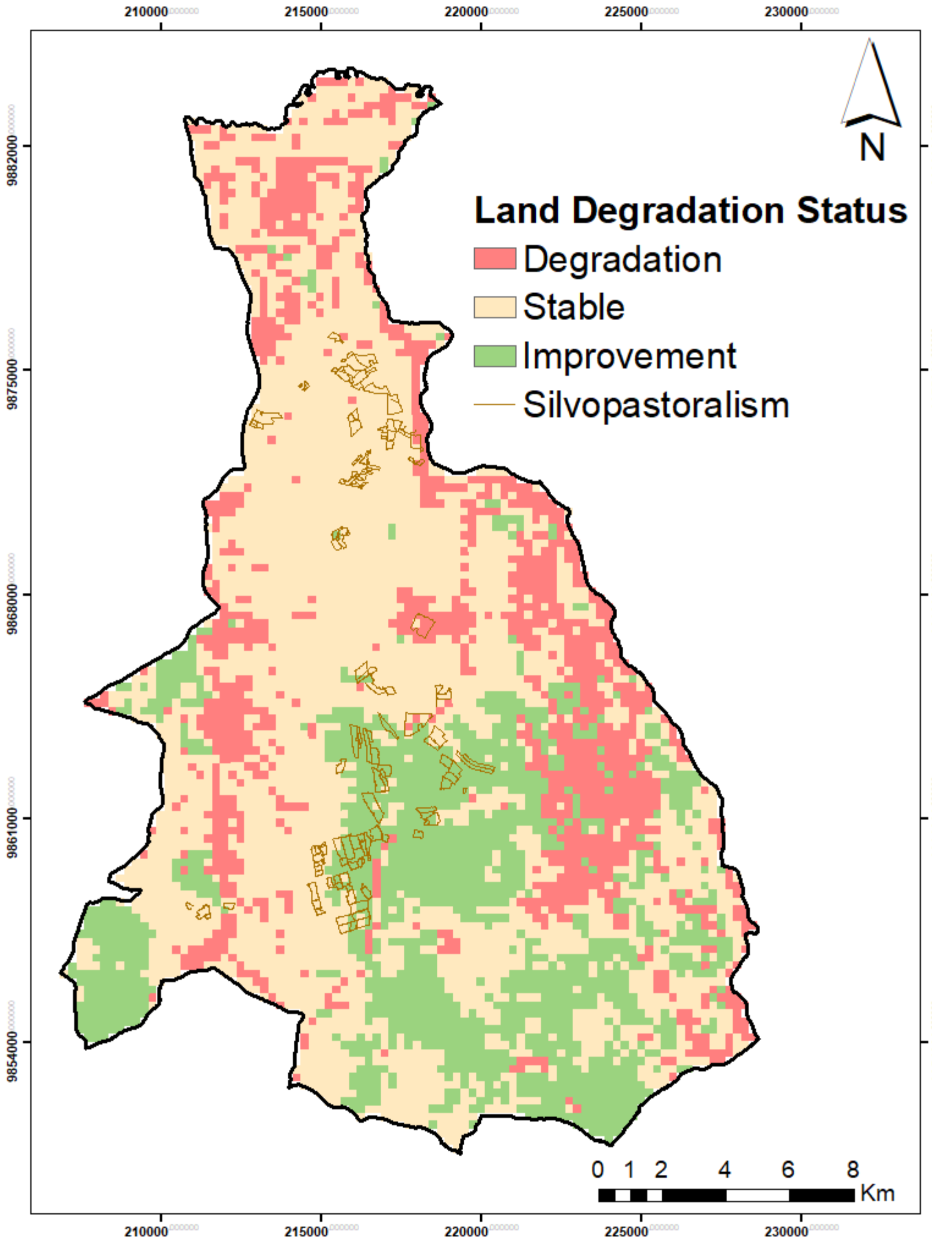

Figure 15: Paddocks with their respective land status

4. Discussion

The evaluation of land degradation in the study area provides critical insights into ongoing environmental challenges and underscores regions requiring immediate intervention. Through a comprehensive mapping of land status changes from 2000 to 2022, the study identifies a significant degradation of 7,347.4 hectares. This degradation primarily results from a 38% reduction in tree coverage, alongside the expansion of cropland, livestock, and settlements, which collectively indicate increasing pressure from human activities driven by population growth and the resultant demand for agricultural and residential land.

These findings align with recent research that critically examines the ecological implications of deforestation, particularly within savanna ecosystems, where trees are essential for maintaining ecological balance. Recent studies by Brancalion et al. (2023) and Estes et al. (2022) emphasize the severe consequences of deforestation, including disruptions to ecosystem functions and loss of biodiversity. Additionally, Saha et al. (2023) highlights the significance of trees in savanna regions for providing ecosystem services, such as habitat provision, water cycle regulation, and nutrient cycling facilitation. Thus, the substantial loss of tree cover observed in this study reflects a broader pattern of ecological degradation prevalent in various contexts, particularly in developing regions where land-use pressures are intensifying.

The feasibility study conducted by the Rwanda Environment Management Authority (REMA, 2022) for the National Adaptation Program (NAP) project identified livestock grazing and agricultural expansion as the primary drivers of land degradation in the area. These drivers, exacerbated by deforestation for agricultural purposes and the pervasive reliance on firewood for cooking, have accelerated landscape degradation. These findings resonate with the work of Laurance et al. (2023), who argue that agricultural expansion and unsustainable land-use practices significantly contribute to environmental degradation in similar contexts. Furthermore, the reliance on firewood, as highlighted by Rijal et al. (2022), exacerbates deforestation and perpetuates a detrimental cycle of environmental decline.

Silvopastoralism, which integrates trees, forage, and livestock into a unified system, demonstrates considerable potential for sustainable land management. The study's findings indicate that nearly half (46.7%) of paddocks practicing silvopastoralism are situated in areas demonstrating measurable land improvement, with an additional 48.9% located in stable regions. These findings correspond with other studies that have underscored the benefits of silvopastoral systems. For instance, research by Murgueitio et al. (2011) found that silvopastoral systems improve soil quality and enhance biodiversity compared to conventional grazing systems. Similarly, a review by Jose (2009) emphasized that silvopastoralism can improve ecosystem services by reducing soil erosion, enhancing water infiltration, and promoting nutrient cycling, thereby improving land quality. The findings suggest that without significant policy interventions promoting silvopastoralism, environmental degradation in the study area, along with similar regions, is likely to persist, potentially resulting in severe land degradation.

5. Conclusion

The findings underscore the urgent state of land degradation in the Matimba and Rwimiyaga sectors of Nyagatare District, Eastern Province, Rwanda. Changes in land cover between 2000 and 2022 revealed a decrease in grassland and forest cover, attributed to the expansion of cropland and settlements. This transformation highlights the increasing pressure from anthropogenic activities, particularly agriculture and urbanization driven by population growth. The degradation of 7,347.4 hectares, primarily due to deforestation, overgrazing, and the expansion of built-up areas, indicates the necessity for sustainable land management practices.

Silvopastoralism implemented in the study area aims to mitigate land degradation. However, only 4% of the paddocks are situated in areas classified as experiencing land degradation, while 48.9% are classified as stable, and 46.7% are in regions showing improvement. This illustrates the need to expand this approach to enhance the resilience of the savanna ecosystem against climate change and anthropogenic pressures. Furthermore, the stability of soil organic carbon (SOC) levels over the study period suggests that silvopastoralism can sustain soil health and carbon sequestration, both of which are essential for long-term ecosystem sustainability.

This study carries implications for policymaking, land management practices, and environmental conservation in Rwanda and similar regions. Firstly, the reduction in tree cover and its ecological consequences necessitate immediate policy interventions to regulate land use, promote reforestation, and integrate sustainable agricultural practices. The potential of silvopastoralism in maintaining land productivity and SOC levels suggests that this practice should be expanded and incorporated into Rwanda's National Adaptation Plan and other relevant policies aimed at combating land degradation.

Moreover, the study emphasizes the importance of a holistic approach to land management that considers long-term ecological impacts. Policymakers should prioritize the development and implementation of sustainable land-use practices that balance agricultural productivity with environmental conservation. The reliance on firewood, which exacerbates deforestation, further underscores the necessity for alternative energy sources to alleviate pressure on natural resources.

Finally, the study recommend that local communities should actively participate in land restoration efforts, given their crucial role in land use. Training and capacity-building programs aimed at promoting sustainable practices, such as silvopastoralism, should be prioritized to ensure that local populations can contribute to and benefit from these initiatives. By adopting such comprehensive strategies, Rwanda can progress towards achieving land degradation neutrality, enhancing ecosystem resilience, and securing sustainable livelihoods for its rural populations.

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Declaration of Conflicting Interests

The authors declare that there are no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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