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Research Article

Keywords: Climate change, Forest productivity, GIS, Remote sensing, NDVI, Socioeconomic factors

Posted Date: September 28th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10789368/v1>

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Additional Declarations: No competing interests reported.

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This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Clinical trial number: not applicable.

Consent to publish: Not applicable, as this manuscript does not contain any individual person's identifiable data, images, or other personally identifiable information.

Ethical approval for this study was obtained from the relevant institutional ethics committee of Gambella University. All participants were informed about the purpose of the study, and informed consent was obtained before participation. Participation was voluntary, and participants were informed that they could withdraw from the study at any time.

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request, subject to applicable ethical and confidentiality restrictions.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request, subject to applicable ethical and confidentiality restrictions.

Accordance

The study was conducted in accordance with the relevant institutional ethical regulations and guidelines of Gambella University. The research procedures involving human participants were conducted in accordance with the approved study protocol and applicable ethical principles.

Ethics and Consent to Participate

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ABSTRACT

Climate change has emerged as a significant environmental issue impacting forest ecosystems and vegetation productivity globally. This research evaluated the effects of climate change on forest productivity by employing integrated Geographic Information Systems (GIS), remote sensing, climate analysis, and socioeconomic techniques in the Itang Special District, Gambella Region, in Southwestern Ethiopia. The research focused on assessing the present condition of forest productivity, investigating the effects of climate fluctuations on plant dynamics, and exploring the socioeconomic elements affecting forest management and productivity in local communities. Both primary and secondary sources of data were utilized. Data from Landsat and Sentinel satellite images, along with climate information and field observations, were assessed through GIS and remote sensing methods, specifically employing the Normalized Difference Vegetation Index (NDVI). Socioeconomic information was gathered via household surveys, Focus Group Discussions (FGDs), and Key Informant Interviews (KIIs). The results showed notable changes in land use and land cover from 2017 to 2025. Forest coverage decreased from 63.71% in 2017 to 47.80% in 2025, whereas agricultural land increased from 31.29% to 45.48%. Climate assessment revealed rising temperature patterns and inconsistent rainfall distribution over the past twenty years, adversely impacting forest development, biomass growth, and plant regeneration. Regions distant from roads showed enhanced vegetation productivity in contrast to those close to roads, where human disturbances were more pronounced. The analysis of socioeconomic factors indicated that the primary causes of forest degradation were agricultural expansion, extraction of fuelwood, population growth, poverty, and the expansion of settlements. The research found that both climate fluctuations and human activities have greatly impacted the reduction of forest productivity in Itang Special District. The combination of GIS, remote sensing, and socioeconomic methods offered essential understanding of the spatial and temporal dynamics within forest ecosystems. The research suggests bolstering sustainable forestry practices, encouraging alternative energy options, advancing reforestation initiatives, and upgrading climate adaptation strategies to decrease forest degradation and enhance ecosystem sustainability in the region.

Keywords: Climate change, Forest productivity, GIS, Remote sensing, NDVI, Socioeconomic factors.

1. INTRODUCTION

1.1 Background of the Study

Climate change is increasingly acknowledged as a significant environmental issue impacting ecosystems and human lives globally (Banu, N. et al. 2025). Forest ecosystems are extremely responsive to climate variations, as their growth, productivity, regeneration, and species diversity depend largely on temperature and rainfall patterns (Haritika and Negi, A.K., 2025). However, the shifting climate, combined with human activities such as deforestation, agricultural expansion,

and unsustainable resource use, has accelerated the destruction and depletion of forests in numerous regions globally (Das, N., 2026).

According to (Raihan, 2023), forests in developing nations provide substantial environmental and economic benefits that help communities adapt to climate variations and environmental issues.

Despite their significance, Ethiopia's forests have been rapidly diminishing over the years. This occurs due to an increase in the local population, expansion of agriculture, deforestation for fuel, construction of new

houses, and improper land management (Demel Teketay & Tesfaye Bekele, 2018). Climate change is increasing pressure on forest ecosystems due to rising temperatures, shifts in rainfall patterns, and increased drought occurrences (Nouh, F.A.A. et al. 2025).

The Gambella Region, situated in the southwest of Ethiopia, contains vital forests and river ecosystems that sustain diverse plant and animal species alongside the livelihoods of local communities (Tefera, W. et al.2025). Nevertheless, these ecosystems are increasingly endangered due to climate shifts and human-induced environmental alterations. (Alemu, 2012) stated that human activities and climate change have increased the vulnerability of lowland forest ecosystems in Ethiopia.

Furthermore, the expansion of agricultural land has accelerated the transformation of forested regions into farmland. (Mulatu et al. 2025) A study in identified that deforestation in multiple areas of Ethiopia is largely driven by agricultural expansion and biomass energy utilization.

2. RESEARCH METHODOLOGY

2.1 Location of the Study Areas

2.1.1 Description of the Study Area

This study was carried out in Itang Special District, located in the Gambella Region of Southwestern Ethiopia. The district is located in the Baro-Akobo River Basin and encompasses approximately 2,188.34 square kilometers of land area. The district holds strategic importance because the Baro River flows through its area, promoting various ecological systems.

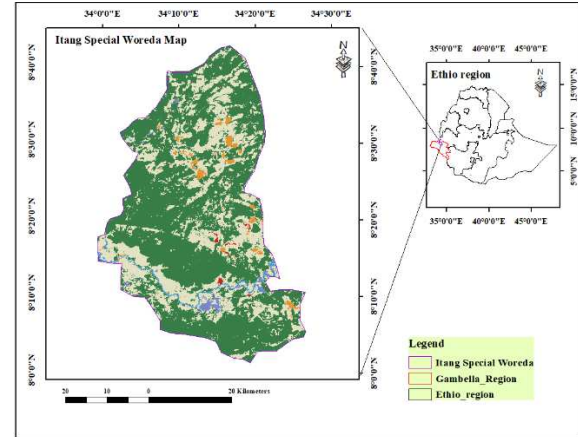


Figure 1: Location map of study area

Source: Arc GIS (2026)

2.2. Data Sources

In this research to meet the study goals, information was obtained from both primary and secondary sources: Primary Data: Data was collected via household surveys, focus group discussions (FGDs), key informant interviews (KIIs) with elders and specialists, and direct field observations utilizing GPS for validation. Secondary Data: This encompassed multi-temporal satellite images (Landsat and Sentinel), extensive climate data (temperature and precipitation) sourced from WorldClim, CRU, and the National Meteorological Agency, along with demographic reports at the district level.

2.3. Data and Analysis

2.3.1 GIS and Remote Sensing Analysis

The research employed ArcGIS or QGIS for spatial analysis. Forest productivity was evaluated using the Normalized Difference Vegetation Index (NDVI), computed as:
$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$
 This index facilitates the categorization of land cover from bare soil/degraded land (0 to 0.2) to

dense vegetation (0.5 to 1.0). Additionally, a Random Forest algorithm or supervised classification was employed to classify changes in land use and land cover (LULC) over time.

2.3.2 Climate Data Analysis

Time-series techniques were employed to analyze historical trends in temperature and precipitation. A correlation analysis was conducted to evaluate the statistical link between these climate factors and the vegetation dynamics indicated by NDVI observed in the district.

2.3.3 Socioeconomic Data Analysis

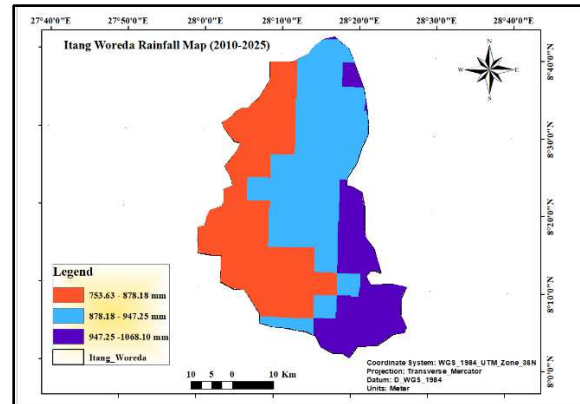
Survey data were examined using statistical tools such as SPSS or Excel. The analysis featured descriptive statistics (frequencies, percentages, and means) along with cross-tabulation to assess how factors like poverty and lack of alternative energy led to the unsustainable use of forest resources. Thematic narration was employed to examine qualitative data derived from interviews and focus group discussions.

3. RESULT AND DISCUSSION

3.1 Rainfall Distribution Analysis

The geographic distribution of rainfall in the research area exhibits significant differences throughout Itang Woreda. The western area of the woreda sees relatively low yearly precipitation between 753.63 mm and 878.18 mm. Moderate rainfall, varying from 878.18 mm to 947.25 mm, is primarily noted in the central regions of the study area. In comparison, the eastern and southeastern regions experience relatively greater annual precipitation between 947.25 mm and 1068.10 mm. Overall, the rainfall distribution shows a

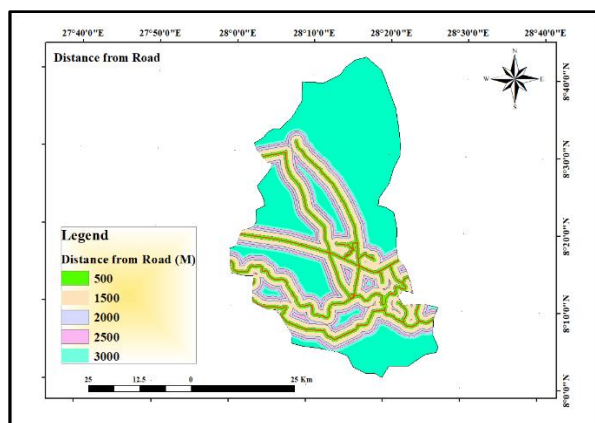
rising trend from the west to the east throughout the study region. This variation could be linked to topographical and climatic elements affecting rainfall distribution.



Source: Arc GIS, 2026

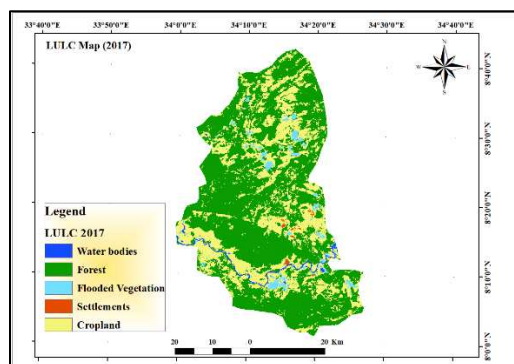
3.1.1 Distance from Road and Forest Productivity Analysis

The assessment of proximity to roads shows that forest regions found within 500 m of roads displayed notably low vegetation productivity because of significant human disturbances like settlement growth, agricultural practices, fuel wood gathering, and accessibility demands. Conversely, forest regions located between 2500 m and 3000 m from roads exhibited superior vegetation conditions, greater biomass accumulation, and enhanced forest regeneration status. This indicates that greater distance from roads diminishes human disturbance and benefits forest health and productivity in the area examined.



Source: Arc GIS, 2026

The 2017 LULC analysis indicates that forest land was the primary land-cover type in Itang Special District, comprising about 63.71% of the overall area, with cropland following at 31.29%. Flooded plants, aquatic areas, and communities occupied relatively lesser portions of the study area.



Source: Arc GIS, 2026

LULC Classification of Itang Special District (2017)

LULC Class	Area (ha)	Area (%)
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Forest	65,818	63.71%
Cropland	32,328	31.29%
Flooded Vegetation	3,681	3.56%
Water Bodies	1,141	1.10%
Settlements	337	0.33%
Total	103,305	100%

Source: SPSS, 2026

LULC Classification of Itang Special District (2021)

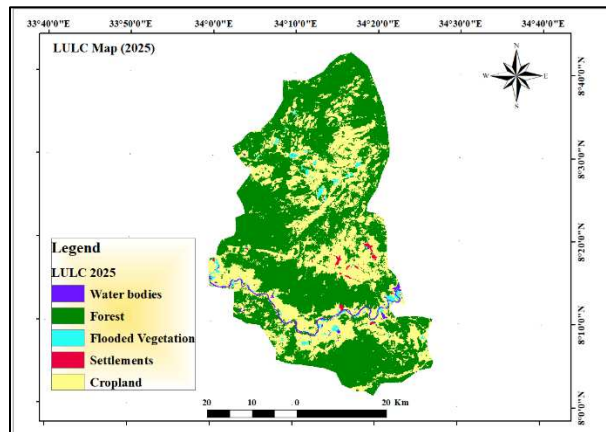
LULC Class	Area (ha)	Area (%)
Forest	55,420	53.62%
Cropland	41,885	40.54%
Flooded Vegetation	3,912	3.78%
Water Bodies	1,498	1.45%
Settlements	590	0.57%
Total	103,305	100%

Source: SPSS, 2026

The 2021 LULC assessment shows significant shifts in land-cover distribution in Itang Special District relative to 2017. Forest continued to be the primary land-cover type, comprising about 53.62% of the overall area. Nonetheless, the share of forest cover decreased in relation to the earlier period, indicating rising stress on forest ecosystems. Agricultural land grew considerably, occupying roughly 40.54% of the study region, suggesting ongoing agricultural development and the transformation of forested areas into farmland. Flooded plant life represented around

3.78%, primarily focused in floodplain and riverine areas. Water bodies accounted for roughly 1.45% of the area, whereas settlements occupied around 0.57%, indicating a gradual expansion of settlement in the district.

LULC Classification of Itang Special District (2025)



Source: Arc GIS, 2026.

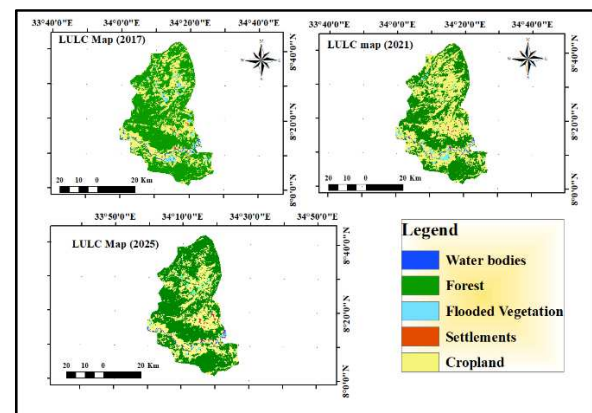
LULC Class	Area (ha)	Area (%)
Forest	49,376	47.80%
Cropland	46,982	45.48%
Flooded Vegetation	4,210	4.08%
Water Bodies	1,865	1.81%
Settlements	872	0.84%
Total	103,305	100%

Source: SPSS, 2026

The 2025 LULC assessment indicates ongoing changes in land use and land cover in Itang Special District. Forest cover continued to be the primary land-cover type, representing roughly 47.80% of the overall

area. Nonetheless, the percentage of forest cover decreased further in comparison to both 2017 and 2021, suggesting rising environmental stress and forest deterioration within the district. Cropland grew significantly, encompassing approximately 45.48% of the study region, indicating continued agricultural growth and the transformation of forest areas into agricultural land. Flooded plant life accounted for about 4.08%, primarily found in riparian and floodplain areas. Water bodies represented roughly 1.81%, whereas settlements comprised about 0.84%, reflecting the gradual expansion of inhabited regions and human endeavors.

LULC Change (2017–2025)



Source: Arc GIS, 2026

LULC Class	2017 (%)	2021 (%)	2025 (%)	Overall Change (2017–2025)
Forest	63.71	53.62	47.80	-15.91
Cropland	31.29	40.54	45.48	+14.19
Flooded Vegetation	3.56	3.78	4.08	+0.52

Water Bodies	1.10	1.45	1.81	+0.71
Settlements	0.33	0.57	0.84	+0.51

Source: SPSS, 2026

The LULC assessment for 2025 indicated significant land-cover changes in Itang Special District. Forest cover decreased notably from 63.71% in 2017 to 47.80% in 2025, whereas cropland rose from 31.29% to 45.48% in that timeframe. The growth of farmland suggests a rising transformation of forest ecosystems into farming zones. Settlement zones also grew steadily, mirroring the increasing population demand and human activities in the area. These results indicate that agricultural growth, fuel wood collection, population increase, and climate fluctuations have led to forest deterioration and reduced vegetation productivity in the research region. The noted alterations in land cover could adversely impact biodiversity preservation, ecosystem resilience, and carbon storage.

3.2 Analyzing the Impacts of Climate Change on Forest Growth, Biomass, and Productivity

3.2.1 Climate Variability Trends

Analysis of climate data showed significant shifts in temperature and precipitation trends in the research area during the past two decades. The average yearly temperature displayed an upward trend, climbing from around 24.8°C in 2005 to 27.1°C in 2025. Conversely, the distribution of rainfall became more erratic, featuring recurrent years of drought and varying intensity during the wet season.

3.2.2 Perceptions of Climate Change Impacts on forest productivity

The household survey carried out with 203 participants also corroborated the climate analysis results. The majority of respondents indicated noticeable environmental changes in the past twenty years.

Table 3.1 Perceptions of Climate Change Impacts on Forest Productivity (N = 203)

Response Category	Frequency	Percentage (%)
Decrease in forest cover	86	42.4
Increased drought occurrence	54	26.6
Reduced rainfall	39	19.2
Increased temperature	24	11.8
Total	203	100

Source: SPSS, 2026

The survey findings showed that 42.4% of participants noted a notable reduction in forest cover, whereas 26.6% linked falling forest productivity to rising drought conditions. Furthermore, 19.2% recognized decreased rainfall as a significant environmental issue impacting plant growth.

Table 3.2 Major Drivers of Forest Productivity Decline

Factors	Frequency	Percentage (%)
Agricultural expansion	71	35.0

Fuel extraction	wood	58	28.6
Climate variability		43	21.2
Settlement expansion		31	15.2
Total		203	100

Source: SPSS, 2026

The findings indicated that the primary cause of reduced forest productivity was agricultural expansion, representing 35% of the responses. The extraction of fuel wood was the second most significant factor, after climate variability and the expansion of settlements.

3.3 Evaluating the Socioeconomic Factors Influencing Forest Management and Productivity among Local Communities

This section details the results gathered from structured questionnaires, Focus Group Discussions (FGDs), and Key Informant Interviews (KIIs) carried out to assess the socioeconomic factors affecting forest management and productivity in Itang Special District. The analysis combines quantitative data assessed with SPSS and qualitative insights gathered from community elders, local officials, agricultural specialists, and forest officers.

3.3.1 Socioeconomic Characteristics of Respondents

The socioeconomic survey included 203 household participants chosen from the sampled kebeles. The demographic traits showed that most participants rely directly on agricultural and forest resources for their livelihoods.

Table 3.3 Demographic Characteristics of Respondents (N = 203)

Variables	Category	Frequency	Percentage
Sex	Male	137	67.5
	Female	66	32.5
Age	18–30 years	41	20.2
	31–45 years	92	45.3
	Above 45 years	70	34.5
Education Level	No formal education	79	38.9
	Primary education	88	43.3
	Secondary and above	36	17.8
Main Livelihood Activity	Farming	112	55.2
	Agro-pastoralism	46	22.7
	Fishing	19	9.4
	Forest product collection	26	12.7

Source: SPSS, 2026

The findings indicated that the majority of participants possessed minimal educational qualifications and depended significantly on climate-dependent economic activities like agriculture and timber

harvesting. This reliance heightens the stress on nearby forest ecosystems since families utilize forests for fuelwood, charcoal creation, grazing, and building supplies.

3.3.2 Household Dependence on Forest Resources

The results from the structured questionnaire showed that local communities heavily rely on forest resources for their daily household needs and income generation.

Table 3.4 Major Uses of Forest Resources by Households

Forest Resource Use	Frequency	Percentage
Fuelwood collection	84	41.4
Charcoal production	39	19.2
Construction materials	31	15.3
Grazing activities	27	13.3
Traditional medicine and food	22	10.8
Total	203	100

Source: SPSS, 2026

The results showed that collecting fuelwood was the primary forest-related activity carried out by households. This outcome illustrates the restricted access to alternative energy sources in the area. Significant reliance on biomass energy leads to ongoing forest deterioration and reduced plant productivity. The results align with research carried out in Ethiopian university archives, especially studies from Jimma University and Wollega University, which indicated that reliance on fuelwood and

charcoal production are key factors contributing to forest degradation in rural Ethiopia.

3.3.3 Results from Focus Group Discussions (FGDs)

Discussions in focus groups were held with local elders, women's organizations, youth representatives, and farmers from chosen kebeles. The discussions indicated that local communities have noticed significant environmental shifts over the last two decades. Participants stated that forests once spanned extensive areas near rivers and inhabited regions, but forest resources have diminished quickly due to agricultural growth, rising population pressures, and over-logging. A participant from Pulkot Kebele in the FGD remarked: "Previously, forests were thick and rainfall was more consistent. Currently, numerous trees are being felled for agricultural land and firewood, and drought is increasingly frequent. One more participant pointed out that migration and the expansion of settlements have heightened competition for natural resources, resulting in unsustainable practices in forest use. FGD participants highlighted that poverty and the absence of job opportunities compel numerous households to rely directly on forests for their livelihood. Women participants pointed out that the distances for fuel wood collection have risen in comparison to previous years due to the dwindling availability of nearby forest resources.

3.3.4 Results from Key Informant Interviews (KIIs)

Interviews with key informants were held with agricultural extension workers, environmental protection specialists, district officials, and forestry personnel. The majority of key informants agreed that climate change and land-use alterations are the

primary environmental issues impacting forest ecosystems in Itang Special District. District forestry specialists report that rising demand for farmland and biomass energy has led to ongoing deforestation.

A forestry specialist noted: "The area is facing swift deforestation as nearby communities depend greatly on forests for charcoal and expanding agricultural land." Climate change is impacting the regeneration of vegetation as well. "Agricultural officers also noted that inconsistent rainfall and extended dry seasons adversely impact plant growth and soil moisture levels." Key informants emphasized that poor enforcement of forest protection laws and a lack of environmental awareness within communities significantly contribute to forest degradation. The KIIs also showcased that there are few community-based forest management initiatives in the district. Experts highlighted the significance of implementing alternative energy technologies, reforestation initiatives, and environmental education to enhance sustainable forest management.

3.3.5 Analysis of Socioeconomic Factors Affecting Forest Productivity

Table 3.5 Socioeconomic Factors Affecting Forest Productivity

Socioeconomic Factors	Frequency	Percentage (%)
Agricultural expansion	67	33.0
Fuel wood and charcoal extraction	59	29.1
Population growth	34	16.7

Poverty and unemployment	25	12.3
Settlement expansion	18	8.9
Total	203	100

Source: SPSS, 2026

The findings indicated that the primary socioeconomic factor influencing forest productivity was agricultural expansion, followed by the removal of fuel wood and charcoal. Growth in population and poverty have also played a major role in unsustainable use of forests. Cross-tabulation analysis indicated that households with lower income and education levels relied more on forest resources compared to those with higher education. This suggests that poverty and insufficient livelihood diversification heighten environmental stress on forest ecosystems.

3.3.6 DISCUSSION

This study's findings indicated notable alterations in forest productivity, land-use trends, and climate variability in Itang Special District throughout the research period. The spatial rainfall analysis revealed significant differences in rainfall distribution throughout the district, with considerably more precipitation observed in the eastern and southeastern regions of the study area. Regions that experienced increased rainfall typically showed improved vegetation health and greater forest productivity in contrast to regions with diminished rainfall levels. This discovery indicates that the availability of rainfall continues to be a significant climatic factor affecting vegetation growth and the stability of forest ecosystems in the area. The IPCC (2021) reported comparable results, showing that variations in rainfall

significantly influence vegetation productivity, biomass growth, and ecological resilience within tropical ecosystems. Alemu (2012) noted that alterations in rainfall patterns greatly affect forest regrowth and plant dynamics in the lowland areas of Ethiopia.

The distance-from-road analysis showed that forest regions nearer to roads had reduced vegetation productivity and increased environmental degradation compared to those located further away. Forest ecosystems located within 500 meters of roads exhibited heightened disturbance linked to agricultural development, population growth, fuelwood collection, and human access. In contrast, forest regions situated 2500 m to 3000 m away from roads showed better vegetation health and enhanced biomass growth. These results bolster the claim that road accessibility hastens land-use transformation and forest degradation by elevating human demand on natural resources. Comparable findings were reported by Geist and Lambin (2002), who recognized infrastructure expansion and accessibility as key factors contributing to tropical deforestation. Tesfaye Gashaw and colleagues (2017) also found that road development greatly impacts forest fragmentation and reduces vegetation productivity in Ethiopia.

The LULC study showed significant changes in land cover from 2017 to 2025. Forest coverage decreased notably from 63.71% in 2017 to 47.80% in 2025, whereas agricultural land rose from 31.29% to 45.48% in that timeframe. The growth of farmland signifies the rising transformation of forest ecosystems into agricultural areas. Settlement areas exhibited steady growth over time, indicating heightened population pressure and a greater demand for land and forest resources. These results indicate that the primary

cause of forest degradation in the district continues to be agricultural expansion. FAO (2020) reported similar results, highlighting agricultural expansion as a significant factor in global forest loss. Research by Solomon Abate (2011), Belay Tegene (2016), and Demel Teketay and Tesfaye Bekele (2018) similarly indicated a swift reduction of forests in Ethiopia caused by agricultural expansion, reliance on fuelwood, and unsustainable land management practices.

The analysis of climate variability also showed rising temperature patterns and inconsistent rainfall distribution during the past twenty years. The average yearly temperature rose from around 24.8°C in 2005 to 27.1°C in 2025, as precipitation patterns became more erratic with regular drought events. Increasing temperatures and varying rainfall patterns could adversely impact plant growth, soil moisture levels, and the ability of forests to regenerate. The IPCC (2021) states that rising temperatures and inconsistent rainfall decrease plant productivity and ecosystem strength, especially in tropical and semi-arid areas. Getachew Alemu (2012) reported similar results, indicating that climate variability plays a major role in the decrease of vegetation productivity in southwestern Ethiopia.

The results of the household survey corroborated the outcomes of the climate and geospatial analyses. A significant number of respondents observed a clear reduction in forest cover and a rise in drought frequency in the past twenty years. The majority of respondents linked decreasing forest productivity to agricultural growth, fuelwood removal, and fluctuations in climate. The SPSS analysis revealed that agricultural expansion represented 35% of answers concerning factors leading to forest

productivity decline, followed by fuelwood extraction (28.6%), climate variability (21.2%), and settlement expansion (15.2%). These results suggest that environmental and human-induced factors combine to affect forest ecosystem deterioration in the research region.

The socioeconomic analysis indicated that local communities rely significantly on forest resources for fuelwood, charcoal manufacturing, building materials, grazing, and traditional healing. Gathering fuelwood was recognized as the primary forest-related activity among households. This significant reliance on biomass energy heightens pressure on forest ecosystems and hastens forest degradation. Comparable results were documented in research carried out at Jimma University and Wollega University, which recognized reliance on fuelwood and charcoal production as significant factors in forest degradation in rural Ethiopia.

Results from Focus Group Discussions (FGDs) and Key Informant Interviews (KIIs) additionally validated that local communities have undergone significant environmental transformations over time. Participants noted that forest regions once spanned extensive areas of the district but have gradually diminished due to agricultural growth, increasing population, and excessive logging. Key informants also stressed that poor forest management practices, a lack of environmental awareness, and insufficient enforcement of forest protection laws lead to ongoing forest degradation. These results align with the views of Demel Teketay and Tesfaye Bekele (2018), who claimed that poor forest governance and rising socioeconomic demands hasten forest resource loss in Ethiopia.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This research evaluated the effects of climate change on forest productivity by employing integrated GIS, remote sensing, climate analysis, and socioeconomic techniques in Itang Special District, Gambella Region, Southwestern Ethiopia. The results showed that climatic changes and human actions have greatly impacted decreasing forest productivity and environmental decline in the research area. The analysis of GIS and remote sensing revealed significant changes in land use and land cover from 2017 to 2025. Forest cover decreased significantly from 63.71% in 2017 to 47.80% in 2025, whereas cropland increased from 31.29% to 45.48% over the same timeframe. This signifies an ongoing change of forest land into farmland. Settlement regions, inundated plant life, and aquatic areas also demonstrated gradual growth over time. The noted reduction in forest cover indicates heightened pressure on natural ecosystems and a decrease in vegetation productivity in the district.

The climate assessment also indicated rising temperature patterns and uneven rainfall distribution over the past twenty years. Average yearly temperature rose consistently, whereas precipitation turned increasingly variable and uncertain. Regions with comparatively increased rainfall exhibited improved vegetation health in contrast to regions with less rainfall. The results indicate that climate variability adversely impacts forest growth, biomass accumulation, and vegetation regeneration in the research area. The distance-from-road analysis revealed that forests near roads faced more degradation from heightened human access, urban growth, farming activities, and fuelwood collection.

Forests located further away from roads showed comparatively healthier plant conditions and improved forest regeneration. The socioeconomic results derived from structured questionnaires, FGDs, and KIIs revealed that local communities rely significantly on forest resources for fuelwood, charcoal manufacturing, grazing, building materials, and income generation. The primary factors contributing to forest degradation and decreased productivity were identified as agricultural expansion and the extraction of fuelwood. Poverty, increasing population, absence of alternative energy options, and ineffective forest management systems additionally

4.2 Recommendations

The results of this study lead to these recommendations aimed at enhancing sustainable forest management and mitigating the effects of climate change on forest productivity in Itang Special District, Gambella Region, Ethiopia. Initially, district authorities, environmental protection agencies, and forestry organizations must enhance forest conservation and management efforts in the area. As the research showed a persistent decrease in forest cover from agricultural expansion, fuelwood collection, and settlement growth, rigorous oversight and application of environmental regulations are essential. Community-driven Forest management initiatives should also be promoted to enhance local involvement in forest conservation efforts and guarantee sustainable use of forest resources.

Secondly, the promotion of sustainable farming methods is essential to reduce the transformation of forest areas into farmland. The research found that the primary cause of forest degradation in the district is agricultural expansion. Consequently, agricultural

extension services ought to encourage agroforestry methods, soil and water conservation practices, climate-resilient agriculture, and sustainable land management strategies. These approaches can enhance farming output while alleviating stress on forest ecosystems.

Third, alternative energy options need to be implemented and grown to lessen reliance on fuelwood and charcoal generation. The results showed that gathering firewood and producing charcoal significantly contribute to forest degradation in the research area. Consequently, governmental entities, non-profit organizations, and development collaborators ought to assist in the dissemination and use of energy-efficient stoves, solar power technologies, and biogas systems. Enhancing access to alternative energy sources can greatly decrease the depletion of forest resources.

Fourth, programs for reforestation and afforestation need to be enhanced in the district's degraded regions. Extensive tree planting initiatives employing native and ecologically suitable tree species are vital for reviving vegetation cover, boosting biodiversity protection, increasing carbon capture, and reducing soil erosion. Encouraging community participation in reforestation initiatives can enhance sustainability and foster local ownership.

Fifth, programs aimed at raising environmental awareness should be strengthened to enhance community comprehension of the effects of climate change and sustainable practices in forest management. The research results indicated that local communities depend greatly on forest resources due to a lack of awareness and alternative livelihoods. Consequently, ongoing environmental education and

training initiatives should be offered via schools, local authorities, agricultural extension agents, and community groups. Enhancing environmental awareness can boost community involvement in conservation efforts and the sustainable use of natural resources.

Sixth, strategies for adapting to and mitigating climate change need to be reinforced within the district. Given that the research highlighted rising temperatures and inconsistent rainfall patterns as key influences on forest productivity, local officials ought to implement efficient climate adaptation strategies. Enhanced early warning systems, improved drought management initiatives, watershed management efforts, and better climate information services should be developed to aid local communities in addressing climate-related environmental issues.

Seventh, enhancing institutional capacity and executing policies need more focus. Institutions focused on environmental protection and forestry departments need sufficient financial resources, technical assistance, qualified personnel, and advanced monitoring technologies to manage forest ecosystems effectively. Enhancing collaboration among government agencies, local communities, and development groups is crucial for better environmental governance and sustainable land-use strategies.

Ultimately, additional studies need to be carried out to enhance comprehension of climate change effects on forest ecosystems in lowland Ethiopia. Future research should utilize sophisticated GIS and remote sensing methods, detailed satellite imagery, and extended climate data records to examine vegetation dynamics, biomass variations, and land-use changes more

comprehensively. Further research on livelihood diversification, community adaptability strategies, and ecosystem restoration methods is also suggested to enhance sustainable environmental management in the Gambella Region and comparable ecological areas of Ethiopia.

Disclaimer (Artificial Intelligence)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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