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Spatio-Temporal Analysis Of Land Use And Land Cover Dynamics And Their Impacts On Smallholder Farmers Productivity In Kamonyi District, Rwanda

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Abstract: LULC dynamics impact agricultural landscapes and smallholder farmers' livelihoods. The study examined spatio-temporal LULC dynamics and the associated impacts on smallholder farmers' productivity in Kamonyi District, Rwanda from 2000 to 2025. A combination of geographic information systems and remote sensing techniques and a household survey of 398 farmers were employed alongside 15 key informant interviews, fieldwork and literature review to understand the changing LULC patterns and their impacts on agricultural productivity, soil characteristics and household food security status. Significant transformation of the landscape was evident, with 90.1% loss in forest cover, 68.0% rise in cultivated land and 669.0% growth in built-up areas. Even though there has been an expansion of the croplands, 98% of the respondents reported a decrease in crop production when compared to the past. Erosion of the soils has been noted as being very high by 63.8% of the respondents, while 37.2% noted low soil fertility. Further, 43.5% reported that food shortages have been common in their homes. This shows that even as there was expansion of the croplands, there has been reported cases of productivity issues within agriculture. It is therefore evident that the combination of spatial data and household information provides crucial insights into the LULC change and its impact on farming.

Keywords: Land Use and Land Cover Change; Remote Sensing; Smallholder Farmers; Agricultural Productivity Soil Erosion.

1. Introduction

LULC dynamics are critical elements of environmental change since they influence how land resources will be utilized and managed over time. Dynamics in forests, agricultural land, grassland, wetlands, settlements, and water bodies can affect the ecological processes and availability of the resources, as well as the environment in which rural households engage in agricultural activities to provide food and livelihoods. In general, global population increase, urbanization, agricultural practices, infrastructural development, changes in consumption patterns, and climate variation have been some of the factors leading to changes in land systems. Land system dynamics become even more critical in agricultural settings, where smallholder farming communities depend on the available land, soil, and water resources for food production and livelihood generation [1].

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In Africa, LULC dynamics are mainly connected to the growth of agriculture, population expansion, the changes in agricultural practices, reduced fallow period, settlement dynamics, and climatic changes. It was found out in the study of LULCC dynamics in Africa that agricultural practices, demographic pressure, and climate factors are the main ones leading to land use dynamics and have an impact on vegetation and the ecosystems [2]. The agricultural intensification and agricultural expansion can help in increasing the area used for cultivation, but they can put pressure on forests and other ecosystems in case the land is not managed properly and preserves its productivity and ecological functions. This proves the dependence of the influence of agricultural management practices on productivity and environmental outcomes [3]. Therefore, changes in the agricultural land use dynamics should not be regarded separately from the environmental resources and smallholders' living conditions. Population pressure, agriculture production, and land have been linked as a subject of agricultural change for some time now. Boserup (1965) pointed out that population pressure could trigger agricultural intensification in response to increased food demands from the available land resource. Agricultural intensification might yield different results based on the available technologies and environmental circumstances. For the livelihood framework, rural households rely on natural, physical, financial, human, and social capitals; hence, changes in land and environment affect more than just agriculture production [4]. It would therefore be important to look at the interaction of LULC and household agricultural production together.

Rwanda offers a relevant case for studying these relations since agriculture still plays a crucial role in the livelihoods of the rural population while land is scarce and densely populated. Landscapes in Rwanda have come under pressure as a result of the growth of population, urbanization, intensification of agriculture and environmental deterioration. Under these conditions, the changes in availability and quality of land can affect the farm size, land fragmentation, soil characteristics, agricultural output and food security of households. Some researches in Rwanda have identified the importance of land use change and environmental factors for the agricultural systems. Sustainable land management, soil and water conservation and agricultural productivity have been highlighted in national and local policies of Rwanda. Similarly, some studies in Africa have found the effect of management decisions on agricultural performance and outcomes. Kamonyi District is an ideal study area with respect to these processes due to its agricultural significance and land use changes taking place. Previous studies carried out in Runda Sector in Kamonyi District have shown that the area has experienced fast urbanization and loss of agricultural land which implies that land development can put pressure on agricultural landscape [5]. Nevertheless, findings made in one sector cannot sufficiently explain the larger landscape transformation happening in Kamonyi District since there are 12 sectors in the district which vary in terms of settlement pattern, agriculture, environmental factors, and land use pressures.

Though there have been many efforts to study land-use and land cover changes in Africa and specifically in Rwanda, there has been a major lack of evidence at the grassroots level. The previous researches have focused on the spatial land cover changes or issues related to environment and agriculture, but few researchers have considered the combination of temporal remote sensing data with evidence of agriculture and livelihoods from household surveys. Especially in Kamonyi district, there is a scarcity of research which shows the long-term changes in the cover of forests, cropland, grassland, wetlands, and water bodies along with the experiences of the farmers regarding changes in yield, soil degradation, food scarcity, fragmentation of land, and income generation through agriculture. This study sought therefore to investigate (1) spatiotemporal patterns in the changing land use and land cover in Kamonyi District from 2000 to 2025; (2) the results of agricultural productivity outcomes reported by smallholder farmers and the environmental problems faced by smallholder farmers in Kamonyi District; and (3) the association between LULC changes and agricultural productivity outcomes of smallholder farmers in Kamonyi District.

1.1 Related literature and analytical perspective

Land degradation assessment for Rwanda gives a context to the study of erosive landscapes [6]. Agricultural support to smallholders is also represented in practitioner reporting for Rwanda [7]. Regional literature about smallholder management of soil fertility is used in understanding the problems with soils that farmers face [8]. There is also literature on crop diversity and food security issues within the context of Kamonyi. Literature review about African land cover change drivers gives a broader context for the observed spatial changes [9]. National environment and outlook report is another document for policy

interpretation [10]. Here, land cover change is considered as spatial reallocation among the mapped land cover types, not as direct evidence of agricultural production by any individual household. Land change science is used in interpretation of landscape changes [11]. Spatial changes should also be interpreted along with human choices and institutions regarding land use [12]. Boserup's work on population pressure and agricultural intensification [13]. However, Malthus gives an alternative approach to demand and resource constraints [14]. Livelihood literature offers reasons why results rely on several assets of the households and not simply on the area of land. Scoones places more emphasis on the importance of institutions and vulnerability on livelihoods [15].

Agriculture is sensitive to land quality and soil management conditions. Soil degradation and food security research offer the environmental context for examining stressors in productivity [16]. Studies on adaptation of farmers assist in formulating the response to climatic risk. There is also research on agricultural adaptation in Kenya that provides a comparative perspective in East Africa [17]. Household approaches and agricultural training have been studied in the region [18].

Land fragmentation should consider the size, distribution, and composition of discrete lands [19]. Diversification of agricultural livelihoods aids in understanding agricultural income beyond crop production [20]. The FAO food security framework distinguishes between food availability and access and stability [21]. Food system vulnerability in the region is addressed in the FAO global food security report. Regarding the spatial component, interpretation of remote sensing classification is key to the interpretation of classified images. The geographic information science enables integration and analysis of environmental variables mapped [22]. Post-classification analysis utilizes common change detection techniques [23]. Conversion of landscapes is also pertinent to urban growth and competition for land. The interpretation layer from national policy includes: National land use master plan which provides long term planning context in Rwanda, Kamonyi's district development strategies provide the local context [24]. The more recent strategy from the district forms a second reference of the planning context. Crop transformation policy provides the context for intervention within farming [25]. The national agricultural reporting provides the context within the institution sector.

Interpretation of land and environment reporting from national level is important during interpretation of local change. Rwanda's environmental status report provides the context for conservation pressures. The environmental report earlier on also provides the landscape management context. Soil information system in Rwanda is pertinent for soil condition analysis [26]. Mapping and assessment of erosion and land degradation provides the context for conservation practices. National statistics document the contexts of population, land use, and agriculture-households [27]. The analysis of agriculture based on census surveys is useful for survey population definitions. The information about living conditions of households is necessary to understand livelihood context. Information on the agricultural household can supplement national information.

The planning of the landscape at local level should take into account the interaction of town expansion and agriculture. The urbanization policy gives the national context [28]. Population, transportation, and agricultural activities can compete for land use, an issue that is taken into account in the African development literature [29]. In long-term planning, the planning of agriculture should take into consideration the changes in the production contexts, not simply cultivated areas. Climate considerations are important to the mechanisms that may link land cover and rainfall with the household effects. The IPCC synthesis gives consideration to the issues of climate risks and adaptation [30]. African soil and resource management literature suggests that it is worth considering the issue of land degradation [31]. Comparison of the changes in land cover is useful in order to analyze the pressure but cannot identify the land conversion causing yield changes [32].

Finally, the relevant literature covers basic views of land use and agriculture [33]. FAOSTAT provides additional statistical perspective for reporting on agriculture. Assessments of forest resources provide more general environmental perspective. Research on regional development and land rights emphasizes institutional aspects in accessing natural resources [49]. This is what the above sources tell us, while the results are based solely on the Kamonyi survey and satellite classification.

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2. Materials and Methods

2.1 Study area description

The research was done in Kamonyi District situated in Southern Province, Rwanda. The district lies between latitudes 2°00′ to 2°20′ south and longitude 29°50′ to 30°10′ east. Kamonyi district has an area of about 655 km² and consists of 12 sectors including Gacurabwenge, Karama, Kayenzi, Kayumbu, Mugina, Musambira, Ngamba, Nyamiyaga, Nyarubaka, Rugarika, Rukoma and Runda. The district is marked by hilly topography and agricultural land cover, and its settlements are scattered in agriculture lands. Agriculture is one of the activities which people are involved in and they rely much on the land and resources for farming and their well-being. In addition, there have been some changes in the land use, settlement, vegetation and other land cover types.The period between 2000 and 2025 was chosen as the time frame for the research to enable the study to reflect changes in land use and land cover within 25 years. The district was chosen because of the relevance of smallholder farming and the growing need for land resources resulting from population increase, increased settlements, land fragmentation, agricultural practices, and environmental degradation. All the twelve sectors were considered for the study to ensure district-level evidence instead of evidence from just one area. The use of spatial LULC data, household-level data, key informants' evidence, and field observations made it possible to look at landscape changes and farmers' agricultural results simultaneously.

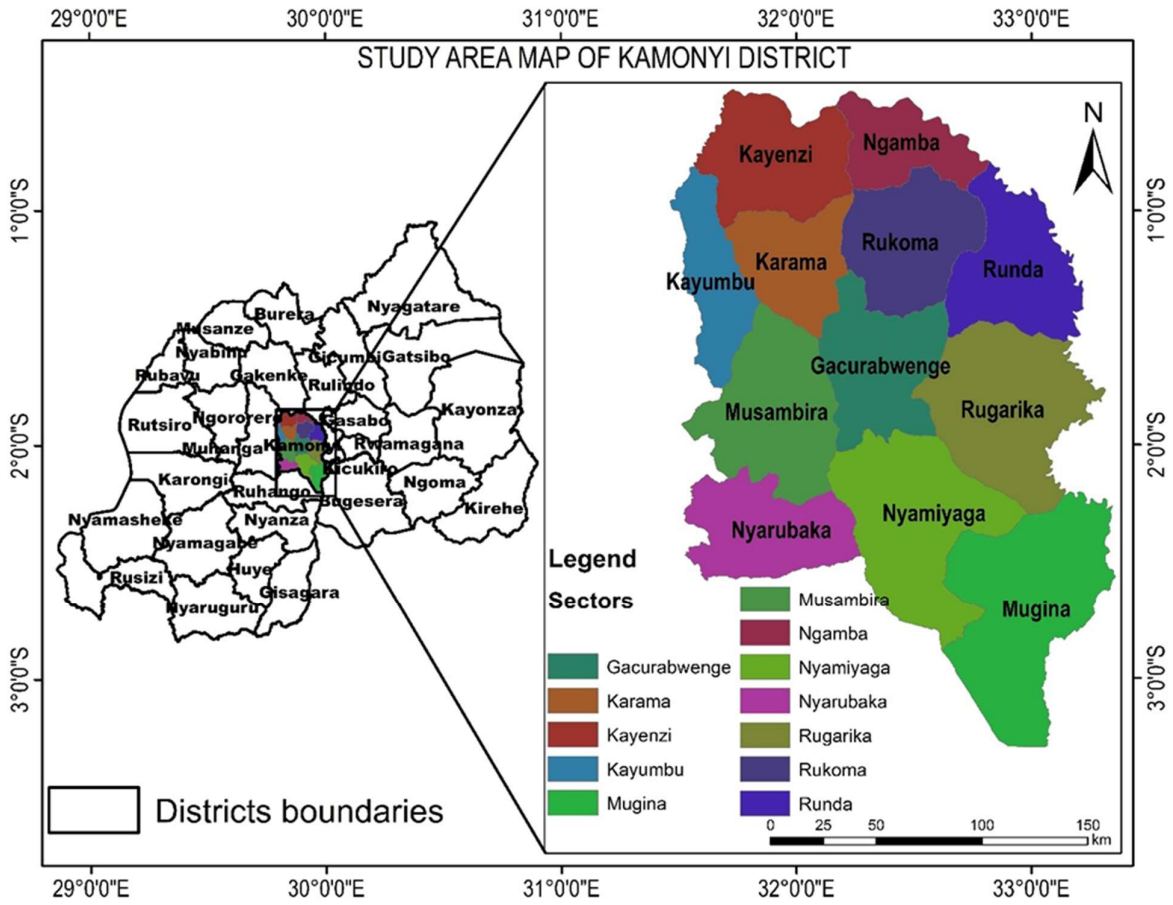

Figure 1. Location of Kamonyi District and the 12 sectors included in the study.

2.2 Data acquisition, sources and processing

The research adopted a mixed methods approach whereby geospatial analysis was done in conjunction with house hold level evidence and qualitative evidence. Multitemporal images were acquired for years 2000, 2008, 2016 and 2025 from sources such as Landsat and Sentinel data as well as Google Earth data for cross referencing and validation purposes. Image pre-processing entailed atmospheric correction, geometric correction, removal of clouds as well as use of Dark Object Subtraction when needed. Projections of the images were done using UTM Zone 36S and classification was done in ArcGIS Pro 3.4 using Maximum Likelihood Classification Algorithm. Classes in LULC included forest, croplands, grasslands, wetlands, water and built-up areas. Accuracy of classification was determined using confusion matrices, overall accuracy and kappa statistics. Post classification change detection analysis was used to determine change between observation years, while landscape pattern was assessed using selected FRAGSTATS metrics.

The primary data from households were obtained from agricultural households in all the 12 sectors through a structured questionnaire. Based on the NISR , Kamonyi District had 116,378 households, out of which 86,514 were agricultural households. The 86,514 agricultural households formed the target population for the household survey. The sample size was estimated based on Yamane's formula [50. where the precision level is 5%, giving an approximate sample size of 398 respondents. The method used was multi-stage sampling where all 12 sectors were sampled with proportionate and random sampling of agricultural households from existing household list. Further, fifteen key informants who comprised of agronomists, land officers, and cooperative leaders were selected purposively due to their knowledge of land use and agriculture conditions.

The tools used in this study include the questionnaire and key informant interview guide, which were constructed based on the research objectives and literature review and evaluated by the supervisor and subject matter experts. Pilot testing was carried out before the actual survey among 20 farmers. The reliability of the 33 questions in the questionnaire was evaluated and was found to have an internal consistency value of 0.757 as measured by Cronbach's Alpha coefficient. The enumerators were trained on how to use the research tools and conduct the survey in accordance with ethical standards.

2.3 Data analysis

Spatial data were classified and quantified into different LULC types and changes from 2000 to 2025 using ArcGIS Pro 3.4. Accuracy of classification was tested by confusion matrix, overall accuracy, and Kappa statistics. Post-classification change detection approach was employed to detect gains and losses of LULC types, and landscape metrics were calculated using FRAGSTATS. Survey data were coded and analyzed using SPSS 30.0 and Microsoft Excel. Frequencies, percentages, and descriptive statistics were used to describe respondents' demographic characteristics and reported agricultural and environmental outcomes. Correlation and regression analysis were used to analyze associations between LULC related variables and reported agricultural productivity outcomes. Key informants' qualitative data were manually coded in Excel. Satellite image analyses, household surveys, field observations, and key informant interviews were triangulated for better interpretation of the findings. Farmers' reported productivity outcomes were treated as reported experiences of farmers and not as an independent measure of yield of crops. Participation in the study was voluntary; respondents were made aware of the purpose of the study; their information was kept confidential and used only for academic purposes.

2.4 Analytical boundaries and quality considerations

The maps document the classifications for the whole district at four different observation points while the household questionnaire records cross-sectional self-reports. These are two separate observational scales. Thus, this research has considered the spatial and survey findings to be complimentary patterns and not paired estimates at the level of farms. A forest-to-crop conversion in the district does not necessarily describe a particular respondent's piece of land.

Accuracy assessment involved confusion matrices, overall accuracies, and Kappa statistics, but this manuscript must provide the per year figures were available in the underlying thesis or classification outputs. Similarly, the patch metrics constitute the methodological backdrop and not the result unless numerical values are provided. No new values have been created.

3. Results

3.1 Socio-demographic characteristics of surveyed farmers

In total, 398 small farmers were involved in the household survey in the 12 sectors of Kamonyi District. From these respondents, 238 (59.8%) were male, whereas 160 (40.2%) were female. In terms of age, 212 (53.3%) respondents were 41-50 years old, 106 (26.6%) were above 50 years old, and 42 (10.6%) and 38 (9.5%) were 18-30 and 31-40 years old, respectively. In terms of education level, 214 respondents (53.8%) were primary educated, 92 (23.1%) were secondary educated, 68 (17.1%) were not educated, and 24 (6.0%) were tertiary educated. The sizes of farms were relatively small. About one-third of the respondents (127; 31.9%) practiced cultivation in between 0.5 ha to 1 ha, 119 (29.9%) of the respondents practiced cultivation in less than 0.5 ha. Additionally, 96 (24.1%) practiced cultivation in 1-2 ha whereas 56 (14.1%) of the respondents had cultivated more than 2 ha. In relation to the farming experience, 168 respondents (42.2%) practiced farming for 11-20 years, 98 (24.6%) had practiced farming for 5-10 years, 80 (20.1%) had practiced farming for more than 20 years whereas 52 (13.1%) practiced farming for less than five years. Similarly, 168 respondents (42.2%) had been living in the same place for 11-20 years.

Table 1. Socio-demographic characteristics of surveyed farmers (n = 398)

Variable	Category	Frequency	Percentage (%)
Sex	Male	238	59.8
	Female	160	40.2
Age	18-30 years	42	10.6
	31-40 years	38	9.5
	41-50 years	212	53.3
	>50 years	106	26.6
Education	No formal education	68	17.1
	Primary	214	53.8
	Secondary	92	23.1
	Tertiary	24	6
Farm size	<0.5 ha	119	29.9
	0.5-1 ha	127	31.9
	1-2 ha	96	24.1
	>2 ha	56	14.1
Farming experience	<5 years	52	13.1
	5-10 years	98	24.6
	11-20 years	168	42.2
	>20 years	80	20.1

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3.2 Spatio-temporal changes in land use and land cover

The satellite images classified revealed that there were huge changes in the LULC categories' spatial distribution in the period between 2000 and 2025. There was a reduction of forest cover from 24,142.59 ha in 2000 to 2,390.58 ha in 2025. This means that there has been a change of 21,752.01 ha or 90.1%. On the other hand, cropland was increasing from 33,137.55 ha to 55,670.58 ha, which implies a change of 22,533.03 ha or 68.0%. Built-up land increased from 130.41 ha in 2000 to 1,002.87 ha in 2025, meaning that there has been an increase of 872.46 ha or 669.0%. Grasslands, wetlands, and waterbodies also changed over the years as shown in table 2.

Table 2. Land use and land cover changes in Kamonyi District, 2000-2025.

LULC category	2000 (ha)	2025 (ha)	Change (ha)	Change (%)
Forest	24,142.59	2,390.58	-21,752.01	-90.1
Cropland	33,137.55	55,670.58	22,533.03	68
Built-up	130.41	1,002.87	872.46	669
Grassland	5,601.06	4,432.50	-1.168.56	-20.9
Wetlands	2,688.03	2,424.96	-263.07	-9.8
Water bodies	402.21	178.47	-223.74	-55.6

The spatial distribution of the LULC classes for each year of observation and also the changes that occurred from the start to the end of observations are illustrated in Figures 2-5.

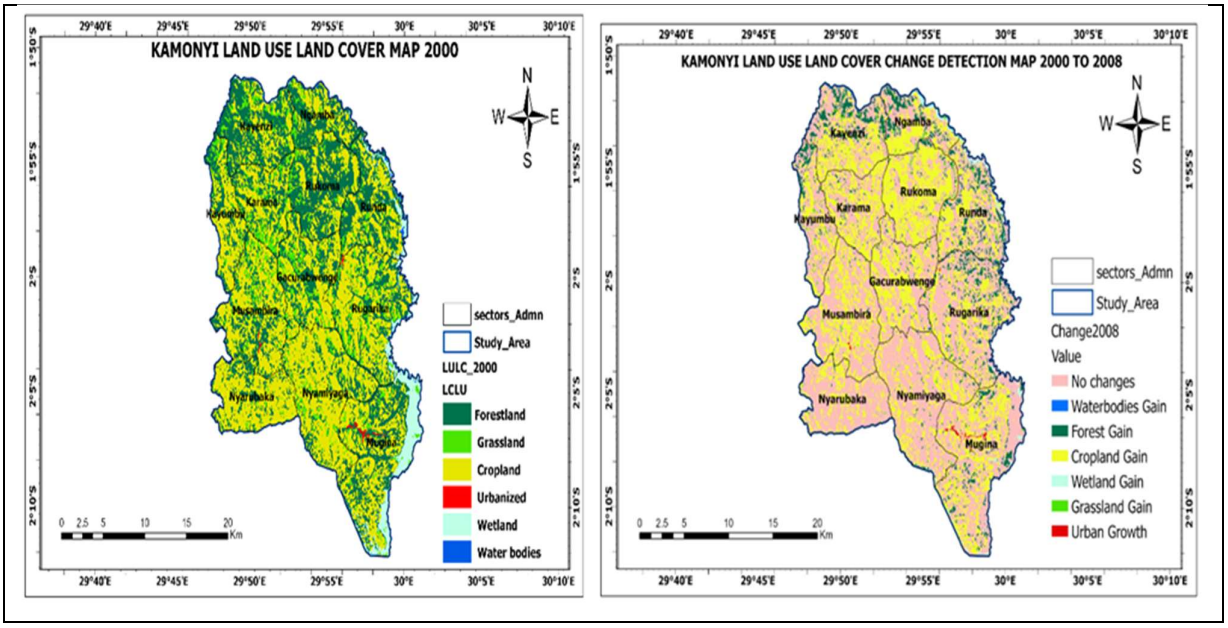

Figure 2: Maps of LULC 2000 and Change Detection 2000-2008

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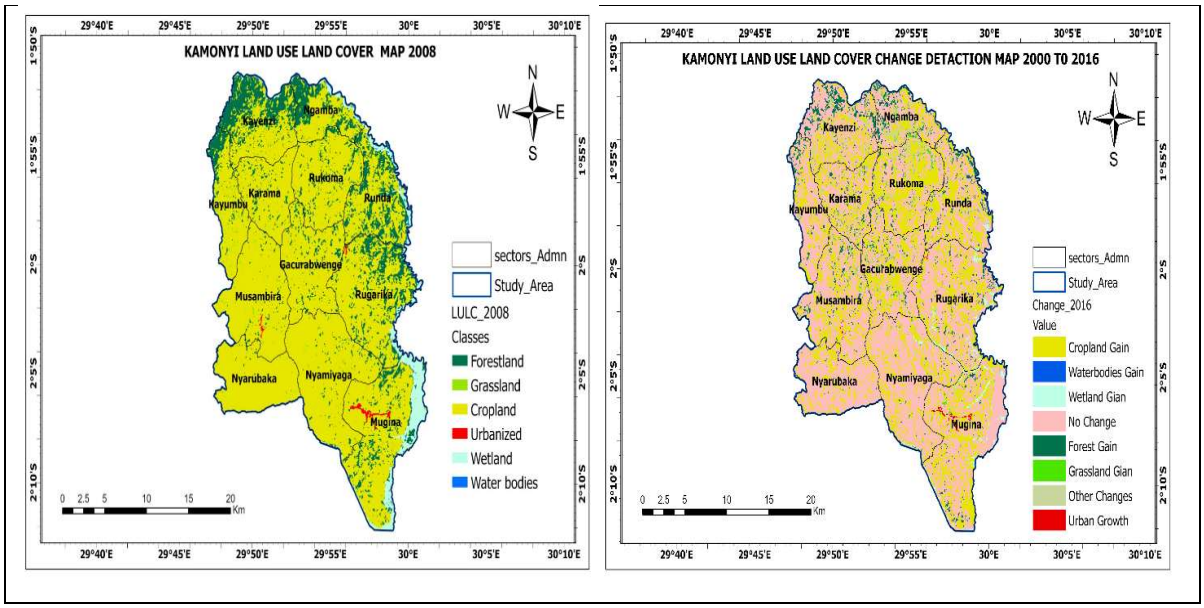

Figure 3: Maps of LULC 2008 and changes detection 2016

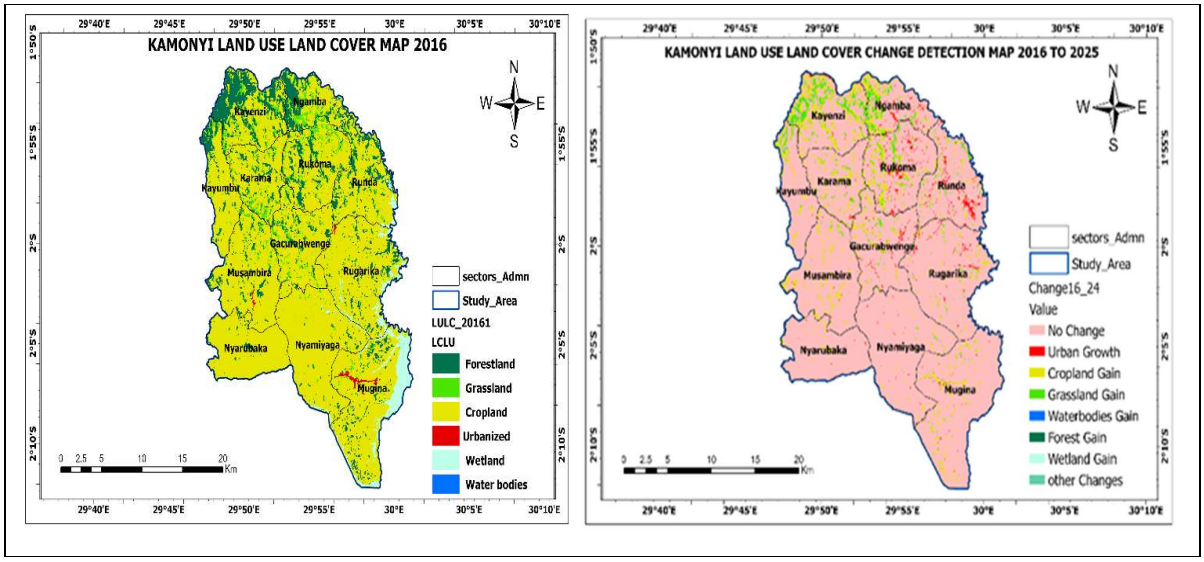

Figure 4: Maps of LULC 2016 and change detection 2016-2025

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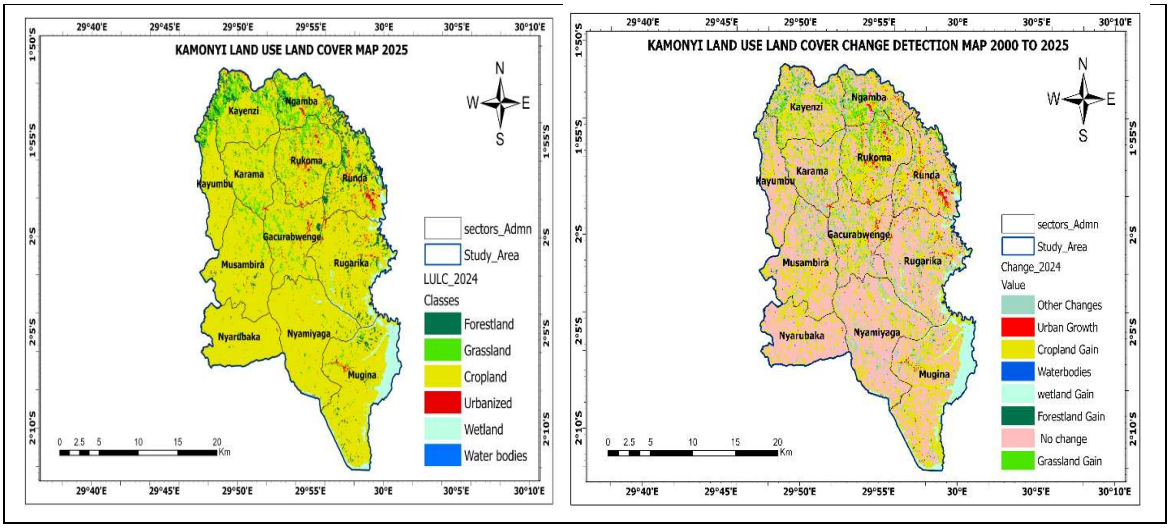

Figure 5: ***Land use and land cover map of Kamonyi District, 2025 and Overall land use and land cover change detection 2025***

3.3 Farmers reported agricultural productivity and environmental outcomes

The household survey indicated that there had been several alterations in agricultural productivity and environmental conditions during the research period. 98% of the farmers reported a reduction in their crop productivity as compared to previous years. In relation to soil quality, 63.8% of the farmers reported that soil erosion had been very high while 37.2% of the respondents reported low soil fertility. 84.2% of the respondents also reported land fragmentation as one of the constraints to agricultural productivity. Farmers also reported several alterations in food security and agricultural incomes. 43.5% of the households reported that they often faced food shortages. The reduction in agricultural income was also reported by 58.5% of the respondents while 98% changes in crop diversity were reported by the respondents. Climate variability and land degradation were reported as major constraints to agricultural productivity by 93.3% of the respondents. In relation to the landscape change, 62% of the respondents reported an increase in cropland while 58% reported a reduction in forest cover.

Table 3. Selected farmer-reported agricultural productivity and environmental outcomes in Kamonyi District.

Indicator	Reported result (%)
Farmers reporting declining crop yields	98
Very high soil erosion	63.8
Low soil fertility	37.2
Land fragmentation reported as a major constraint	84.2
Households often experiencing food shortages	43.5
Climate variability and land degradation reported as major constraints	93.3
Farmers reporting increased cropland	62
Farmers reporting forest decline	58
Agricultural income decline	58.5
Reduced crop diversity	98.0

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3.4 Relationships between LULC dynamics and reported agricultural productivity outcomes

The correlation analysis shows that there exist significant correlations between different LULC variables and perceived impacts on agriculture. Expansion of settlements is positively correlated to farmland reduction ($r = 0.770$, $p < 0.001$). Reduction of forests is positively correlated to soil erosion ($r = 0.606$, $p < 0.001$). Fragmentation of land is positively correlated to yield decline ($r = 0.761$, $p < 0.001$) and agricultural income decline ($r = 0.811$, $p < 0.001$). Fertility of soils is negatively correlated to crop yields ($r = -0.366$, $p < 0.001$). Expansion of settlements is positively correlated to food shortage ($r = 0.713$, $p < 0.001$), while reduction of forests is positively correlated to food shortage ($r = 0.580$, $p < 0.001$). Climate variability is positively correlated to productivity decline ($r = 0.359$, $p < 0.001$) and food insecurity ($r = 0.595$, $p < 0.001$).

Table 4. Pearson correlations between selected LULC-related factors and reported agricultural outcomes.

LULC/environmental factor	Agricultural outcome	r	p-value
Settlement expansion	Farmland reduction	0.77	<0.001
Forest decline	Soil erosion	0.606	<0.001
Land fragmentation	Reported yield decline	0.761	<0.001
Land fragmentation	Agricultural income decline	0.811	<0.001
Soil fertility	Reported crop yields	−0.366	<0.001
Settlement expansion	Food shortages	0.713	<0.001
Forest decline	Food shortages	0.58	<0.001
Climate variability	Reported productivity decline	0.359	<0.001
Climate variability	Food insecurity	0.595	<0.001

All correlations presented were statistically significant at 0.001 level. These findings indicate the presence of statistical relationships between variables under investigation but cannot be interpreted causally.

4. Discussion

The study reveals considerable changes in the landscape of Kamonyi District from 2000 to 2025. It was a significant decrease in forest cover by 90.1%, an increase in cropland by 68.0%, and an increase in built-up areas by 669.0%. These data reveal a tendency of changing the landscape into an intensive agricultural landscape, which is intensively developed. The increase in the area of built-up areas can be attributed to the information given in the study conducted in Runda Sector, where urban expansion leads to the pressure on agricultural lands . The same processes have been studied in Africa, where population pressure, settlement expansion, and agriculture were seen as factors in LULC changes.

In addition, the growth in cropland while reduction in forestation and other land cover types is important in understanding agricultural productivity. On one side, from an intensification of agriculture perspective, increase in cropland might be due to an increasing demand for food products coupled with lack of land availability, as postulated by Boserup theory of agricultural intensification. However, the results obtained in this research indicate that increase in cropland was not associated with increased productivity according to farmers. Although there was a 68.0% increase in the proportion of cropland between 2000 and 2025, 98% of the interviewed farmers experienced reduced yield of crops. Such discrepancy indicates that increase in the number of

croplands may not necessarily translate into increased productivity. Factors such as soil quality, fragmentation, degradation, climatic variability, and agricultural practices may play a role in agricultural performance together with the number of cultivated lands. Similarly, studies carried out on African farmers have revealed that agricultural management practice may influence agricultural and environmental performance differently.

The environmental conditions reported here also add additional perspective on the productivity figures. Very high soil erosion was indicated by 63.8% of the participants, while low soil fertility was noted by 37.2% of the respondents. The positive relationship between the decline of forest cover and soil erosion ($r = 0.606$, $p < 0.001$) is also in line with the role of vegetation cover as a protector of the soil. On the other hand, the negative relationship between soil fertility and crop production ($r = -0.366$, $p < 0.001$) shows that the soil-related conditions were statistically associated with the reported agricultural productivity. This can be seen in light of the general knowledge about how land degradation affects the productive capacity of agricultural land due to lack of soil and water conservation measures. However, it must be noted that the soil fertility levels indicated here are the result of farmers' reports and not laboratory soil analysis.

The issue of land fragmentation became an additional significant variable that is related to the performance of agriculture. Strong correlations between land fragmentation and perceived yield decrease ($r = 0.761$, $p < 0.001$) and land fragmentation and perceived decrease in agricultural income ($r = 0.811$, $p < 0.001$) show statistical association within the survey participants. Fragmented and small parcels may limit the opportunities for farmers to manage their land effectively, apply for any conservation efforts or achieve any economies of scale. Dominance of small parcels in the survey 61.8% of respondents cultivate less than one hectare becomes an important aspect of this observation at household level. It is essential to highlight the cross-sectional nature of the survey and to stress the fact that there are no causal relationships between land fragmentation and yield/income decrease.

Moreover, it is necessary to analyze the relationship between the settlement expansion and agricultural conditions. The positive relationships have been established between the settlement expansion and the farmland loss ($r = 0.770$, $p < 0.001$), as well as the food shortage ($r = 0.713$, $p < 0.001$). In addition, there has been the positive relationship between the forest loss and food shortage ($r = 0.580$, $p < 0.001$). Thus, there has been the simultaneous change in the availability of agricultural land and environmental conditions along with the food security problems at the household level. From the point of view of the sustainable livelihood approach, rural households rely greatly on the environment and production factors, so any change in the environmental condition and resource availability can influence the livelihood strategy.

Climate variability was another stress factor affecting agriculture-based livelihoods. Climate variability was found to have a positive correlation with productivity decline ($r = 0.359$, $p < 0.001$) and food security ($r = 0.595$, $p < 0.001$). The above findings imply that farmers were also affected by climatic stresses, apart from the LULC and environment issues raised in the study. The interplay between land fragmentation, soil erosion, poor soil fertility, settlements and climate variability could generate interacting stresses on smallholder production systems. This highlights the significance of agricultural and land management strategies that would concurrently improve productivity, soil and water conservation, and resilience against climate variability. Experiences from agriculture in Africa show that productivity and resilience can be improved using context-specific practices for agriculture . The combination of the evidence obtained from remote sensing, household surveys, fieldwork, and key informant interviews enhances the interpretation of the overall pattern. Remote sensing showed tangible physical changes in the landscape, while the survey responses captured the farmers' experiences of changes in production, land availability, soil quality, incomes, and food security. The findings thus provide evidence on the district level for considering the LULC change in Kamonyi not only as a geographic issue but also as a factor related to livelihood conditions of smallholders. This finding supports integrated land use planning, protection and rehabilitation of environmentally significant areas, soil and water conservation and agriculture practices that could maintain the agricultural productivity in the face of increasing pressures on the land and climate (REMA, 2021). It is necessary to note that the study finds the relationship between LULC change and agricultural outcomes but not proves the causal effects.

4.1 Implications for land-use and agricultural policy

The findings with respect to space validate integrated district-level planning, where decisions must include both forest rehabilitation and protection, along with other needs such as cropland area, settlement area, and basic services. The change from 24,142.59 hectares of forests to 2,390.58 hectares represents a change large enough to validate classification accuracy and land cover definitions prior to regulation based on the findings alone. A growth in cropland area that is concurrently witnessing yield reductions highlights the need to distinguish between agricultural growth and yield per hectare of farmland. District level plans need to track both farmland area and independently collected crop yields, along with indicators for soil quality and food security of the household.

The extent to which fragmentation is considered a constraint among 84.2% of the farmers calls for the need to carefully assess issues related to land access and parcels at the farm level. The process of consolidation must be evaluated in relation to the costs of access, tenure, and household crop choice; otherwise, the dataset alone would not provide information regarding the impacts of any particular policy. The emphasis placed on erosion, declining fertility levels, and climate variability suggests that the appropriate response would be a package involving conservation of the soil and water resources, slope-adapted cropping, agroforestry, and local agricultural extension services. The impact of the particular program must be assessed through field measurements and not correlations. Research has been done to explain different adaptations.

4.2 Study limitations and directions for future research

Imagery is at four time points over 25 years, so it will not capture all short-term land transitions. The classification from the satellite imagery could be influenced by different sensors, seasonality issues, mixture effects, and classification errors. The household survey data depends on retrospective information, which could be impacted by recall bias, response bias, and selection bias. The correlation coefficient does not imply a causal relationship. For future studies, it would be useful to have georeferenced farm plots matched to repeated measurements of yield per hectare, agricultural practices, soil fertility, rainfall, and input usage. The package for reproducing results should have dates of the source imagery, training/validating samples, classification schemes, and annual confusion and land-cover transition matrices.

5. Conclusion

This research investigated the spatio-temporal changes in land use and land cover (LULC) and associated impacts on agricultural productivity by smallholder farmers in Kamonyi District, Rwanda from 2000 to 2025. These findings suggest significant change in the district's land use pattern with 90.1% reduction in forest cover, 68.0% increase in croplands and 669.0% increase in built-up areas. In spite of the increase in croplands, 98% of the respondents indicated that the crop yields have reduced. Soil erosion, low soil fertility, land fragmentation, climatic variability and food shortages were found to be the challenges of agriculture. Significant relationships were found between LULC variables and the agricultural productivity with respect to land fragmentation, yield and income decline and forest reduction with soil erosion and food shortage. Incorporating the remote sensing analysis and geospatial techniques with the information obtained through household survey, field observation and key informant interviews, the study provides district level evidence about LULC changes in conjunction with the smallholder farming system. However, the assessment of agricultural productivity depended mainly upon farmers' reports and field observation and not on the actual independent measurements of crop yield. These results advocate for increased coordination between land use planning, environmental restoration, and agriculture within Kamonyi District. The district government and agriculture-related organizations need to invest more in soil and water conservation measures, conservation of existing forests and other environmentally sensitive regions, agricultural land restoration, and implementation of climate-smart farming practices. Future research needs to utilize spatial analysis along with measurements of crop yield, soil quality, and economics from longitudinal studies on farms to determine changes in agricultural productivity.

6. SUPPLEMENTARY INFORMATION

Author Contributions: Conceptualization, methodology, investigation, data collection, formal analysis, writing-original draft, and visualization: R.E. Supervision and methodology: P.N. Review and editing: P.N. Both authors must approve author contributions prior to submission.

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