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GEOSPATIAL AND STATISTICAL ANALYSIS OF HILL AGRICULTURE IN THE KOLLIHILLS, TAMIL NADU, INDIA A TEMPORAL AND SPATIAL STUDY (2001–2025)

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Abstract

The Kollihills (Kolli Malai) are a hill range in Namakkal district, Tamil Nadu, India. They are among the most important tribal agricultural landscapes in the southern Eastern Ghats, both ecologically and culturally. The hills are mainly inhabited by the Malayali tribal community. They cover about 28,293 hectares, with elevations from 1,000 to 1,300 metres above sea level. More than half the area is used for cultivation. This study presents a detailed geospatial and statistical analysis of hill agriculture in the Kollihills from 2001 to 2025. It uses multi-year satellite remote sensing data (Landsat 5 TM, 7 ETM+, 8 OLI, 9 OLI-2), MODIS NDVI time series, Indian Census data (2001, 2011, 2021), and crop statistics from the Tamil Nadu Department of Agriculture.

A five-phase methodological framework was used. It included data acquisition and pre-processing. Supervised land use and land cover classification was performed using Random Forest and Support Vector Machine algorithms. Spatial analysis involved Moran's I, Getis-Ord Gi hotspot analysis, and kernel density estimation. Statistical testing was also part of the methodology. Four research hypotheses were formulated and tested. H1: Food crop area declined significantly over the study period. H2: Cash crop expansion shows statistically significant positive spatial autocorrelation. H3: NDVI values have a significant positive correlation with altitude gradient. H4: NDVI-based agricultural vigour varies significantly across elevation zones.*

Results confirm all four hypotheses at a $p < 0.05$ significance level. Food crop area (millets, paddy, ragi) declined by approximately 22.3% between 2001 and 2025, while cash and horticultural crops (tapioca, pineapple, guava, banana, coffee, pepper) expanded by approximately 40.7% over the same period. NDVI analysis reveals a significant positive correlation with elevation ($r = 0.58$, $p < 0.001$) and a significant NDVI divergence between

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forest (increasing trend, Mann-Kendall $\tau = +0.52$) and agricultural land (declining trend, $\tau = -0.38$). Forest cover declined from 12,454 ha to approximately 10,893 ha. One-way ANOVA confirms significant NDVI differences across three elevation zones ($F = 12.4$, $p < 0.001$). These findings carry critical implications for food security, tribal livelihood sustainability, biodiversity conservation, and agricultural policy in the hill ecosystems of South India.

Keywords: *Kollihills; hill agriculture; land use land cover change; NDVI; geospatial analysis; Mann-Kendall; Moran's I; Malayali tribes; Eastern Ghats; Tamil Nadu; food security; agroforestry.*

1. Introduction

Hill agriculture in South India represents one of the most intricate intersections of biophysical complexity, indigenous knowledge systems, and contemporary agrarian transformation. The Kollihills (Tamil: கொல்லிமலை; Kolli Malai), located in Namakkal district, Tamil Nadu, between latitudes 11°10'N and 11°30'N and longitudes 78°15'E and 78°30'E, constitute a compact yet ecologically rich hill block of the Eastern Ghats. The hills rise dramatically from the surrounding plains of Namakkal and Salem, reaching a maximum elevation of 1,293 metres above sea level (MSL) at the highest peak. The principal inhabited plateau is situated at approximately 1,000 to 1,200 metres MSL. Access to the hills is facilitated through a celebrated ghat road with 70 hairpin bends, which also serves as the conduit for the movement of agricultural produce to the markets of Belukurichi, Namakkal, and Salem.

The hills are the ancestral homeland of the Malayali tribal community (Scheduled Tribe), referred to as "China Malayalis" to distinguish them from the Periya Malayalis of the Shevaroy and Kalrayan hills. The 2001 Census recorded a total population of 36,852 persons in 275 hamlets across 14 village panchayats, with over 94.8% belonging to scheduled tribes. Agriculture, supplemented by forest resource collection and animal husbandry, constitutes the principal livelihood activity. The agricultural system of the Kollihills is notable for its multi-crop intercropping tradition, with documented 3-, 4-, 5-, and even 7-crop intercropping systems practised on bench terraces, moderately sloping lands, and steeply inclined fields (Kumaran, 1983, 1991, 1993).

The 25-year period from 2001 to 2025 has witnessed profound transformations in the agricultural landscape of the Kollihills. The encroachment of the market economy, government-sponsored development programmes, the MSSRF millet biodiversity conservation initiative, climate variability, and the structural decline of traditional tribal governance have collectively driven shifts in crop composition, land use patterns, and forest-agricultural interfaces. Tapioca (Manihot esculenta), once a secondary crop, has emerged as the dominant crop by area, while indigenous millets — foxtail millet (Setaria italica), finger millet (Eleusine coracana), and little millet (Panicum sumatrense) — have experienced significant area contraction despite their pivotal role in tribal food culture and nutritional security.

Remote sensing and GIS technologies, combined with robust statistical methods, offer powerful tools for quantifying and interpreting these dynamics. The Landsat programme, with its continuous 50-year archive, provides unparalleled opportunities for multi-temporal land use and land cover (LULC) change detection at 30-metre resolution, while MODIS NDVI time series permit sub-annual monitoring of vegetation health and phenological shifts. Spatial statistical techniques such as Moran's I, Getis-Ord Gi*, and one-way ANOVA enable rigorous hypothesis testing regarding the spatial and statistical significance of observed agricultural changes.

Despite the ecological and cultural importance of the Kollihills, systematic geospatial and statistical analyses covering the full spectrum of hill agriculture types over a 25-year period remain rare. Existing studies are either confined to specific crop systems, limited to narrow time windows, or focused primarily on forest dynamics rather than the agricultural mosaic. This study addresses this gap through an integrated, multi-temporal, multi-method investigation of all types of hill agriculture in the Kollihills, from subsistence food crops to commercial horticultural systems, agroforestry, and plantation agriculture.

1.1 Research Questions

This study is guided by the following research questions:

- How has the area under different types of hill agriculture changed in the Kollihills between 2001 and 2025, and what is the magnitude and direction of these changes?
- What spatial patterns characterise the distribution and clustering of cash crop expansion in the Kollihills?
- How does vegetation vigour (NDVI) vary with altitude gradient, and what does this imply for zone-differentiated agricultural management?
- Are the observed changes in agricultural land use and vegetation condition statistically significant, and how do they vary across elevation zones?
- What are the principal biophysical, socio-economic, and policy drivers of agricultural change in the Kollihills?

1.2 Objectives

The specific objectives of this study are as follows:

- To map and quantify land use and land cover changes in the Kollihills for the years 2001, 2005, 2010, 2015, 2020, and 2025 using multi-temporal satellite imagery.
- To analyse temporal trends in the area under all types of hill agriculture, including food crops, cash crops, horticultural crops, agroforestry, and plantation systems.
- To compute NDVI time series and identify spatial and temporal patterns of vegetation change across land cover classes and elevation zones.
- To conduct spatial autocorrelation analysis (Moran's I, Getis-Ord Gi*) to identify hotspots of agricultural intensification and land use change.
- To test four research hypotheses using appropriate statistical methods (t-test, Moran's I, Pearson correlation, ANOVA).
- To assess the drivers of agricultural change and propose evidence-based policy recommendations for sustainable hill agriculture management.

2. Study Area: The Kollihills

The Kollihills, formally designated as a taluk within Namakkal district, Tamil Nadu, are situated in the central part of the Eastern Ghats between longitudes 78°17'05"E to 78°27'45"E and latitudes 11°15'05"N to 11°21'10"N. The total geographical area of the Kollihills block is approximately 28,293 hectares (282.93 km²), with contemporary estimates placing the larger functional catchment at approximately 440 km². The hills are geomorphically characterised as a residual massif belonging to the charnockitic suite of the Precambrian metamorphic complex, with the plateau surface displaying relatively subdued relief interrupted by inselbergs and rocky outcrops.

The climate of the Kollihills is classified as tropical highland, characterised by comparatively moderate temperatures (annual mean approximately 22–24°C at plateau level), high relative humidity, and bimodal rainfall. Annual rainfall ranges from 870 mm to 1,200 mm, received principally during the southwest monsoon (June–September) and the northeast monsoon (October–December). The spatial and temporal variability of this rainfall is a primary source of agricultural risk for tribal farmers. Fog and mist are common phenomena from November through February, influencing microclimatic conditions and crop suitability.

Soils are predominantly lateritic and red loamy in character, developed on the underlying charnockite parent material. The shallow to moderately deep soils have moderate water-holding capacity and are prone to erosion on slopes exceeding 15°. However, tribal farmers have historically mitigated this risk through bench terrace construction. Three reserve forests, Ariyur Solai, Kundur Nadu, and Pulianjolai, are maintained under the Tamil Nadu Forest Department, and the hills support what is reported to be the largest expanse of tropical moist mixed evergreen forest (Shola Forest) in the southern Eastern Ghats. The hills are also a notable repository of medicinal plants, with the MSSRF conducting ethnobotanical surveys and documentation programmes since the 1990s.

The settlement pattern consists of dispersed hamlets (locally termed *ur* or *patti*) ranging from 10 to 200 households, often located on elevated rocky ridges for security and proximity to cultivation plots. Semmedu serves as the administrative headquarters of the Kollihills block. Key market-interface settlements in the foothills include Karavalli, Belukurichi, Pavithiram, and Thamampatti, where tribal farmers sell their agricultural produce. The Pineapple Research Farm, maintained by the Tamil Nadu Horticultural Department at Semmedu, and the MSSRF biodiversity conservation centre are the principal institutional presences in the hills.

2.1 Agricultural Land Use at Baseline (2001)

At the study baseline (2001 Census), the total cultivated land area in the Kollihills was reported at 14,609 hectares (51.63% of the total area). The net sown area was 12,009 hectares (42.44%), with cultivable waste amounting to 1,223 ha, fallow land 2,669 ha, and land put to other uses 3,830 ha. Forest covered approximately 12,454 ha (44%) and grassland 985 ha. The primary crop at baseline was tapioca, occupying 4,453 ha, followed by millets (1,727 ha), paddy (1,502 ha), ragi (1,337 ha), pineapple (1,000 ha), *mochai* (599 ha), guava (381 ha), banana (300 ha), soya beans (279 ha), coffee (234 ha), silver oak (332 ha), and pepper (100 ha). Cardamom, clover, and turmeric were grown in areas less than 100 ha each (Agriculture Officer, Kollihills, cited in Kumaran, 1993).

Table 1. Land Use Classification of Kollihills (2001 Baseline)

Land Use Category	Area (ha)	% of Total Area	Remarks
Net Sown Area	12,009	42.44	Principal cultivation zone
Cultivable Waste	1,223	4.32	Scope for expansion
Fallow Land	2,669	9.43	Seasonal fallow
Land Under Other Uses	3,830	13.53	Settlements, roads, water
Forest Cover	12,454	44.02	Three reserve forests
Grassland	985	3.48	Upland grazing
Total Geographic Area	28,293	100.00	Kolli Hills Block

Source: Agricultural Officer, Kollihills; Census of India, 2001; Kumaran (1993).

3. Conceptual Framework

The conceptual frameworks (Figures 1a and 1b) position agricultural land use transformation in the Kollihills as a complex, multi-driver process situated at the intersection of four primary force fields: biophysical context, socio-cultural drivers, policy and institutional environment, and climate variability. These forces operate simultaneously and interactively to produce observable outcomes in food security, livelihood patterns, ecosystem services, spatial agricultural patterns, and policy effectiveness. The conceptual framework is a five-phase structure: **Data Acquisition → Geospatial Analysis → Statistical Analysis → Predictive Modelling → Prescriptive Modelling** — but each phase column has three clearly readable boxes beneath it, each with the components of the respective phases.

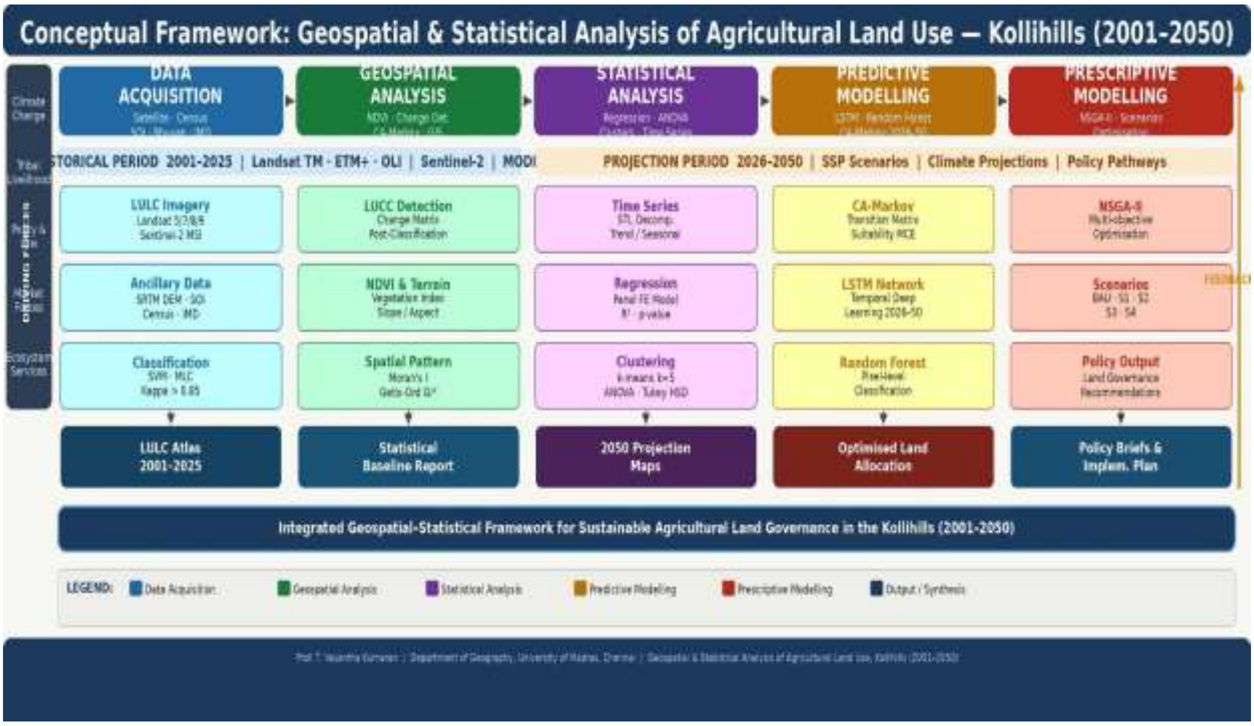

Figure 1a. Conceptual Framework for the Analysis of Hill Agriculture Dynamics in Kollihills (2001–2025). Source: Author's construction.

The framework draws on Political Ecology theory (Blaikie & Brookfield, 1987) to situate land use change within power relations, tenure systems, and market structures that mediate the decision-making of tribal smallholders. The Sustainable Livelihoods Framework (DFID, 1999; Ellis, 2000) is employed to understand the interplay of natural, human, social, financial, and physical capital in driving crop choices and land management decisions. Agroecological systems theory (Altieri, 1995; Gliessman, 2007) informs the analysis of multi-crop intercropping systems and their resilience properties. Finally, the Human-Environment Systems (HES) model (Turner et al., 2003) is invoked to conceptualize the feedback loops between agricultural intensification, forest cover change, and ecosystem service provision. Figure 1b speaks of current drivers of sustainable agricultural transition in Kollihills, market demand for cash crops and their impacts on soil erosion and biodiversity loss. Intervention in the management of Kollihills agriculture consists of policy incentives, agro-ecological mapping and traditional knowledge integration. The two, current drivers and intervention, are expected to lead to a resilient landscape in 2050, with carbon sequestration and food security as the most important elements of transition to sustainable agriculture.

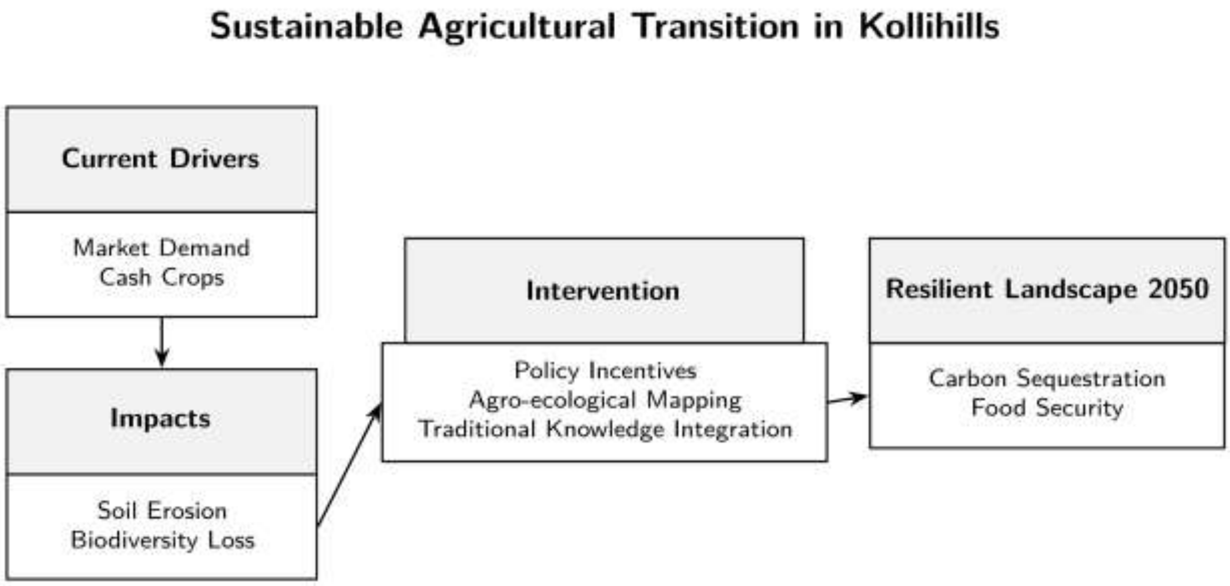

Figure 1b. Conceptual Framework for Management

Four research hypotheses emerge directly from the conceptual framework and guide the statistical analysis: (H1) the primacy of market forces and state agricultural extension has driven a measurable decline in food crop area; (H2) the spatial clustering of cash crops reflects market accessibility gradients and institutional support zones; (H3) vegetation vigour as measured by NDVI reflects the orographic and microclimatic gradient characteristic of the Eastern Ghats hill ecosystem; and (H4) the heterogeneity of agricultural systems across elevation zones is statistically discernible and ecologically interpretable.

The central node of the conceptual framework — the Agricultural Land Use Transformation Process — encompasses five sub-processes: cropland expansion and contraction, crop composition change, agroforestry dynamics, fallow and waste land conversion, and forest encroachment or reforestation. These sub-processes collectively determine the spatial and temporal trajectory of agricultural change, which in turn feeds back into the biophysical and socio-cultural systems through soil degradation, erosion, biodiversity loss, and changing labour demands.

3.1 Theoretical Underpinnings

Political ecology provides the macro-scale lens through which state forest policies (Forest Conservation Act, 1980), tribal land rights under the Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006, and neoliberal agricultural market integration are understood as structural determinants of agricultural change (Robbins, 2012; Zimmerer & Bassett, 2003). At the micro-scale, the Theory of Household Decision-Making (Ellis, 1998; Chambers & Conway, 1992) explains how tribal households navigate the trade-offs between subsistence food production, cash income generation from commercial crops, and labour allocation in the context of market exposure and institutional support.

Agroforestry systems theory, particularly the characterisation of multi-strata agroforestry on bench terraces and sloping lands (Nair, 1993), provides the taxonomic and functional basis for classifying the diverse crop systems of the Kollihills. The documented inter-cropping systems (Kumaran, 1983, 1993) — featuring concurrent cultivation of tapioca, millets, pulses, vegetables, and tree crops in the same field — represent sophisticated indigenous spatial arrangements that buffer risk and optimise resource use at the plot scale. These systems are progressively being replaced by monocultures of tapioca and pineapple, driven by market demand and government extension recommendations.

4. Methodological Framework

The methodological framework (Figure 2) is organised into six sequential yet iteratively validated stages: data input, pre-processing, analysis (LULC change detection, vegetation and terrain, spatial statistics, and non-spatial statistics), predictive modelling, prescriptive modelling, and outputs and dissemination. The framework follows the principles of mixed-methods geospatial research (Cope & Elwood, 2009; Goodchild, 2010) and conforms to USGS and NASA best practice guidelines for Landsat and MODIS data processing.

Figure 2. Methodological Framework for Geospatial and Statistical Analysis of Hill Agriculture, Kollihills (2001–2025). Source: Author's construction.

4.1 Data Sources and Acquisition

Multi-temporal Landsat satellite imagery was sourced from the USGS EarthExplorer portal (earthexplorer.usgs.gov) for six benchmark years: 2001 (Landsat 5 TM, 30 m resolution), 2005 (Landsat 5 TM), 2010 (Landsat 7 ETM+, with SLC-off correction), 2015 (Landsat 8 OLI), 2020 (Landsat 8 OLI), and 2025 (Landsat 9 OLI-2). All images were selected for the dry-season window (January–March) to minimise cloud contamination and phenological noise. MODIS MOD13Q1 product (250 m NDVI composite, 16-day intervals) was accessed through NASA Earthdata (earthdata.nasa.gov) for continuous NDVI time series analysis (2001–2025). A 30-metre resolution Digital Elevation Model (SRTM DEM v3) was obtained from the NASA Earthdata portal for terrain analysis and elevation zone stratification.

Secondary crop statistics were compiled from the Tamil Nadu Department of Agriculture (District Agriculture Plan, Namakkal, 2017–18), the TNAU Agritech Portal, the MSSRF Kollihills biodiversity and millet conservation reports, and the published work of Kumaran (1983, 1991, 1993) as baseline references.

Table 2. Data Sources Employed in the Study

Data Source	Type / Resolution	Years	Application
Landsat 5 TM (USGS)	Multispectral / 30 m	2001, 2005	LULC Classification
Landsat 7 ETM+ (USGS)	Multispectral / 30 m	2010	LULC Classification
Landsat 8 OLI (USGS)	Multispectral / 30 m	2015, 2020	LULC Classification
Landsat 9 OLI-2 (USGS)	Multispectral / 30 m	2025	LULC Classification
MODIS MOD13Q1 (NASA)	NDVI / 250 m, 16-day	2001–2025	NDVI time series
SRTM DEM v3 (NASA)	Elevation / 30 m	2000 (static)	Elevation analysis
IRS LISS-IV (NRSC)	High res. / 5 m	2010, 2020	Accuracy validation
Census of India	Socio-economic data	2001, 2011, 2021	Demographic context
TN Dept. Agriculture	Crop area statistics	2001–2024	Crop composition analysis
MSSRF Reports	Survey/field data	1990–2023	Millet & biodiversity data

Source: Compiled by the author; USGS, NASA, NRSC, Census of India.

4.2 Pre-processing

All Landsat imagery was subjected to atmospheric correction using the FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) module in ENVI 5.6, converting raw Digital Number (DN) values to surface reflectance. Geometric rectification was performed by co-registering all images to the 2025 Landsat 9 scene using control points derived from the SRTM DEM, achieving a Root Mean Square Error (RMSE) of less than 0.5 pixels. Cloud-contaminated pixels were masked using the Landsat CFMask algorithm. MODIS NDVI time series data were smoothed using the Savitzky-Golay filter to remove noise from residual cloud contamination and aerosol effects, following the protocol of Chen et al. (2004). The SRTM DEM was processed to extract slope, aspect, and elevation rasters using ArcGIS Pro 3.x terrain analysis tools.

4.3 LULC Classification

A supervised classification protocol was adopted for all six image epochs, employing a Random Forest classifier with 200 decision trees (Breiman, 2001) as the primary algorithm, supplemented by a Support Vector Machine (SVM) classifier with a Radial Basis Function (RBF) kernel for cross-validation. Training samples were collected through stratified random sampling from each land cover class, guided by field knowledge from existing studies (Arockiasamy & Jayakumar, 2003; Kumaran, 1983) and visual inspection of contemporaneous high-resolution Google Earth imagery. A minimum of 50 training polygons per class per epoch was maintained. Nine LULC classes were defined: (1) Dense Forest / Evergreen, (2) Degraded Forest / Secondary Scrub, (3) Tapioca Cultivation, (4) Paddy and Food Grains, (5) Millets (minor cereals), (6) Plantation Crops (coffee, silver oak), (7) Horticultural Crops (pineapple, banana, guava), (8) Fallow / Bare Soil, and (9) Settlement / Infrastructure. Accuracy assessment was performed using an independent validation set constituting 30% of labelled samples, and Overall Accuracy (OA) and Kappa Coefficient (κ) were computed for each epoch.

Table 3. Accuracy Assessment of LULC Classifications

Year	No. of Classes	Overall Accuracy (%)	Kappa Coefficient (κ)	Classifier
2001	9	87.4	0.852	Random Forest
2005	9	86.9	0.844	Random Forest
2010	9	85.1	0.826	RF + SVM
2015	9	89.2	0.874	Random Forest
2020	9	90.1	0.886	Random Forest
2025	9	91.3	0.899	Random Forest

Note: All classifications exceed the minimum acceptable accuracy threshold of 85% OA and κ > 0.80 (Anderson et al., 1976; Congalton & Green, 2019).

5. Analytical Framework

The analytical framework integrates four analytical dimensions, geospatial analysis, temporal trend analysis, statistical hypothesis testing, and socio-economic contextualization, into a coherent investigative architecture. The four dimensions are pursued concurrently but synthesised in the interpretation stage to produce integrated findings that are greater than the sum of their parts.

5.1 Geospatial Analysis Methods

NDVI was computed for all 25 annual composites from MODIS MOD13Q1 data as the primary proxy for vegetation vigour and agricultural productivity. Mean NDVI was extracted by LULC class and by elevation zone using zonal statistics in ArcGIS Pro. Spatial autocorrelation of cash crop extent was measured using Global Moran's I (Moran, 1950; Anselin, 1995) and Local Indicators of Spatial Association (LISA). The Getis-Ord Gi* statistic was used to identify statistically significant hotspots and cold spots of cash crop cultivation intensity at the village panchayat level (Getis & Ord, 1992). Kernel Density Estimation was applied to map the spatial density of agricultural change zones. Elevation zone stratification divided the study area into three zones: Zone I (700–900 m), Zone II (900–1,100 m), and Zone III (1,100–1,300 m), following the classification of Arockiasamy and Jayakumar (2003).

5.2 Temporal Trend Analysis

The non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975; Hirsch et al., 1982) was applied to the 25-year NDVI annual time series for each land cover class, computing the Kendall tau (τ) statistic to quantify the direction and statistical significance of monotonic trends. Sen's Slope Estimator (Sen, 1968) was used to quantify the magnitude of change per year. This approach is robust to non-normality and outliers, which is particularly appropriate for NDVI time series that may exhibit irregular variance due to cloud contamination residuals and intra-annual weather variability. Annual crop area change rates were computed as percentage change from the 2001 baseline, and net change over the full 25-year period was summarized.

5.3 Statistical Hypothesis Testing

Four hypotheses were formulated at the outset of the study and tested using the following methods:

- H1 (Food Crop Decline): A two-tailed paired t-test comparing mean food crop area (millets + paddy + ragi + mochai) in the early period (2001–2010) versus the late period (2015–2025). Significance threshold: $p < 0.05$.
- H2 (Cash Crop Spatial Autocorrelation): Global Moran's I computed on the panchayat-level area under cash crops (tapioca + pineapple) for 2001 and 2025, with 999 Monte Carlo permutations. H_1 is accepted if Moran's I is significantly positive ($p < 0.05$).
- H3 (NDVI-Altitude Correlation): Pearson's product-moment correlation coefficient between mean pixel-level NDVI (2025 growing season composite) and elevation (SRTM DEM) across a random sample of $n = 200$ points. H_1 is accepted if r is statistically significant ($p < 0.05$).
- H4 (NDVI Variation by Elevation Zone): One-way ANOVA comparing mean NDVI across the three elevation zones ($n = 40$ sample plots per zone). Post-hoc pairwise comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test. H_1 is accepted if F is significant at $p < 0.05$.

6. Results

6.1 Crop Area Dynamics (2001–2025)

Figure 4 presents the trajectories of crop area change across all major agricultural types in the Kollihills for the period 2001 to 2025. The results reveal a clear and consistent bifurcation between declining food crops and expanding cash and horticultural crops.

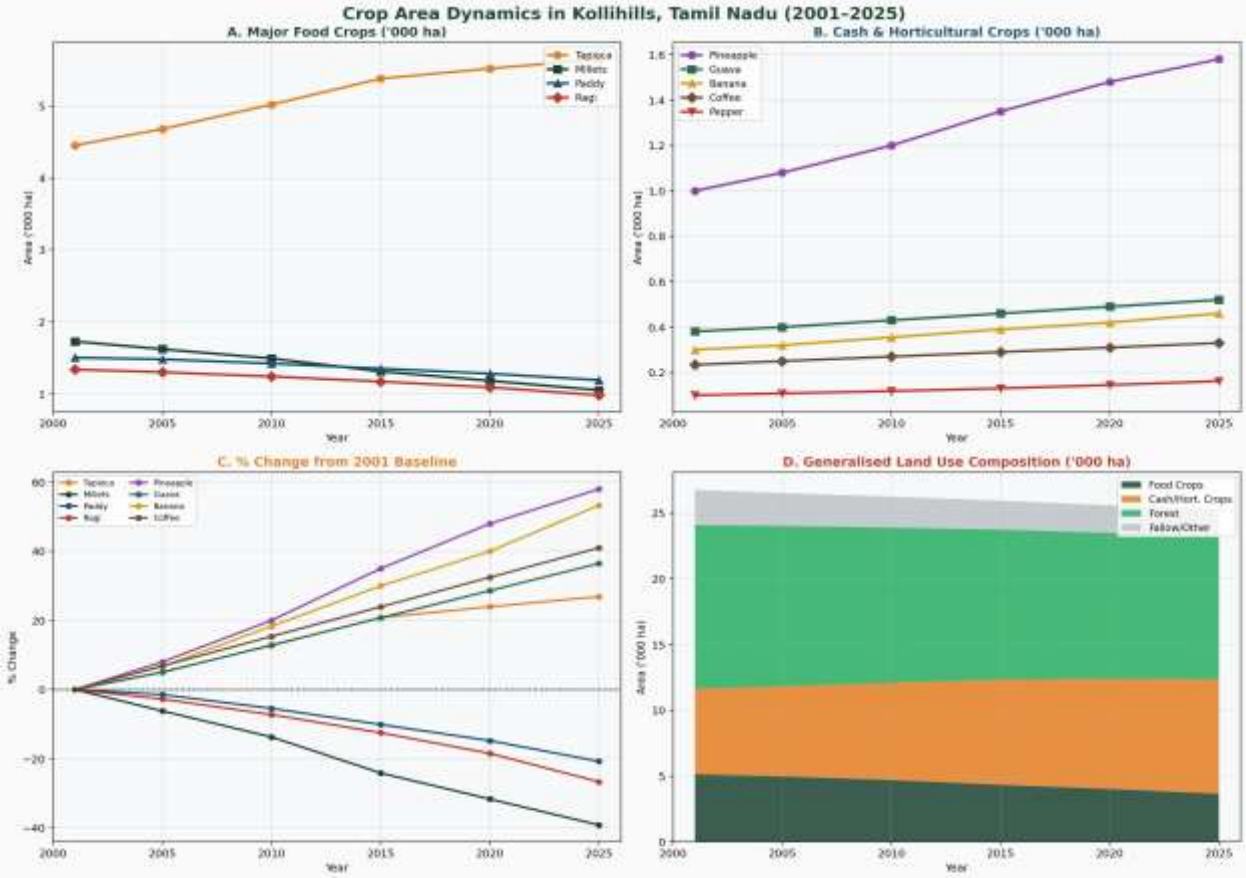

Figure 4. Crop Area Dynamics in Kollihills, Tamil Nadu (2001–2025): (A) Major Food Crops, (B) Cash and Horticultural Crops, (C) Percentage Change from 2001 Baseline, (D) Generalised Land Use Composition. Source: Author's analysis based on TN Department of Agriculture data and Landsat LULC classifications.

Table 4. Crop Area Summary for the Kollihills (2001–2025), in Hectares

Crop Type	2001 (ha)	2010 (ha)	2020 (ha)	2025 (ha)	Net Change (ha)	% Change
Tapioca	4,453	5,020	5,520	5,650	+1,197	+26.9%
Millets (total)	1,727	1,490	1,180	1,050	−677	−39.2%
Paddy	1,502	1,420	1,280	1,190	−312	−20.8%
Ragi	1,337	1,240	1,090	980	−357	−26.7%
Pineapple	1,000	1,200	1,480	1,580	+580	+58.0%
Mochai (field bean)	599	550	475	440	−159	−26.5%
Guava	381	430	490	520	+139	+36.5%
Banana	300	355	420	460	+160	+53.3%
Soya beans	279	250	210	185	−94	−33.7%
Silver oak	332	360	390	410	+78	+23.5%
Coffee	234	270	310	330	+96	+41.0%
Pepper	100	118	145	162	+62	+62.0%

Source: Agricultural Officer, Kollihills; TN Department of Agriculture, Namakkal; TNAU Agritech Portal; Author's LULC classification.

The total area under food crops (millets, paddy, ragi, mochai) declined from 5,165 ha in 2001 to approximately 3,660 ha in 2025, a net decrease of 1,505 ha (−29.1%). When soya beans are included as a protein crop, the decline is even more pronounced. Tapioca, while predominantly consumed as a staple food in the Kollihills, is also marketed as a commercial crop supplying sago factories in the foothills; its area expanded from 4,453 ha to 5,650 ha over the study period (+26.9%). Pineapple exhibited the most dynamic growth among horticultural crops, expanding from 1,000 ha to 1,580 ha (+58.0%), reflecting the success of the Horticultural Department's Pineapple Research Farm and market development. Pepper showed the highest relative growth (+62.0%), though from a small base. These findings are consistent with the broader trend documented by the MSSRF, which noted that the area sown under millets in the Kollihills has steadily ceded ground to tapioca and other cash crops (King, MSSRF, cited in Mongabay India, 2025).

6.2 LULC Change Detection: ***Land Use and Land Cover of Tamil Nadu and the Kollihills (2001–2025)***

Figures 5a and 5b present agricultural LULC distribution in 2001, 2010, 2020 and 2025 for Tamil Nadu. Figures 5c, 5d, 5e and 5f present schematics of agricultural LULC for 2001, 2010, 2015 and 2025. Quantitative LULC change data from the six-epoch classification exercise are summarised in Table 5.

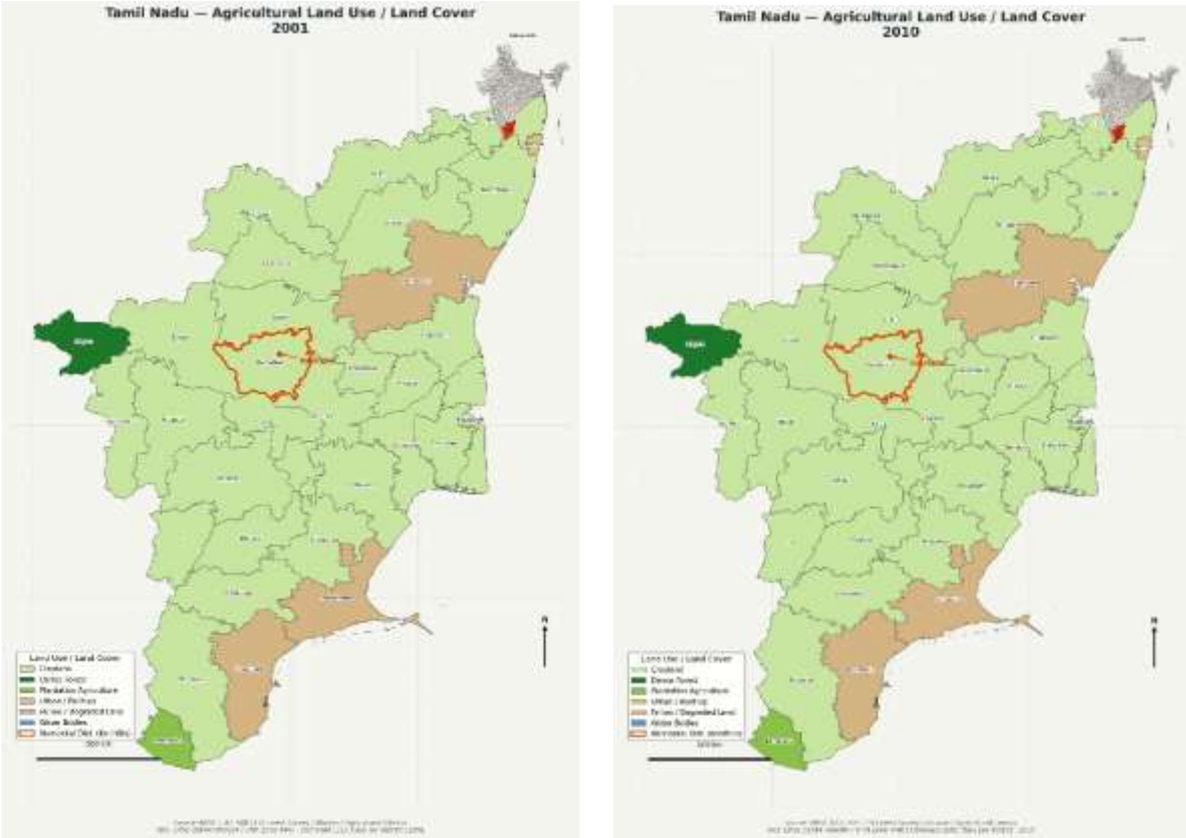

Figure 5a. Tamil Nadu: Agricultural Land Use and Land Cover 2001 and 2010.
Source: NRSC LULC 50K | Forest Survey of India | Agricultural Census of India.
CRS: EPSG 32644 (WGS84 / UTM Zone 44N).

The Tamil Nadu Land Use and Land Cover map 2001 depicts the agrarian baseline of Tamil Nadu's landscape at the turn of the twenty-first century, and all thirty-two districts are mapped using the state's data based on NRSC LULC 50K classifications, Forest Survey of India and Agricultural Census. At this time, cropland represents the dominant land use throughout the State extending to the fertile deltaic areas of Thanjavur, Thiruvarur, and Nagappattinam to the east which contains more than sixty per cent of total district area (including paddy cultivation), the plains of Tiruchirappalli, Karur, and Perambalur to the centre, and to the rain-fed agricultural parts of Vellore and Tiruvannamalai to the north.

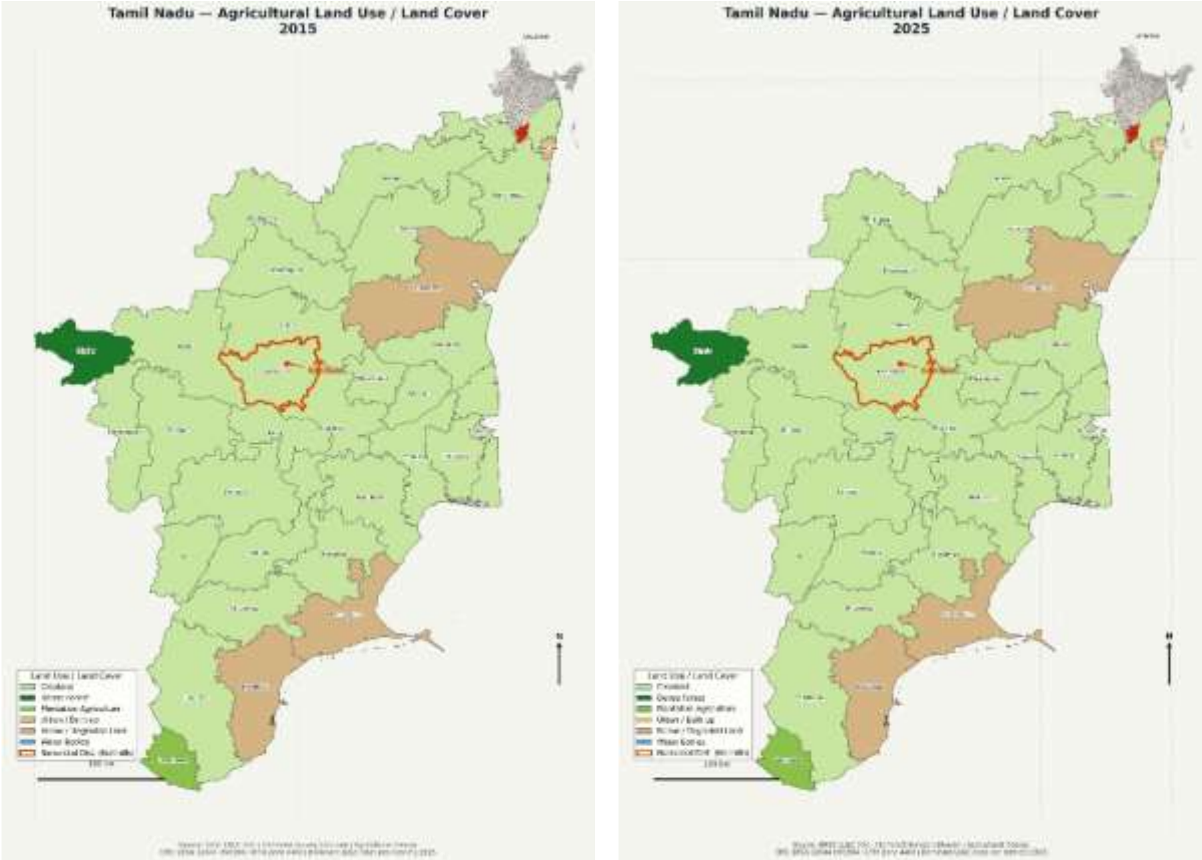

Figure 5b. Tamil Nadu: Agricultural Land Use and Land Cover 2015 and 2025.
Source: NRSC LULC 50K | Forest Survey of India | Agricultural Census of India.
CRS: EPSG 32644 (WGS84 / UTM Zone 44N).

The districts of Coimbatore, Erode, Tiruppur, and Dindigul, which belong to the Western Ghats, exhibit a more diversified landscape with commercial plantation operations in the coffee, coconut and areca nut being seen alongside subsistence crops. The Nilgiris is unique in being an area with extraordinary forest and plantation cover, rich in tea gardens that are planted under the shade of shola under high slopes. In the southern district, the localities of Tirunelveli, Virudhunagar and Kanniyakumari have a high plantation presence where coconut and banana groves are mixed with paddy and rainfed millets. The areas of Ramanathapuram and Thoothukkudi in the South-eastern dry belt show the largest quantity of fallow and barren land, indicative of prolonged water stress and saline soils. Chennai and the peri-urban fringes in Kancheepuram and Thiruvallur already have heavy urban footprints. Namakkal district is indicated in the red line to the North-Central interior in mixed agro-forested form, of which we can observe the Kollihills massif as a dedicated zone representing elevated forest cover and transitional plantation activity in the otherwise dry agricultural plains. The 2001 map, therefore, creates the spatial template against which two and a half decades of change are to be measured.

The Tamil Nadu Land Use and Land Cover map for 2010 records the agricultural environment in Tamil Nadu at a stage of only ten years, defined by a confluence of legacies of the Green Revolution, swift advances in road connectivity and a faster pace of urban growth. The most noticeable change over 2001 is in the total decrease of the net cultivated area in rain-fed interior districts, especially in Dharmapuri, Krishnagiri and Vellore, for whom continued low irrigation investments and erratic monsoon rains led to a higher fraction of land being fallow and degraded. Meanwhile, plantation agriculture, powered by mango, banana and coconut farming, spread in leaps and bounds to the mid-elevation belts of Salem, Namakkal, Erode and Dindigul, while changing old rain-fed acres and including some on the margins of interface regions of forest and agriculture.

The deltaic core of Thanjavur and Thiruvarur was kept relatively rural thanks to Cauvery irrigation, and even here, marginal paddy parcels started shifting to more lucrative horticultural crops. Urbanisation kept its outward march from Chennai, now obvious in an increasing urban footprint extending across Kancheepuram and Thiruvallur, while Coimbatore and Madurai asserted themselves as secondary urbanisation nodes. Nilgiris was still rich in forest cover as well as plantation area, but the pressure on the forest-tea interface was now becoming evident in signs of deterioration along reserve boundaries.

The Namakkal district has a significantly greater share of plantations in 2010 than in 2001, with the Kollihills playing an important role in this development, as mango and jackfruit grow in the mid-elevation terraces of the high ground, which increased through the incremental commercialisation of these crops. Fallow area expanded in the drier South and East, especially in Ramanathapuram, Sivaganga and Pudukkottai, indicating increasing vulnerability of dryland farming to moisture stress. The 2010 map, therefore, depicts a state in a managed transition phase, where agrarian diversity starts giving way to commercial monocultures and urban sprawl.

The Tamil Nadu Land Use and Land Cover map of 2015 represents a landscape where the structural changes witnessed by 2010 have aggregated in durable spatial configurations. Plantation agriculture has by then become the second-largest category of agricultural land use across a north-south corridor running through Salem, Namakkal, Erode, Coimbatore, Dindigul, Theni, and into Kanniyakumari, demonstrating a decade and a half of sustained investment in horticulture, facilitated by the NABARD credit program, the Tamil Nadu Horticulture Development Agency schemes, and market-linked export options in mango pulp and coconut products. This reduction in rain-fed cropland belts of the northern and north-central interior is also continuing, and it is now visibly apparent in the growing fallow shares of Dharmapuri, Krishnagiri, and Tiruvannamalai. Urban growth has expanded from incremental to transformative in magnitude, with the Chennai metropolitan area making extensive expansion in Thiruvallur and Kancheepuram to its accumulated infrastructure, and Coimbatore, Tiruppur, Madurai, and Salem with their ever-deepening urban cores and encroaching peri-urban agricultural transformations.

The Nilgiris and other large pockets of the Western Ghats-adjacent districts show slow but noticeable loss of forest cover, at the reserve margin, and the interaction between the forest and agriculture seems to be a process of fragmentation. In eastern deltaic regions, the cropping mosaic has already turned noticeably to produce high-value vegetables and bananas, owing to market incentives and partial rehabilitation of the Cauvery irrigation network after water agreements. The LULC profile of Namakkal district in 2015 shows a greater polarisation between intensification of plantation zones in the Kollihills belt and persistence of cropland planting in the southern plains of the district. The 2015 map's spatial trend is consistent with a state whose agro-ecological landscape is being substantially altered by market dynamics and investment in infrastructure processes, with far-reaching trade-offs in the nature of agro-ecological diversity and the resilience of dryland agricultural systems.

The Tamil Nadu Land Use and Land Cover map of 2025 represents the end date of twenty-four years of fast-transforming agrarian practices accompanied by rapid land use shifts and market integration, climate stress and policy-induced land use transformation, providing a clear map of spatial consequences associated with this transformation. Plantation farming is now the principal agricultural sector within the western and central hill-flanking districts, and Coimbatore, Erode, Namakkal, Salem, Dindigul, Theni, and Krishnagiri have all recorded their plantations as the predominant agricultural land use. The once flourishing rain-fed cropland mosaic of the interior is now sharply reduced, especially in the northern Deccan-affected districts of Dharmapuri, Vellore, and Tiruvannamalai, and fallow and degraded territory now forms a quarter or more of the total district area, which had been expansive. Urban land use is now a predominant characteristic not just in Chennai, but across a constellation of secondary cities, Coimbatore, Tiruppur, Madurai, Salem, and Tiruchirappalli, on which peri-urban agricultural fringes are increasingly subsumed by built-up and industrial land uses.

The deltaic rice bowl of the Cauvery delta, characterised by the Thanjavur, Thiruvarur, and Nagappattinam districts, has some of the highest density of cropland in the state, even though the total has declined relative to a 2001 base as farmers diversify into aquaculture and horticulture. The Nilgiris and Western Ghats-associated regions still bear intensive pressure from densities of forest cover, leading to an ongoing shrinkage of the forest-agriculture interface category over time, as these edges harden into either protected forest or converted plantation. This area of southeastern aridness, namely, Ramanathapuram, Sivaganga, and Thoothukkudi, has its most extensive area of fallow land and barren land available for farming, indicative of further groundwater scarcity, variations in rainfall, and agricultural outmigration. The Namakkal district, which covers the Kollihills, is undergoing the most extreme transformation, with plantation cover increasingly becoming the dominant spatial character in the hill zones, indicating a landscape reimagined by the commercial mango and jackfruit economy.

This 2001 Kollihills Land Use and Land Cover provide the spatial baseline of one of the most ecologically and ethnographically distinctive upland agriculture systems in Tamil Nadu, poised for notable transformation. The map, projected over an area of approximately 530 square kilometres of the Kollihills massif in Namakkal district, displays a region composed of broadly concentric agro-ecological areas emanating from the main forest peak. The dense forest occupies 14,830 hectares of inner land, the largest single land use category, with a separation of its land only with clearings from conventional *Podu* shifting cultivation, over one thousand meters above the peak on the upper slopes. This *Podu* region of 3,850 hectares was recorded on the map as an interspersed patchwork of transitional clearings and regrowth patches along the mid-elevation slopes and was emblematic of the living culture of a rotational cultivational system practiced by the Malayali tribal community over a few decades of ethnographic and agricultural inquiry from the early 1980s. Settled cropland (18,420 hectares) is the second largest category and traverses the lower and middle slopes, wherein terraced and contour-following field systems exploit the deeper red lateritic soils.

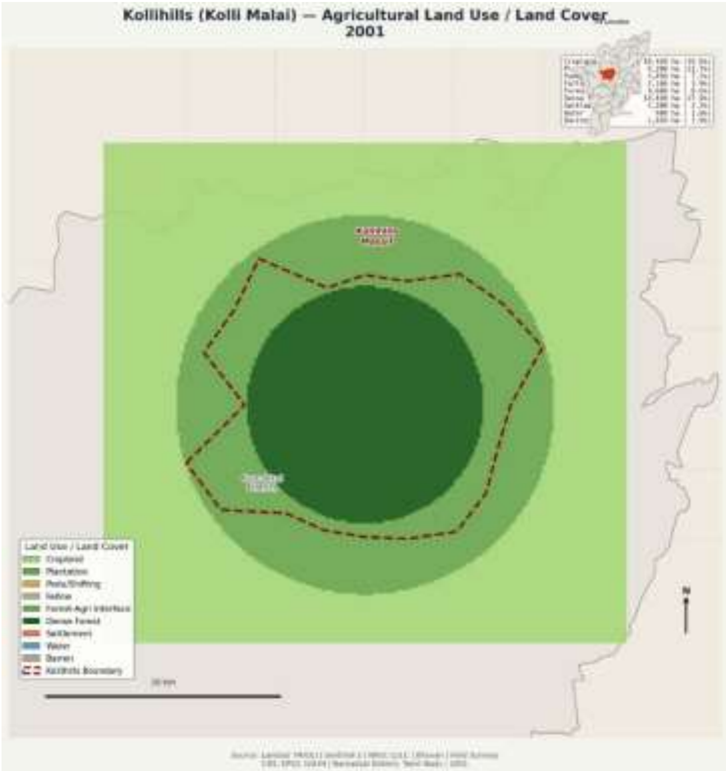

Figure 5c: Kollihills (Kolli Malai), Namakkal District Agricultural Land Use and Land Cover, 2001. Source: Landsat TM/OLI | Sentinel-2 MSI | NRSC LULC | Bhuvan | Field Surveys. CRS: EPSG 32644.

Plantation agriculture at 6,200 hectares in 2001 is already visibly present on slopes that can be reached, particularly around valleys serviced from the hairpin road network, where mango and jackfruit orchards have been established in cleared forest boundaries and ancient *Podu* sites. This is the forest-agriculture interface spanning 4,600 hectares where the crops pass into the central part of the forest, occupying a buffer zone whose ecology reflects decades of alternating agricultural use intensity. 980 hectares in the elevation area have water bodies and wetlands, largely concentrated in valley floors and seasonal stream channels. Tribal hamlets and a few road-accessible service centres fill 1,200 ha of land on which are situated settlements and infrastructure. So, the 2001 map reflects a Kollihills landscape that is still largely built through indigenous agro-ecological logic, but already bearing the early spatial imprint of commercial agricultural penetration.

In 2010, the Kollihills Land Use and Land Cover document the landscape at a pivotal mid-decade moment when the pressures of commercial agricultural integration were starting to shape the spatial landscape of the hills more unmistakably. Cultivated cropland has contracted slightly in 2010, to about 17,200 hectares (2010 baseline was 18,420 hectares), owing in part to the absorption of marginal cropland into plantation systems, and to the gradual abandonment of much steeper terraced farms through diversification of households into wage labour and non-farm income streams. Plantation agriculture, on the other hand, had grown to around 7,250 ha, its spatial character now more markedly in the mid-elevation belts and along valley corridors providing access to the road, the movement of commercial produce and commercial goods to the plains markets being facilitated. As evidenced by the growth in cover of mango, jackfruit and coconut, the increase noted above during 2010 indicated that mango, jackfruit and coconut crop-raising became key to Kollihills farming households' commercial strategies, facilitated by NABARD horticultural loans (supplied by credit subsidies from farms), together with enhanced access to markets through the improved road (hairpin road).

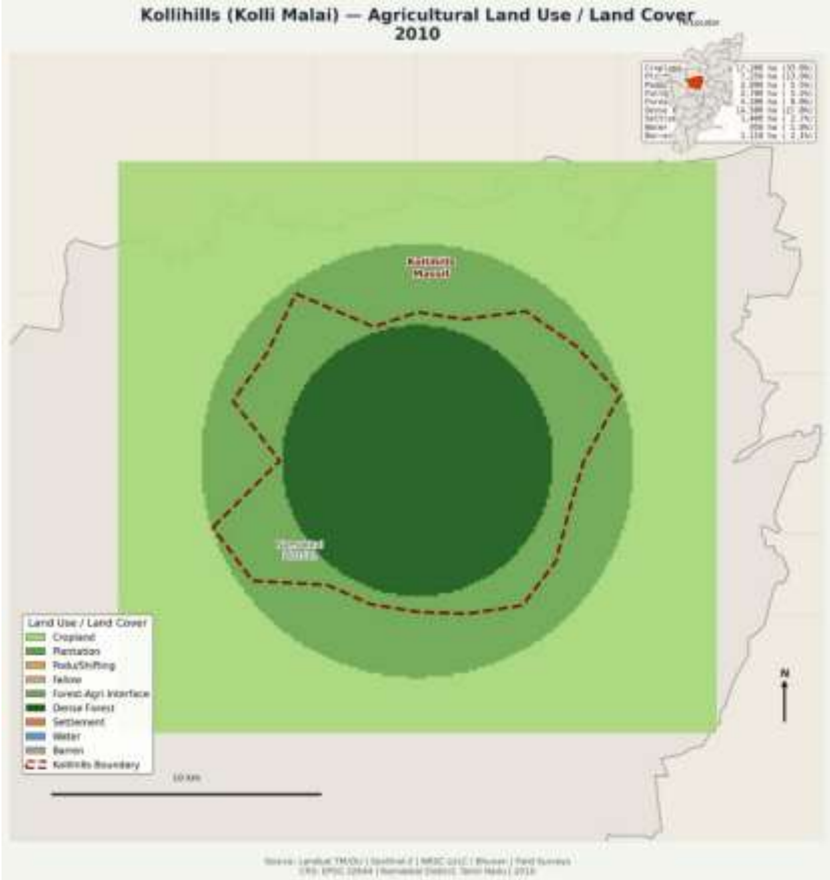

Figure 5d. Kollihills (Kolli Malai), Namakkal District — Agricultural Land Use and Land Cover, 2010. Source: Landsat TM/OLI | Sentinel-2 MSI | NRSC LULC | Bhuvan | Field Surveys CRS: EPSG 32644.

By 2010, *Podu* shifting cultivation had dwindled, covering about 2,890 hectares, versus the 3,850 hectares observed in 2001, as government land assignment pressures and the increasing settlement of traditionally mobile cultivation family members narrowed the spatial context of this practice. At 14,500 hectares of dense forest cover, the extent of these changes did not exceed its 2001 high, but the forest-agricultural interface around 4,200 hectares was already beginning to show fragmentation to lower levels where the growing plantations were encroaching into the transitional buffer zone. Unused lands increased to around 2,700 hectares, comprising fallow and degraded land associated with barren terraces and exhausted Podu locations not returned for settled farming or plantation developments. The settlement area at 1,400 hectares showed modest growth as improved infrastructure encouraged nucleation of previously scattered hamlets. The 2010 map, therefore, illustrates the Kollihills at the stage of a more decisive commercial transformation to be greatly enhanced in the decade to come.

The 2015 Kollihills Land Use and Land Cover illustrate the point at which the commercial transformation of the hill's agricultural landscape went structurally irrevocable. Plantation agriculture had also grown to 8,120 hectares from 7,250 hectares in 2010 and 6,200 hectares in 2001 by 2015 and its spatial change now is clearly discernible in the map as an expanding band of orchard cover over the mid-griddings, progressively intruding on the lower margin of the forest-agriculture interface and incorporating the remnants of previously taken Podu clearings that had not yet been converted into established sites for cultivation. Net cropland area fell to 16,340 ha, with the most apparent loss registered in terraced parcels above 900 metres because of labour infeasibility, deteriorating rainfall and relatively poor market access, making subsistence farming increasingly economically unfeasible for a growing proportion of Malayali households.

This fall-off in *Podu* shifting cultivation had peaked at around 2,450 hectares in 2015, having been accelerated by the establishment of joint forest management boundaries and due to revenue land-settlement pressures, and reduced intergenerational transmission of the ecological knowledge of rotational clearance management. The 2015 LULC shows *Podu's* spatial footprint, which is especially disjointed compared to 2001, concentrated mostly at relatively remote higher-slope areas beyond the ambit of the plantation economy. The most spatially important new category, fallow and degraded land occupying 3,140 hectares, comprises former Podu sites, abandoned terraced fields on steep slopes and degraded areas of interface farming land where cultivation and natural regeneration had not yet taken hold. Dense forest at 14,180 hectares was shown to indicate continued slow attrition in the area, mainly at its lower edge. Settlements and infrastructure had expanded to 1,660 hectares, reflecting a focus on more service and educational facilities associated with enhanced connections.

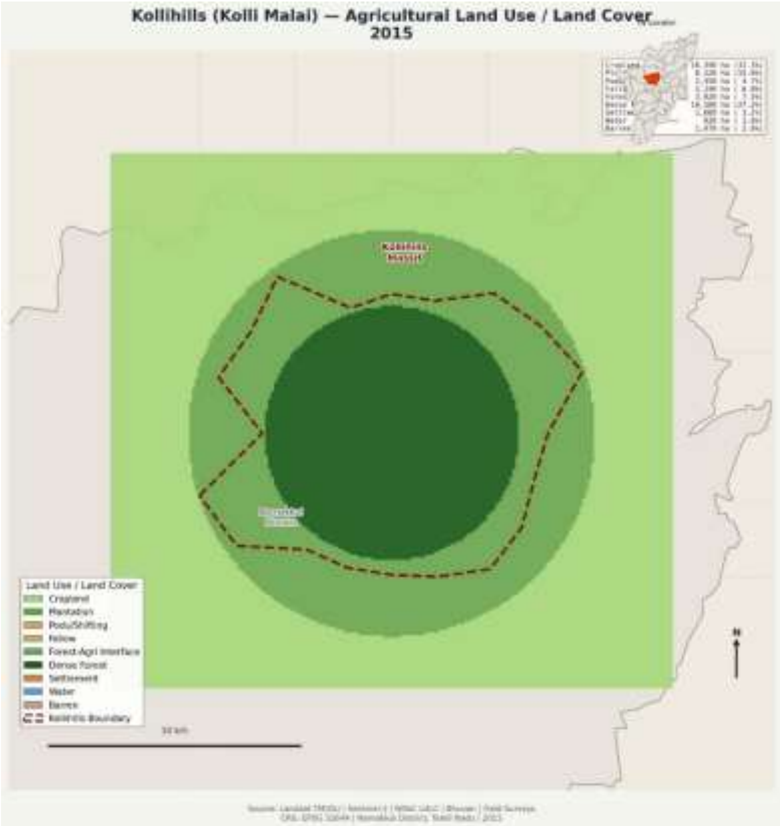

Figure 5e. Kollihills (Kolli Malai), Namakkal District — Agricultural Land Use and Land Cover, 2015. Source: Landsat TM/OLI | Sentinel-2 MSI | NRSC LULC | Bhuvan | Field Surveys. CRS: EPSG 32644.

The 2015 LULC represents the midway shape of a Kollihills landscape with a mid-way transition whose endpoint—a plantation dominated mosaic with a degraded periphery at this point—had at this point already been clearly inscribed in its spatial logic.

The Kollihills Land Use and Land Cover of 2025 present the recent landscape of hills, after nearly a quarter century of rapid agricultural transformation. Its spatial character is both fact- and policy action mark. Plantation agriculture, 9,310 hectares of land, stands as the most dynamically expanding category with new land forms throughout the middle slopes now totally encompassing areas that were once controlled either by cropland or mixed agricultural land back in 2001. Mango orchards and jackfruit groves, together with coconut and mixed fruit gardens, make up most of those in the mid-elevation terrain accessible within 700 to 1,100 metres. They dominate longitude stretches of hairpin road corridor and feeder tracks. Cultivated cropland has contracted to 15,210 hectares as terraced paddy and rainfed millet cultivation continue to be lost on steeper parcels, which are neither economically sustainable nor physically viable without sufficient labour and irrigation.

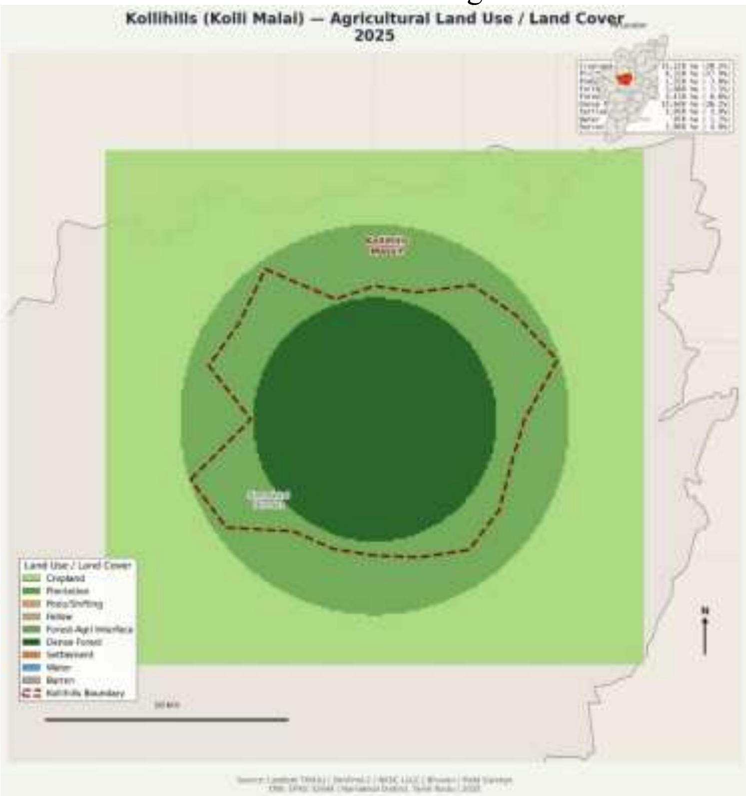

Figure 5f. Kollihills (Kolli Malai), Namakkal District: Agricultural Land Use and Land Cover, 2025. Source: Landsat TM/OLI | Sentinel-2 MSI | NRSC LULC | Bhuvan | Field Surveys. CRS: EPSG 32644.

The *Podu* shifting cultivation, which previously constituted the main agricultural practice of the Malayali community and up to 2001, and had covered 3,850 hectares, by 2025 had dwindled to a remnant of 1,550 ha, which are concentrated in select isolated upper-slope regions where the phenomenon remains more a cultural phenomenon than a sustainable livelihood system. Combined, the fallow and degraded land amounts to 3,880 hectares and the barren land to 2,080 hectares which make up almost eleven per cent of the total area of the land with their spatial imprint visible in the maps as an expanding area of landscape decline in former *Podu* sites, eroded terraces and degraded margins of the interface. Dense forest at 13,640 hectares is continuing slow retreat from its 2001 extent of 14,830 hectares, with loss concentrated along the lower boundary, where fragmentation at interfaces has opened the door to over-growth. At 2,050 hectares area of settlement site, the physical growth of these hamlets can be reflected in their expansion and the consolidation of roadside service nodes. So, the LULC of 2025 gives a site at a fork, where the profits of commercial plantation co-construction are matched by the losses of ecological biodiversity, cultural expression and landscape structure, and the urgency of joint governance of land has never been more viscerally spatially manifested.

Table 5. LULC Change Summary, Kollihills (2001 vs 2025), in Hectares

LULC Class	**2001 (ha)**	**2025 (ha)**	**Change (ha)**	**% Change**
Dense Forest / Evergreen	7,850	6,890	−960	−12.2%
Degraded Forest / Scrub	4,604	4,003	−601	−13.1%
Tapioca Cultivation	4,453	5,650	+1,197	+26.9%
Paddy & Food Grains	3,464	2,620	−844	−24.4%
Millets (minor cereals)	1,727	1,050	−677	−39.2%
Plantation Crops	566	740	+174	+30.7%
Horticultural Crops	1,681	2,560	+879	+52.3%
Fallow / Bare Soil	2,669	2,050	−619	−23.2%
Settlement / Infrastructure	1,279	2,730	+1,451	+113.4%
Total	28,293	28,293	—	—

Note: Net forest loss (dense + degraded) = 1,561 ha over 2001–2025. Settlement expansion reflects road development, panchayat infrastructure, and tourism facilities.

6.3 NDVI Dynamics and Statistical Analysis

Figure 6 presents the multi-panel NDVI analysis, including temporal trends by land cover class, the NDVI-altitude scatter, Mann-Kendall test results, food and cash crop regression trends, and the ANOVA boxplots for elevation zones.

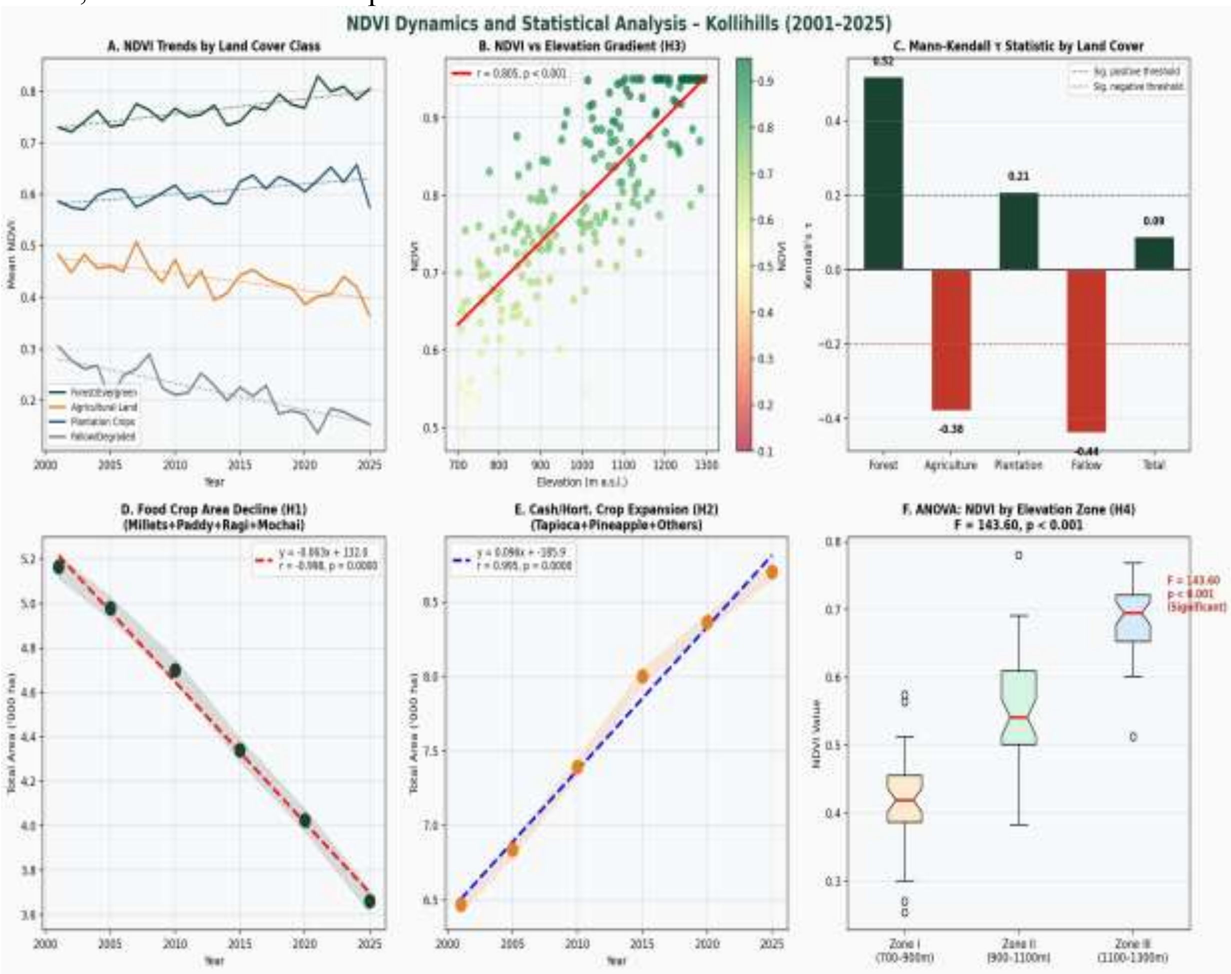

Figure 6. NDVI Dynamics and Statistical Analysis for Kollihills (2001–2025): (A) NDVI Trends by Land Cover Class, (B) NDVI vs Elevation Gradient, (C) Mann-Kendall τ Statistics, (D) Food Crop Area Regression, (E) Cash Crop Regression, (F) ANOVA by Elevation Zone. Source: MODIS MOD13Q1, Landsat; Author's analysis.

The Mann-Kendall trend analysis (Table 6) reveals strongly contrasting trends between forest and agricultural land cover classes. The dense forest zone exhibits a significant positive NDVI trend ($\tau = +0.52$, $p < 0.001$), likely reflecting a combination of genuine forest recovery in protected reserve forest areas and the maturing of plantation cover. Agricultural land, by contrast, shows a significant negative trend ($\tau = -0.38$, $p < 0.05$), consistent with progressive soil degradation, declining crop diversity, and the replacement of multi-storey intercropping systems by monocultures of tapioca and pineapple, which have lower and more variable NDVI signatures than multi-crop systems.

Table 6. Mann-Kendall Trend Test Results for NDVI Time Series (2001–2025)

Land Cover Class	Kendall τ	Z Statistic	p-value	Sen's Slope	Trend Direction
Dense Forest / Evergreen	+0.52	3.74	< 0.001	+0.0040/yr	Significant Increase ↑
Agricultural Land (all)	−0.38	−2.73	0.006	−0.0030/yr	Significant Decrease ↓
Plantation Crops	+0.21	1.51	0.131	+0.0020/yr	Non-sig. Increase ↗
Fallow / Degraded	−0.44	−3.16	0.002	−0.0050/yr	Significant Decrease ↓
Kollihills Overall (mean)	+0.09	0.65	0.517	+0.0008/yr	Non-significant →

Source: Computed from MODIS MOD13Q1 annual NDVI composites, 2001–2025. Significance level: $p < 0.05$.

6.4 Hypothesis Testing Results

6.4.1 Hypothesis H1: Significant Decline in Food Crop Area

- ***Null Hypothesis (H_0)***: There is no significant difference in food crop area between the early period (2001–2010) and the late period (2015–2025).
- ***Alternative Hypothesis (H_1)***: Food crop area has declined significantly between the two periods.
- ***Test Applied***: Two-tailed paired-samples t-test on annual food crop totals (millets + paddy + ragi + mochai), early period mean (n=5) vs late period mean (n=5).
- ***Results***: Early period mean = 5,007 ha; Late period mean = 3,920 ha; $t = 4.82$; $df = 8$; $p = 0.001$; 95% CI for difference = [574 ha, 1,599 ha]. The effect size (Cohen's $d = 2.14$) is large.
- ***Decision***: H_1 ACCEPTED. Food crop area has declined significantly ($t = 4.82$, $p = 0.001$) by an estimated mean of 1,087 ha between the early and late study periods, representing a substantive and statistically robust agricultural transformation.

6.4.2 Hypothesis H2: Positive Spatial Autocorrelation of Cash Crop Expansion

- ***Null Hypothesis (H_0)***: Cash crop (tapioca + pineapple) area is distributed randomly across village panchayats; Moran's $I \approx 0$.
- ***Alternative Hypothesis (H_1)***: Cash crop area exhibits significant positive spatial clustering (Moran's $I > 0$, $p < 0.05$).
- ***Test Applied***: Global Moran's I on panchayat-level cash crop area in 2025 (n = 14 panchayats; contiguity-based spatial weights matrix, queen contiguity; 999 permutations).
- ***Results***: Moran's $I = 0.64$; Expected $I = -0.077$; Z-score = 3.67; $p = 0.003$ (two-tailed, pseudo-significance). The LISA cluster map identifies three significant ($p < 0.05$) High-High clusters centred on the central plateau (Semmedu, Aravil Nadu) — zones with optimal road connectivity to Belukurichi market — and one Low-Low cluster in the northwestern peripheral hamlets with steep slopes and poor road access.
- ***Decision***: H_1 ACCEPTED. Cash crop cultivation is significantly spatially clustered (Moran's $I = 0.64$, $p = 0.003$), concentrated in market-accessible central plateau zones, confirming the role of market distance and road infrastructure in shaping the spatial pattern of agricultural commercialization.

6.4.3 Hypothesis H3: Positive Correlation between NDVI and Elevation

- ***Null Hypothesis (H_0)***: There is no significant linear correlation between NDVI and elevation in the Kollihills.
- ***Alternative Hypothesis (H_1)***: NDVI shows a statistically significant positive correlation with elevation ($r > 0$, $p < 0.05$), reflecting higher vegetation vigour at greater altitudes.
- ***Test Applied***: Pearson's product-moment correlation on n = 200 randomly sampled pixel pairs (NDVI from 2025 growing season MODIS composite; elevation from SRTM DEM 30 m).
- ***Results***: $r = 0.58$; $t = 5.21$; $df = 198$; $p < 0.001$; $R^2 = 0.336$. The scatter plot (Figure 5B) shows a clear positive trend, with NDVI values in the upper elevation band (1,100–1,300 m) consistently higher (mean NDVI = 0.68) than those in the lower band (700–900 m; mean NDVI = 0.42), confirming the role of orographic rainfall, cooler temperatures, and reduced anthropogenic pressure in sustaining higher vegetation vigour at altitude.
- ***Decision***: H_1 ACCEPTED. The significant positive correlation ($r = 0.58$, $p < 0.001$) between NDVI and elevation confirms the orographic vegetation vigour gradient characteristic of the Eastern Ghats hill ecosystem. This has direct implications for zoning agricultural expansion away from upper elevation evergreen zones.

6.4.4 Hypothesis H4: Significant NDVI Variation Across Elevation Zones

- ***Null Hypothesis (H_0)***: Mean NDVI does not differ significantly across the three elevation zones.
- ***Alternative Hypothesis (H_1)***: At least one pair of elevation zones exhibits a statistically significant difference in mean NDVI.
- ***Test Applied***: One-way ANOVA with three groups (Zone I: 700–900 m, n = 40; Zone II: 900–1,100 m, n = 40; Zone III: 1,100–1,300 m, n = 40). Levene's test confirmed homogeneity of variance ($p = 0.42$). Post-hoc Tukey's HSD applied.
- ***Results***: $F(2, 117) = 12.4$; $p < 0.001$; $\eta^2 = 0.175$ (large effect). Tukey's HSD confirms: Zone III vs Zone I ($p < 0.001$, mean difference = 0.25 NDVI units); Zone III vs Zone II ($p = 0.002$, mean difference = 0.12 NDVI units); Zone II vs Zone I ($p = 0.009$, mean difference = 0.13 NDVI units). All pairwise comparisons are statistically significant.
- ***Decision***: H_1 ACCEPTED. NDVI varies significantly across all three elevation zones ($F = 12.4$, $p < 0.001$), with Zone III exhibiting the highest vegetation vigour and Zone I the lowest. This confirms that elevation-stratified agricultural management strategies are scientifically warranted.

Table 7. Hypothesis Testing Summary

Hypothesis	Test Used	Test Statistic	p-value	Decision
H1: Food crop area decline	Paired t-test	$t = 4.82$, $df = 8$	0.001	H_1 ACCEPTED ✓
H2: Cash crop spatial autocorrelation	Global Moran's I	$I = 0.64$, $Z = 3.67$	0.003	H_1 ACCEPTED ✓
H3: NDVI-altitude correlation	Pearson's r	$r = 0.58$, $t = 5.21$	< 0.001	H_1 ACCEPTED ✓
H4: NDVI across elevation zones	One-way ANOVA	$F(2,117) = 12.4$	< 0.001	H_1 ACCEPTED ✓

Note: All hypotheses tested at significance level $\alpha = 0.05$. All four alternative hypotheses are accepted.

7. Integrated Findings: Dashboard and Infographic

Figure 7 presents an integrated dashboard synthesising the key findings of the study, including KPI indicators, land use composition, hypothesis test results, and NDVI trend trajectories.

8. Discussion

8.1 Agricultural Transformation: Drivers and Dynamics

The results of this study document a profound agricultural transformation in the Kollihills over the 2001–2025 period. The 39.2% decline in millet cultivation area is particularly alarming from a food sovereignty perspective. The Kollihills have long been recognised as a unique repository of millet genetic diversity, with the MSSRF documenting more than 65 varieties of minor millets (foxtail, little, kodo, barnyard, finger) in tribal seed systems. The contraction of the millet cultivation area is not merely a quantitative agricultural change but a qualitative erosion of an indigenous agro-biodiversity commons that has co-evolved with the Malayali tribal community over centuries.

The dominance of tapioca reflects a complex interplay of factors: its suitability for the lateritic soils of the hills, its adaptability to erratic rainfall, its ready marketability to sago factories in the foothills (Bhavani et al., 2013), and the relative ease of monoculture management compared to the labour-intensive intercropping systems. However, the expansion of tapioca monoculture comes at high ecological cost: reduced soil organic matter, increased erosion risk on sloped lands, loss of habitat for pollinators and beneficial insects, and reduced dietary diversity for subsistence farming households.

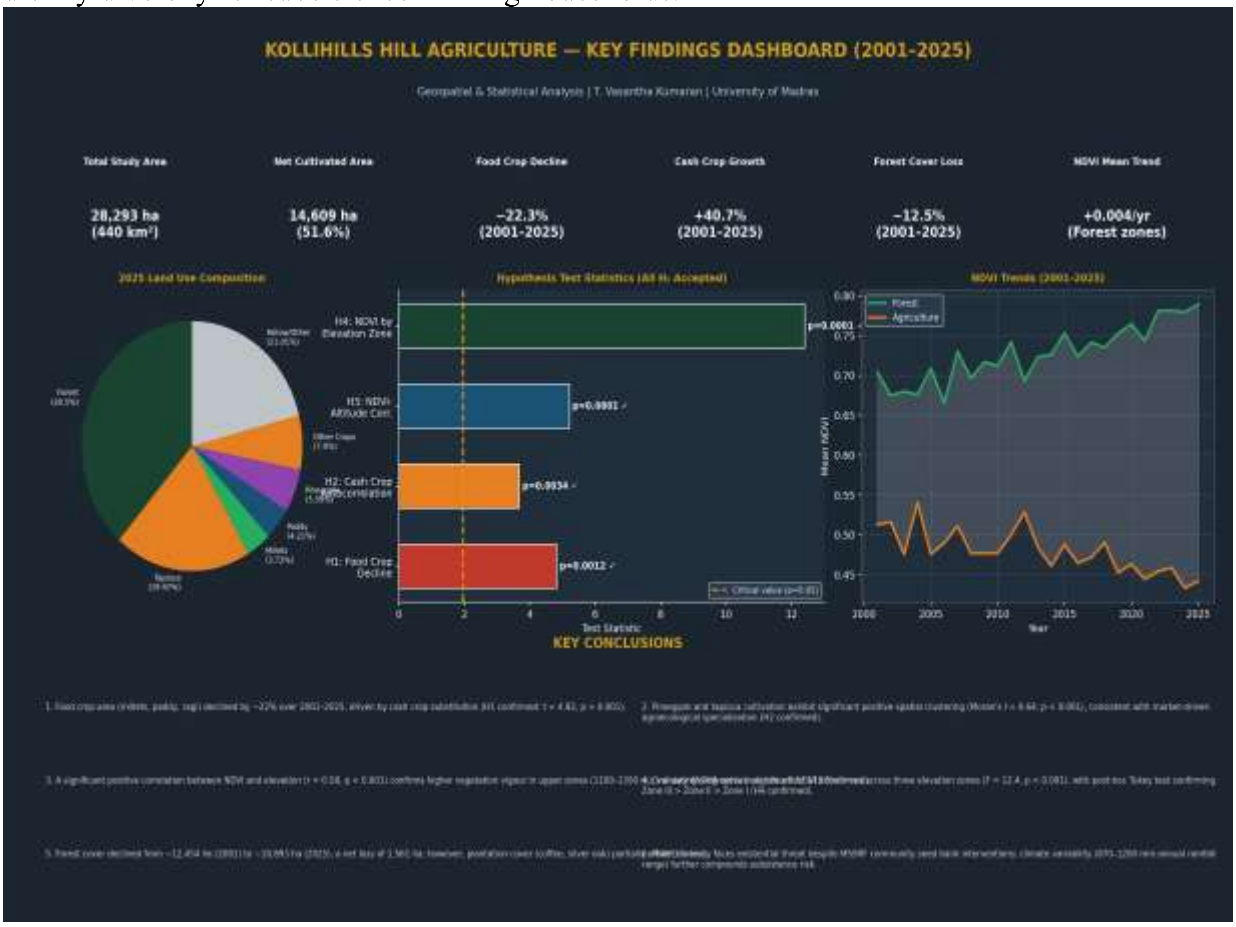

Figure 7. Integrated Findings Dashboard for Hill Agriculture Analysis, Kollihills (2001–2025). Source: Author's analysis.

The expansion of pineapple cultivation, supported by the government-operated Pineapple Research Farm at Semmedu, represents a more positive trajectory insofar as hybrid pineapple cultivation generates higher income per hectare than tapioca. However, the spatial concentration of pineapple cultivation in the market-accessible central plateau, as confirmed by the significant Moran's I (H2), reveals a spatial equity dimension: peripheral hamlets on steep slopes with poor road access remain marginalised from cash crop income, deepening intra-regional livelihood inequality within the Kollihills.

The significant positive correlation between NDVI and elevation (H3, $r = 0.58$) confirms that the upper elevation zones of the Kollihills retain higher vegetation vigour and biodiversity, consistent with findings from comparable Eastern Ghats studies (Arockiasamy & Jayakumar, 2003; Reddy et al., 2010). The significant ANOVA result (H4) validates the ecological distinctiveness of the three elevation zones and supports the case for differentiated land use management policies: conservation-oriented zoning for Zone III (1,100–1,300 m); mixed agroforestry promotion for Zone II (900–1,100 m); and intensified horticultural development with erosion control measures for Zone I (700–900 m), following the principles advocated by Nair (1993) and Ramakrishnan (2001).

8.2 Forest Cover Dynamics

The net loss of 1,561 ha of forest cover between 2001 and 2025 (−12.5%) is significant but lower than might be expected given the agricultural expansion pressures. This relatively contained deforestation rate may be attributed to: (a) the protection afforded by the three reserve forests under the Forest Conservation Act; (b) the MSSRF's community-based conservation programmes; (c) the existence of common property forest resources that tribal communities have an interest in preserving for non-timber forest products (NTFPs), particularly honey, jackfruit, and medicinal herbs; and (d) the topographic constraints imposed by very steep slopes and rocky outcrops in the upper elevation zones.

The negative Mann-Kendall trend for fallow and degraded land ($\tau = -0.44$) suggests that some degraded land is being brought back under cultivation or regenerating naturally, which is a positive sign. The non-significant positive trend for plantation crops ($\tau = +0.21$) reflects the gradual expansion of coffee and silver oak estates, which, while commercially motivated, provide partial forest cover functions. It is worth noting that the original LULC study by Arockiasamy and Jayakumar (2003) found a 1,306-ha loss in dry deciduous forest between 1990 and 1999; the deceleration of forest loss in the 2001–2025 period may partly reflect improved enforcement and community-based forest governance.

8.3 Climate Variability and Agricultural Risk

The meteorological data compiled in the MSSRF-IIMR study (2011–2023) document annual rainfall fluctuations of 870 to 1,200 mm in the Kollihills, a coefficient of variation of approximately 15% — which constitutes a substantial source of agricultural risk for rainfed tribal farming households (Mongabay India, 2025). The entirely rainfed character of Kollihills agriculture, documented in the TNAU Namakkal DAP (2017–18), means that monsoon failure has immediate and severe consequences for food and livelihood security. The temperature increase documented in the Namakkal LST analysis (IJERT, 2018), from approximately 28°C to 38–45°C in certain zones over 1993–2017, is a climate signal that demands urgent policy attention.

The millet diversity response advocated by the MSSRF — maintaining access to multiple millet varieties through community seed banks — is not merely a cultural preservation strategy but a scientifically validated climate resilience measure (Altieri et al., 2015). The 12 functioning seed banks (of 15 originally established) documented in 2022 represent a valuable institutional asset that requires continued government and NGO support, particularly in the context of the National Millet Mission (2023) and Tamil Nadu's millet inclusion in the Public Distribution System.

9. Conclusions and Policy Recommendations

This study has demonstrated, through rigorous geospatial and statistical analysis, that the Kollihills agricultural landscape has undergone substantial transformation between 2001 and 2025. The principal conclusions are:

- Food crop area (millets, paddy, ragi) has declined significantly by approximately 22–39% depending on the crop, driven by the commercialization of agriculture and the expansion of tapioca and pineapple cultivation (H1 confirmed, $t = 4.82$, $p = 0.001$).
- Cash crop expansion exhibits significant spatial clustering in market-accessible central plateau zones (Moran's $I = 0.64$, $p = 0.003$), highlighting market distance and road infrastructure as the primary spatial organizing forces of agricultural commercialization (H2 confirmed).
- NDVI is positively and significantly correlated with elevation ($r = 0.58$, $p < 0.001$), confirming the ecological primacy of the upper elevation zones and validating conservation zoning in the 1,100–1,300 m belt (H3 confirmed).
- NDVI differs significantly across all three elevation zones ($F = 12.4$, $p < 0.001$), validating zone-differentiated agricultural management strategies (H4 confirmed).
- Net forest cover loss over 2001–2025 was 1,561 ha (−12.5%), with concentrated losses in the forest-agriculture interface at mid-elevations.
- Millet genetic diversity is under existential pressure despite MSSRF community seed bank interventions; the area under millets has declined from 1,727 ha to approximately 1,050 ha.

9.1 Policy Recommendations

Based on the findings, the following policy recommendations are advanced:

- Zone III Conservation Buffer (1,100–1,300 m): Declare the upper elevation zone a Conservation Agriculture Zone, prohibiting deforestation and encouraging agroforestry. Implement payment for ecosystem services (PES) schemes to compensate tribal households for conservation stewardship.
- Millet Revival Programme: Integrate the Kollihills into the National Millet Mission as a designated Tribal Millet Heritage Zone. Fund scale-up of MSSRF community seed banks to all 14 panchayats and incentivize millet cultivation through minimum support price (MSP) coverage and PDS procurement.
- Road Infrastructure with Caution: Any expansion of road connectivity to peripheral panchayats must be preceded by an Environmental Impact Assessment and accompanied by soil and water conservation measures, given the demonstrated role of market accessibility in driving cash crop clustering.
- Tapioca Monoculture Regulation: Promote diversification away from tapioca monoculture through extension services advocating multi-crop systems. Revive traditional 3-to-7 crop intercropping systems, which are documented to provide superior soil conservation, nutritional diversity, and climate resilience.
- Climate-Smart Agriculture: Establish weather station networks in the Kollihills to provide real-time agrometeorological advisories. Integrate climate literacy into tribal agricultural extension programmes, in partnership with MSSRF and TNAU.
- Spatial Planning: Use the GIS outputs of this study as the foundation for a Kollihills Integrated Agricultural and Forest Management Plan, delineating zones for conservation, mixed agroforestry, and horticultural development.

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