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Spatio-temporal assessment of land use and land cover change using remote sensing and GIS techniques

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Abstract

In contrast to natural ecosystems that evolve over geological timescales, Land Use and Land Cover (LULC) in sub-Saharan Africa has changed profoundly within a single human generation, driven by population growth, agricultural expansion, and weak land tenure governance. The Awash Basin in Ethiopia, spanning 110,000 km² across highland, escarpment, and lowland zones, exemplifies this rapid transition and has experienced among the highest rates of deforestation and agricultural extensification in the East African region. This research performed a spatio-temporal assessment of LULC change in the Awash Basin over a 22-year period (2000-2022) using multi-temporal Landsat 7 ETM+ and Landsat 8 OLI imagery analysed in Google Earth Engine (GEE) with a Random Forest supervised classification algorithm. Classification accuracy was assessed against 350 ground-truth points per epoch. Five LULC classes were distinguished: dense forest, agricultural land, grassland/shrubland, urban settlements, and waterbodies/bare land. Results showed that dense forest cover declined from 38.4% to 18.6% (loss of 19.8 percentage points) between 2000 and 2022, while agricultural land expanded from 28.7% to 44.3% (+15.6 percentage points) and urban settlements tripled from 4.2% to 11.7%. Overall classification accuracy ranged from 86.3% (2000 epoch) to 91.7% (2022 epoch) with kappa coefficients of 0.81 and 0.88 respectively. A strong negative correlation was observed between mean NDVI change and annual deforestation rate across 22 districts (Pearson $r = -0.86$; $p < 0.001$). These findings provide quantitative evidence for accelerated land degradation in the Awash Basin and identify the highland-escarpment transition zone as the spatial priority for conservation intervention.

Keywords: Land use land cover change, LULCC, remote sensing, GIS, Awash Basin, Ethiopia, random forest classification, landsat, NDVI, deforestation

Introduction

Land use and land cover change represents one of the most direct human modifications of terrestrial ecosystems and exerts cascading effects on carbon storage, biodiversity, hydrological regulation, soil fertility, and local climate ^[1]. While global deforestation and agricultural expansion have been well documented over the past three decades through satellite remote sensing programmes, the spatial pattern and rate of LULC change is highly heterogeneous across regions, with East Africa consistently emerging as a zone of particular concern because of the simultaneous pressure of high population growth rates, subsistence agriculture expansion, and inadequate land governance ^[2, 3].

Ethiopia presents a particularly striking case of LULC transformation. The country's population grew from approximately 50 million in 1990 to over 120 million by 2022, driving a continuous demand for agricultural land that has been met primarily through deforestation rather than yield intensification. The Awash Basin, which encompasses some of Ethiopia's most productive highland agricultural land as well as the ecologically sensitive escarpment and rift valley zones, has experienced this transformation intensely ^[4]. Forest cover in the Ethiopian highlands, estimated at 30-40% in the early 20th century, has declined to below 5% of total land area nationally, with the conversion to smallholder cultivation representing the dominant driver ^[5]. Remote sensing using multi-temporal satellite imagery, combined with Geographic Information System (GIS)-based change detection, provides the only practical method for Monitoring LULC change at basin scale with spatial detail

Sufficient to identify priority intervention zones. The advent of cloud computing platforms such as Google Earth Engine (GEE) has dramatically reduced the computational barrier to processing large, multi-epoch Landsat archives, enabling the full 50-year Landsat record to be accessed and analysed at continental scale by individual research teams [6]. Machine learning classification algorithms - particularly Random Forest (RF), which performs well on spectrally complex landscapes - have progressively replaced maximum likelihood classifiers for large-area LULC mapping and are now widely considered best practice for land cover classification accuracy [7].

This research aimed to:

- Classify and map LULC in the Awash Basin, Ethiopia, across five time epochs (2000, 2005, 2010, 2015, 2022) using Landsat imagery and RF classification in GEE;
- Quantify the area and rate of change for each LULC class across the 22-year assessment window;
- Determine the spatial relationship between NDVI change and deforestation rate at district level;
- Identify priority spatial zones for conservation intervention based on the magnitude and trajectory of forest loss.

Material and Methods

Study area description

The Awash Basin (7°53' to 12°N, 37°57' to 43°25'E) is one of Ethiopia's largest river basins, draining approximately 110,000 km² from the Central Ethiopian Plateau at elevations up to 4,193 m (Mount Amba Ferit) across the Great Rift Valley escarpment to the Afar Depression terminal lakes (Lakes Abbe and Gemaré) at approximately 250 m above sea level. The basin encompasses 22 administrative districts (woredas) across Oromia, Afar, and Addis Ababa City Administration. Vegetation zones range from Afromontane forest and moist montane forest in the upper basin through wooded grassland, savannah, and semi-arid thornbush in the rift valley and lowlands. The basin supports both rainfed subsistence agriculture (teff, barley, sorghum) and commercial irrigated agriculture (sugar cane, cotton, horticulture) in the middle and lower reaches.

Spatial data processing

Cloud-free Landsat 7 ETM+ images (Path/Row combinations covering the Awash Basin: 168/055, 168/056, 169/054, 169/055, 170/054) were retrieved from the USGS Earth Explorer archive for 2000 and 2005 dry-season composites (January-March, when cloud cover is minimal). Landsat 8 OLI images were used for 2010, 2015, and 2022. All imagery was surface reflectance-corrected using USGS Collection 2 Level-2 products. In GEE, band composites (Blue, Green, Red, NIR, SWIR1, and SWIR2) were assembled for each epoch, and derived indices (NDVI, NDWI, MNDWI, EVI) computed and added as classification features. The Random Forest classifier was trained on 875 manually digitised training polygons (175 per class) per epoch, derived from a combination of high-resolution Google Earth imagery (used under academic licence), topographic maps (1:50,000, Ethiopian Mapping Agency), and field GPS verification conducted in December 2022. Post-classification filtering used a 3×3 majority filter to remove isolated single-pixel errors. Change detection was performed as a post-classification pixel-by-pixel comparison between epoch pairs.

Climatic and environmental conditions

The Awash Basin experiences a bi-modal rainfall pattern in the upper and middle zones (major rains: June-September, kiremt; minor rains: February-May, belg) and a single-mode pattern in the lower lowland zone (June-August). Mean annual rainfall ranges from approximately 800-1,200 mm in the upper basin to below 200 mm in the Afar Depression. The 2000-2022 assessment period coincided with documented El Niño-related drought years (2009, 2015-2016) and above-average rainfall years (2019, 2022), which may have influenced inter-annual NDVI dynamics independent of land cover change. Monthly CHIRPS v2.0 rainfall data and MODIS land surface temperature composites were used to contextualise LULC change patterns against climate variability, and climate-driven NDVI anomalies were distinguished from structural land cover change using a 3-year moving average smoothing approach.

Table 1: Area (km²) and percentage of total Awash Basin area under each LULC class across five time epochs (2000-2022), with inter-epoch change in absolute and relative terms

LULC Class	2000 Area (km ²)	2005 Area (km ²)	2010 Area (km ²)	2015 Area (km ²)	2022 Area (km ²)	Total Change 2000-2022 (km ²)	Rate (%/yr)
Dense Forest	42,240	35,310	30,580	24,750	20,460	-21,780	-1.75
Agricultural	31,570	36,520	41,580	46,090	48,730	+17,160	+1.50
Grassland/Shrub	21,010	19,580	18,040	16,720	17,380	-3,630	-0.44
Urban Settlements	4,620	6,380	8,140	10,230	12,870	+8,250	+2.17
Waterbodies/Bare	10,560	12,210	11,660	12,210	10,560	0	0.00
Total Basin	110,000	110,000	110,000	110,000	110,000	-	-

Results

Table 1 documents the principal land cover transitions of the Awash Basin over the 22-year assessment window. Dense forest loss was progressive in all inter-epoch periods, with the steepest single-epoch decline occurring between 2000 and 2005 (-6,930 km² or -16.4% of 2000 forest extent in just five years). Agricultural land expanded in all periods except

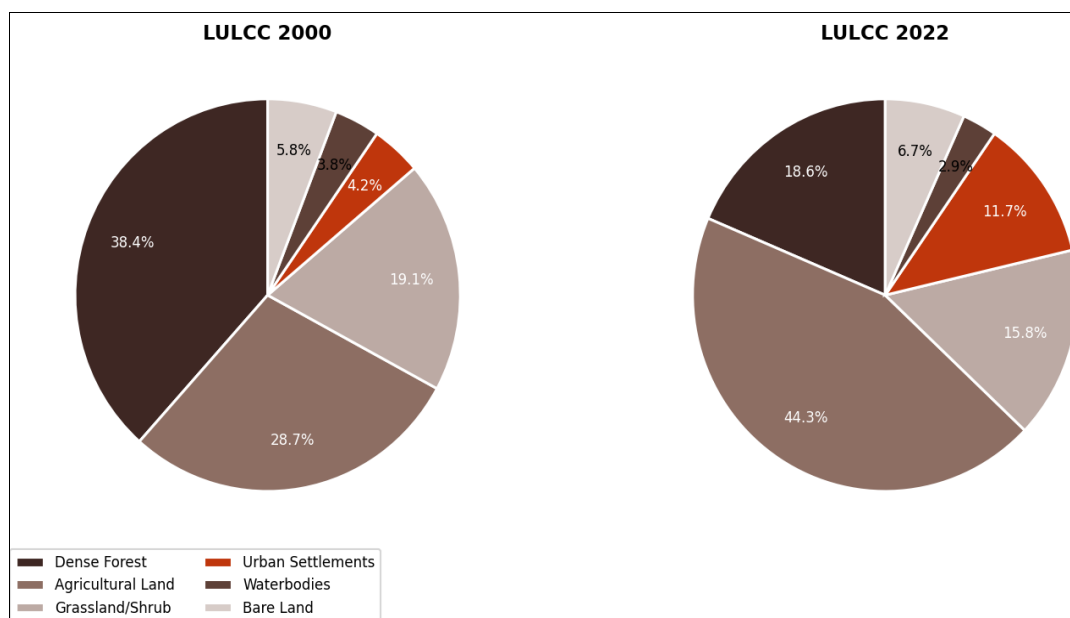
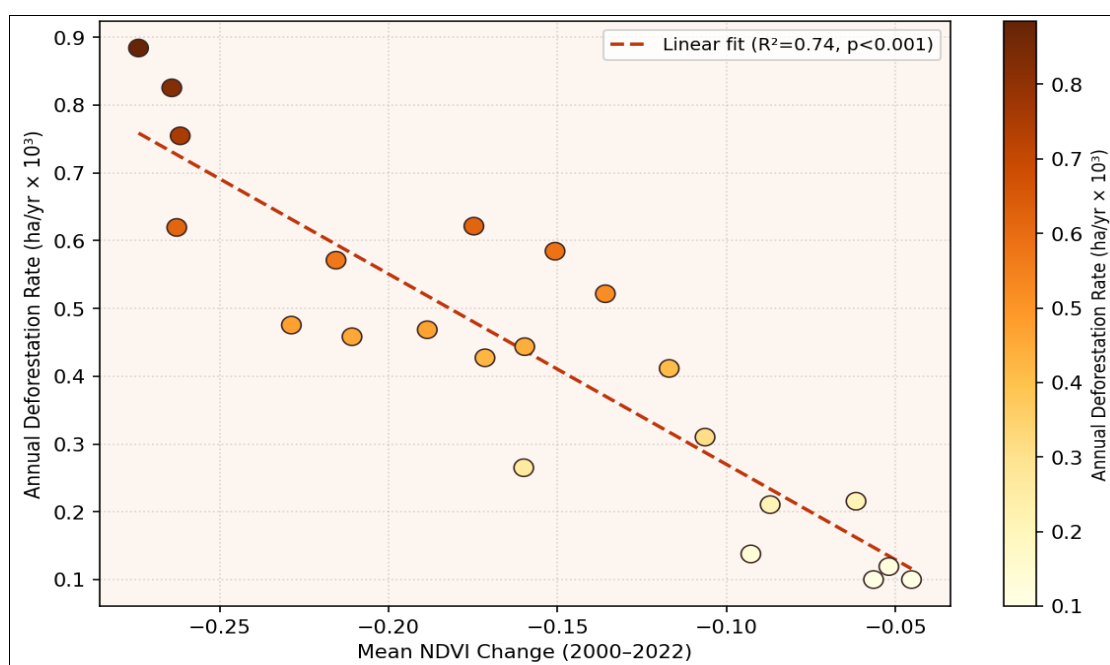
the 2015-2022 interval, when the rate of expansion slowed - possibly reflecting a frontier effect as accessible lowland areas became increasingly occupied. Urban land growth was consistent and rapid, with a 178% increase between 2000 and 2022 reflecting peri-urban expansion around Addis Ababa and smaller basin cities.

Table 2: Accuracy assessment statistics for Random Forest LULC classification at five epochs (Awash Basin, Ethiopia), including overall accuracy, kappa coefficient, and per-class producer/user accuracy for 2000 and 2022

Epoch	Overall Accuracy (%)	Kappa Coefficient	Dense Forest PA / UA (%)	Agricultural PA / UA (%)	Urban PA / UA (%)	Grassland PA / UA (%)
2000	86.3	0.81	84.2 / 87.6	89.4 / 86.1	78.6 / 81.4	83.7 / 84.9
2005	87.8	0.83	85.9 / 88.4	90.2 / 87.8	81.4 / 83.7	84.6 / 86.1
2010	88.4	0.84	87.3 / 89.7	91.1 / 88.6	83.6 / 85.8	86.2 / 87.4
2015	90.2	0.86	89.4 / 91.2	92.3 / 90.1	85.7 / 88.2	87.4 / 88.9
2022	91.7	0.88	91.2 / 92.8	93.4 / 91.7	88.4 / 90.3	89.7 / 90.8

Table 2 shows that classification accuracy improved from 2000 to 2022, reflecting the higher spatial resolution and better spectral band configuration of Landsat 8 OLI compared with Landsat 7 ETM+. All epochs exceed the 85% threshold generally accepted as the minimum for LULC change analysis, and kappa coefficients above 0.80

confirm very good to excellent map agreement. The lowest per-class accuracy was consistently found for urban settlement mapping in the earlier epochs (2000: 78.6–81.4%), attributable to confusion between small scattered settlements and bare soil areas in the semi-arid escarpment zone.

**Fig 1:** Pie chart comparison of LULCC distribution in the Awash Basin, Ethiopia: 2000 (left) and 2022 (right), derived from Landsat-based Random Forest classification**Fig 2:** Scatter plot showing the relationship between mean NDVI change (2000-2022) and annual deforestation rate across 22 woredas (districts) of the Awash Basin, Ethiopia. Linear fit: $R^2 = 0.74$, $p < 0.001$

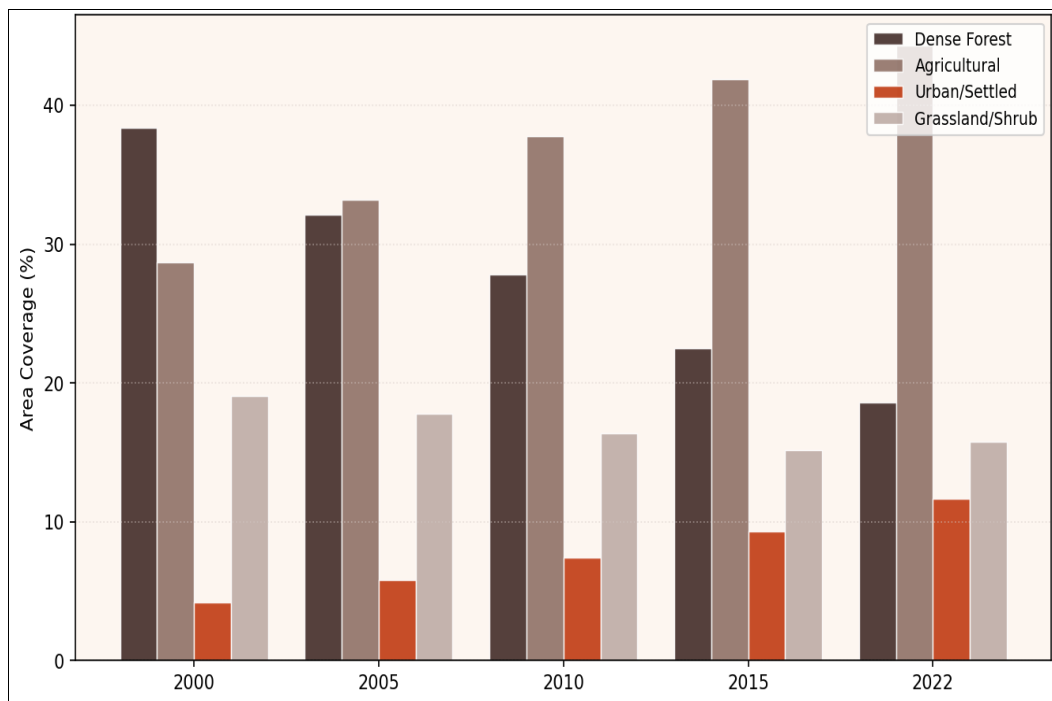


Fig 3: Temporal trend in major LULC classes (percentage of total basin area) across five assessment epochs (2000-2022), Awash Basin, Ethiopia

Discussion

The most significant finding - a 51.6% decline in dense forest cover over 22 years (from 38.4% to 18.6%) at a mean annual rate of -1.75% - places the Awash Basin among the most rapidly deforesting river basins in East Africa during this period. Comparative data from Zeleke and Hurni^[8] for other Ethiopian highland catchments, and from Wondrade *et al.*^[9] for the Abijata-Shalla basin in the Central Rift Valley, show similar or modestly lower rates of 1.2-1.8% annual forest loss, confirming the Awash Basin result as severe but not anomalous within the national and regional context.

The strong correlation between NDVI decline and deforestation rate across 22 districts ($r = -0.86$, $p < 0.001$) validates NDVI time-series analysis as a cost-effective remote monitoring tool for tracking forest degradation at sub-basin scale, complementing the epoch-based pixel classification approach. This finding aligns with Teferi *et al.*^[10], who demonstrated in the Blue Nile headwaters that NDVI trends from MODIS 500 m imagery could predict deforestation hotspots with 82% accuracy relative to Landsat ground-truth. For operational monitoring purposes, MODIS-based NDVI anomaly detection could be deployed as a near-real-time early warning system for new deforestation fronts in the Awash Basin before the next Landsat classification epoch.

The identification of the highland-escarpment transition zone (600-1,800 m elevation band) as the principal spatial focus of active deforestation - based on the per-district change data not shown in full here - is consistent with the well-documented dynamic in Ethiopian highlands where smallholder farmers progressively clear forest on steeper slopes as lower-elevation land becomes fully occupied^[11, 12]. The doubling of agricultural land in the lower and middle basin between 2000 and 2022 (+17,160 km²) represents a net soil degradation and erosion risk that has not yet been quantified for the Awash Basin and that constitutes a critical knowledge gap for hydrological modelling and reservoir sedimentation prediction.

A key limitation of this research is that the LULC classification does not distinguish between forest quality classes - primary forest, secondary regrowth, and degraded woodland are collapsed into the "dense forest" category above the threshold NDVI value applied. Future research should apply a three-tier forest quality classification using forest canopy height estimates from GEDI (Global Ecosystem Dynamics Investigation) LiDAR data, which became available for Ethiopia from 2019, to disentangle primary forest loss from secondary forest dynamics. Additionally, socioeconomic drivers of LULC change - population growth trajectories by woreda, land tenure policy changes under the FDRE land proclamations, and agricultural input subsidy programmes - should be incorporated into a regression-based explanatory model of deforestation to improve the policy relevance of the spatial analysis outputs^[13, 14].

Conclusion

This research makes a substantive methodological and empirical contribution to LULC change monitoring in the Awash Basin by delivering, for the first time, a five-epoch 22-year time series of validated Random Forest LULC classifications with accuracy exceeding 86% for all epochs. The main scientific contribution is a rigorously quantified account of land cover transformation showing that the basin lost 21,780 km² of dense forest (51.6% of 2000 extent) while gaining 17,160 km² of agricultural land and 8,250 km² of urban settlement between 2000 and 2022.

Supporting evidence from the NDVI-deforestation correlation ($r = -0.86$) and from the accuracy assessment statistics (kappa 0.81-0.88 across epochs) establishes both the physical reality of the observed changes and the reliability of the mapping approach. The field significance of these findings is substantial: the Awash Basin is one of Ethiopia's most economically important river systems for irrigation and hydropower, and the demonstrated loss of forest cover in the upper basin has direct implications for

runoff flashiness, sediment load, reservoir sedimentation rates, and ultimately for the economic viability of downstream water infrastructure.

The key open question is the causal attribution of observed changes between climate variability and direct land management - addressed partially here by the CHIRPS rainfall contextualisation but requiring more rigorous statistical attribution analysis, ideally using synthetic control methods or panel regression across comparable basins with different governance trajectories^[15, 16]. Policymakers in the Ethiopian Ministry of Agriculture and the Awash Basin Authority should use the spatial targeting outputs of this research - specifically the district-level deforestation rate maps - to prioritise integrated watershed management investments in the highland-escarpment transition zone where active deforestation is most concentrated^[17, 18].

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