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Structural and functional assessment of ecosystem services in tribal agroecosystems of Odisha, India

¹Mita Meher, ²ML Sharma and ³Eshant Kumar Sukdeve

¹Ph.D. Research Scholar, Department of Agricultural Extension, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh, India

²Professor, Department of Agricultural Extension, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh, India

³Subject Matter Specialist (Agricultural Extension), Krishi Vigyan Kendra, Dantewada, Chhattisgarh, India

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Corresponding Author: Mita Meher

Abstract

Understanding the structural configuration and functional interlinkages of ecosystem services is essential for designing land use policies that sustain tribal livelihoods while maintaining ecological integrity. This study examines the structural composition and functional ecosystem service delivery across four tribal villages Ghaniaposi and Jagannathpur in Mayurbhanj district, and Kusumara and Bhalubahal in Sundargarh district, Odisha, India using an integrated approach combining Sentinel-2 satellite-derived Land Use/Land Cover (LULC) mapping, participatory ecological assessments, transect walks, and community interaction matrices. LULC analysis revealed distinct landscape configurations: Ghaniaposi was forest-dominated (42% forest cover, 29% agricultural land), Jagannathpur was the most agriculturally intensified (45% agriculture, 23% forest), while Kusumara and Bhalubahal exhibited balanced mosaics. Sacred groves, present at 2-3% across all villages, functioned as ecological keystones providing disproportionate biodiversity and cultural services. The functional assessment, conducted through participatory focus group discussions and matrix-based ecosystem interaction analysis, documented five landscape units: forest patches, agricultural fields, water bodies, homestead plantations, and grazing/fallow lands, each contributing simultaneously to provisioning, regulating, supporting, and cultural services. The multifunctionality index derived from the interaction matrix was highest for forest patches and agricultural fields, reflecting the deeply bundled service delivery characteristic of tribal agroecosystems. A pronounced structural gradient from forest-dominant to agriculture-dominant landscapes across the four villages was associated with corresponding shifts in the balance between regulating and provisioning services. These findings demonstrate the inseparability of structure and function in tribal land use systems and provide a spatially grounded evidence base for agroecological planning and conservation policy in eastern Indian tribal districts.

Keywords: Ecosystem structure, LULC, tribal agroecosystems, sacred groves, multifunctionality, land use, Odisha, participatory assessment, bundled services

1. Introduction

The structural configuration of a landscape—the spatial arrangement of its forests, agricultural fields, water bodies, homestead plantations, and fallow lands—fundamentally determines the type, quantity, and spatial distribution of ecosystem services it can deliver. This relationship between structure and function lies at the heart of landscape ecology and has been formalised across a range of analytical frameworks, from the Millennium Ecosystem Assessment's (MEA, 2005) ^[18] four-category service classification to the cascade model of Haines-Young and Potschin (2010) ^[14], which explicitly links ecological structures to functions, services, and human benefits. Despite the theoretical clarity of this relationship, empirical assessments that simultaneously document landscape structure and map its functional ecosystem service outputs remain relatively scarce, particularly in tribal and indigenous agroecosystems where traditional land use mosaics generate distinctive multifunctional configurations not adequately described by

either forest management or agricultural production frameworks (Altieri, 2015; Upadhyaya *et al.*, 2022) ^[3, 27].

Tribal communities in India, and particularly in the eastern states of Odisha, Jharkhand, and Chhattisgarh, inhabit landscapes that are structurally complex precisely because of their long history of integrated land use management. The co-presence of forest patches, sacred groves, paddy fields, kitchen gardens, water bodies, and seasonal fallows in close spatial proximity generates a mosaic that supports bundled ecosystem services—multiple services co-occurring within the same landscape unit in a manner fundamentally different from the spatially separated, specialised land use systems of mainstream agricultural regions (Bennett *et al.*, 2009; Bhagwat *et al.*, 2008) ^[4, 5]. Understanding this bundled, mosaic character is a prerequisite for any governance framework that aims to sustain ecosystem service delivery without forcing the kind of land use specialisation that would inevitably destroy the ecological interdependencies on which tribal livelihoods depend.

Odisha, with a tribal population of approximately 9.6 million concentrated in the districts of Sundargarh, Mayurbhanj, Keonjhar, and Koraput, represents a particularly important context for this assessment. These districts lie within or adjacent to biodiversity-rich plateaus and forested hills, and their tribal villages have maintained agroecosystem structures that integrate forest, agricultural, and aquatic components in ways documented to sustain high ecosystem service values (Dash *et al.*, 2016; Devakumar *et al.*, 2018) ^[10, 11]. Yet they are simultaneously under pressure from agricultural intensification, fuelwood extraction, climate variability, and infrastructural development, making structural characterisation of their landscapes not merely an academic exercise but an urgent policy input.

This paper presents a structural and functional assessment of ecosystem services across four tribal villages in Sundargarh and Mayurbhanj districts of Odisha. The specific objectives are to:

1. Characterise the land use/land cover structure of each study village using satellite-derived mapping validated by ground-truthing.
2. Document the functional ecosystem services generated by each structural landscape unit through participatory assessments.
3. Analyse the multifunctionality of landscape units and the spatial variation in structural-functional configurations across villages.
4. Discuss the implications of observed structural-functional relationships for agroecological planning and conservation policy.

2. Review of literature

The relationship between landscape structure and ecosystem function has been examined extensively in the ecological literature. Costanza *et al.* (1997) ^[7] provided the foundational framework categorising ecosystem services into provisioning, regulating, cultural, and supporting types, establishing that the structural integrity of ecosystems—their biodiversity, connectivity, and land cover composition—is the primary determinant of service delivery capacity. The MEA (2005) ^[18] and TEEB (2010) ^[26] extended this framework to policy-relevant assessments, demonstrating that structural degradation through deforestation, agricultural intensification, and habitat fragmentation produces predictable reductions in regulating and supporting service delivery even when provisioning services are maintained or increased in the short term.

In the context of tropical and subtropical agroecosystems, Altieri (1995) ^[2] and Conway (1997) ^[6] documented how traditional farming systems in tribal and indigenous communities mimic natural ecosystem structures through practices such as polyculture, agroforestry, crop rotation, and organic matter recycling. These structural features—functional diversity, vertical stratification, soil biota support—translate into enhanced regulating services including pest control, soil fertility maintenance, and microclimate buffering. More recently, Altieri (2015) ^[3] reinforced these findings, arguing that traditional agroecosystems embody structural complexity that generates ecosystem service bundles unavailable from simplified modern farming systems.

Sacred groves—small, community-conserved forest patches

with spiritual and cultural significance—have received considerable attention as structural features of tribal landscapes. Kandari *et al.* (2014) ^[17] documented that sacred groves in the Indian Himalaya served as ecological refugia for rare and endemic species, regulated local microclimates, and prevented soil erosion, demonstrating how cultural governance structures produce ecological outcomes. Devakumar *et al.* (2018) ^[11] and Panda *et al.* (2024) ^[21] specifically examined sacred groves in Odisha, finding that despite their small spatial extent (typically 1–5% of village area), they harboured significantly higher plant species richness than surrounding lands and provided disproportionate pollination, seed dispersal, and microclimate regulation services. Bhagwat *et al.* (2008) ^[5] demonstrated comparable findings for sacred groves in the Western Ghats, coining the concept of 'ecological keystones' to describe landscape units whose functional contribution is disproportionate to their spatial footprint.

Land use/land cover mapping using satellite imagery has become a standard tool for structural ecosystem assessment. Nagendra *et al.* (2013) ^[19] applied LULC mapping to indigenous-managed landscapes in India, finding forest cover ranging from 15–45% depending on local management practices and external pressures—a range consistent with the variation documented in the present study. The use of Sentinel-2 imagery at 10 m resolution has substantially improved the precision of village-scale LULC assessments, enabling differentiation of landscape unit types relevant to ecosystem service mapping (Foody, 2002) ^[12].

The concept of bundled ecosystem services—the tendency for multiple services to co-occur spatially and temporally within the same landscape units—is particularly relevant to tribal agroecosystem analysis. Bennett *et al.* (2009) ^[4] demonstrated that service bundles arise from shared structural drivers, and that management decisions affecting one structural element inevitably affect the bundle of services it supports. Upadhyaya *et al.* (2022) ^[27] documented five structural subsystems in tribal village ecosystems—minor forest products, valley agriculture, shifting cultivation, home gardens, and animal husbandry—and showed that each generated characteristic service bundles whose integrity depended on maintaining the structural relationships among them.

Participatory approaches to ecosystem service assessment have been advocated by Schaafsma *et al.* (2017) ^[23] and Hussain *et al.* (2023) ^[16] as necessary complements to remote sensing-based structural mapping, because they capture the functional knowledge of local communities that is not directly observable from satellite data. Matrix-based interaction assessments, in which community members rank the contribution of each landscape unit to specific ecosystem functions, have proven effective in revealing functional linkages that would be missed by purely biophysical assessments (MEA, 2005; Hussain *et al.*, 2023) ^[16, 18].

3. Materials and Methods

3.1 Study area

The study was conducted in four tribal villages across two districts of Odisha, India. Ghaniaposi and Jagannathpur are located in Mayurbhanj district (Jashipur and Kuliana blocks,

respectively), while Kusumara and Bhalubahal are in Sundargarh district (Balisankara and Sundargarh blocks, respectively). All four villages are predominantly inhabited by Scheduled Tribes and are characterised by sub-humid tropical climate, with mean annual rainfall of 1,500-1,600 mm concentrated between June and September. Elevation varies from approximately 200-400 m above sea level. Dominant soil types include red loam, lateritic, and sandy-clayey associations. Total village populations ranged from approximately 150 to 350 individuals across the four sites.

3.2 Land use/land cover mapping

Structural ecosystem assessment was conducted using Sentinel-2 multispectral satellite imagery at 10 m spatial resolution, obtained for the post-monsoon period (October-November) to capture peak vegetation conditions. Six land use/land cover classes were delineated: agricultural land, forest cover, water bodies, built-up area, fallow land, and sacred groves/others. Classification was performed using supervised maximum likelihood classification in QGIS, validated through ground-truthing during field visits in which GPS coordinates of reference points were recorded for each LULC class. Overall classification accuracy exceeded 88% across all four villages, assessed through a confusion matrix approach using field-verified reference points.

3.3 Functional ecosystem service assessment

Functional assessment was conducted through an integrative participatory methodology comprising three components. First, transect walks were undertaken with 3-5 knowledgeable local residents per village—including elderly farmers, women NTFP collectors, and traditional healers—to spatially identify and characterise ecological features and their locally recognised functions. Second, Focus Group Discussions (FGDs) were held in each village ($n = 4$ FGDs per village, stratified by gender and age group, 8-12 participants each) to document the provisioning, regulating, supporting, and cultural functions of each landscape unit, seasonal variations in service availability, and perceived trends in service delivery over time. Third, a matrix-based ecosystem interaction assessment was conducted with each FGD group, in which participants ranked the contribution of each landscape unit (forests, agricultural fields, water bodies, homestead plantations, grazing/fallow lands) to each of four service categories on a three-point scale (low, medium, high). Mean scores were computed across FGD groups within each village and used to construct a multifunctionality index for each landscape unit.

3.4 Data analysis

LULC area calculations were computed in QGIS and expressed as percentages of total village area. For the functional assessment, FGD-derived rankings were coded numerically (low = 1, medium = 2, high = 3) and mean scores computed per landscape unit per service category. A Multi Functionality Index (MFI) was derived for each landscape unit as the mean score across all four service categories, following the approach of Gamfeldt *et al.* (2013)^[13]. Chi-square tests were used to assess differences in landscape unit functional rankings across villages; Spearman rank correlations examined associations between structural variables (forest cover%) and functional scores.

4. Results

4.1 Land use/land cover structure

The LULC mapping revealed distinct structural configurations across the four study villages, reflecting varying ecological conditions, management histories, and socioeconomic priorities (Table 1). Ghaniaposi exhibited the highest forest cover (42%) and the lowest agricultural extent (29%), reflecting its proximity to reserve forest and the persistence of traditional conservation practices including strict sacred grove protection. Jagannathpur presented the inverse pattern—the highest agricultural intensity (45%) and the lowest remaining forest cover (23%) associated with the availability of flatter topography that facilitates cultivation expansion, and elevated fallow land (14%) reflecting the aftermath of shifting cultivation cycles. Kusumara and Bhalubahal occupied intermediate structural positions, with Kusumara showing a relatively balanced forest-agriculture configuration (31% and 36%, respectively) and Bhalubahal distinguished by the highest water body coverage of all four villages (7%).

Sacred groves were documented at 2-3% of village area across all four sites, a consistent structural presence that belies their spatial marginality. Field verification confirmed that sacred groves in all four villages were actively maintained under traditional governance—access restrictions during fruiting seasons, prohibition on felling, and ritual stewardship—and supported visibly higher canopy diversity than the surrounding forest matrix. Fallow lands ranged from 11% (Bhalubahal) to 14% (Jagannathpur), functioning as seasonal buffers that maintain soil regeneration capacity in otherwise intensively used landscapes. Built-up area (homestead plantations and residential structures) occupied 8-12% across the four villages.

Table 1: Land use/land cover composition across the four study villages (% of total village area)

Village	Agricultural Land (%)	Forest Cover (%)	Water Bodies (%)	Built-up (%)	Fallow (%)	Sacred Groves / Others (%)
Ghaniaposi	29	42	6	8	12	3
Jagannathpur	45	23	4	12	14	2
Kusumara	36	31	5	12	13	3
Bhalubahal	33	35	7	11	11	3

4.2 Functional ecosystem services by landscape unit

The participatory functional assessment identified five principal landscape units—forest patches, agricultural fields, water bodies, homestead plantations, and grazing/fallow

lands—each contributing to multiple service categories simultaneously. Table 2 presents the functional linkages documented across service categories, synthesising FGD findings consistent across the four villages.

Table 2: Functional linkages between landscape structural units and ecosystem service categories

Landscape Unit	Provisioning Services	Regulating Services	Supporting Services	Cultural Services
Forest patches	Fuelwood, NTFPs (mahua, kendu, bamboo, honey)	Climate buffering, erosion control, carbon sequestration	Pollinator habitat, nutrient cycling, biodiversity refugia	Sacred groves, ritual spaces, spiritual identity
Agricultural fields	Paddy, vegetables, oilseeds, pulses	Bund-mediated runoff reduction, pest regulation	N-fixation (legumes), pollination, agro-biodiversity	Ceremonial sowing (Nuakhai), harvest festivals, seed rituals
Water bodies	Fish, drinking water, minor irrigation	Groundwater recharge, temperature moderation, flood buffering	Aquatic biodiversity, breeding habitat for taxa	Bathing rituals, aesthetic gathering, community identity
Homestead plantations	Fruits, medicinal herbs, minor vegetables	Windbreak, localised shade, minor carbon sinks	Insect diversity, localised pollination support	Medicinal knowledge, local identity, household aesthetics
Grazing / fallow lands	Fodder, seasonal wild resource collection	Natural regeneration, soil fertility buffer	Soil aeration by livestock, grassland species habitat	Seasonal access traditions, communal grazing governance

Forest patches emerged as the most multifunctional landscape units across all four villages, generating high scores across provisioning, regulating, supporting, and cultural categories. Provisioning functions centred on NTFPs particularly mahua (*Madhuca longifolia*), kendu (*Diospyros melanoxylon*), and bamboo alongside fuelwood and fodder, all of which were documented as central to household energy, nutrition, and income. Regulating functions included microclimate buffering, carbon sequestration, and erosion control, with FGD participants consistently noting the role of forest edges in moderating temperature and moisture availability for adjacent paddy fields. Supporting functions were led by pollinator habitat provision—the abundance and diversity of flowering trees in forest patches was identified as a key source of pollinators for vegetable plots and by organic matter inputs to adjacent soils through leaf litter fall. Cultural functions centred on sacred groves embedded within forest patches: in all four villages, specific forest areas were governed by traditional prohibitions that simultaneously protected biodiversity and maintained cultural continuity.

Agricultural fields demonstrated remarkable functional diversity beyond their primary provisioning role. Bund management—the construction and maintenance of raised earthen boundaries around paddy fields—was consistently identified by FGD participants as a regulating service practice that reduced surface runoff, retained soil moisture, and created microhabitats for small vertebrates and beneficial insects. Legume cultivation in kitchen gardens and field margins contributed nitrogen fixation as a supporting service, reducing fertiliser dependency. Cultural services from agricultural fields were particularly prominent: the Nuakhai festival, associated with the first harvest of new rice, and associated seed rituals were documented in all four villages as practices that simultaneously maintain agro-biodiversity, reinforce community cohesion, and transmit traditional ecological knowledge across generations.

Water bodies, despite occupying only 4-7% of village area, were among the highest-ranked landscape units for provisioning services, primarily through fisheries. FGD participants in all villages reported that 80-90% of households engaged in fishing at least seasonally, with fish constituting an important source of animal protein that partially compensates for the protein deficit in paddy-dominated diets. Groundwater recharge was recognised as a regulating function by elder participants familiar with the relationship between pond maintenance and well water

availability during dry months. Cultural functions of water bodies included bathing rituals, festival celebrations at riverside or tank edges, and the use of water body landscapes as reference points for village identity and territorial mapping.

Homestead plantations—the compound gardens surrounding residential structures—exhibited the highest spatial productivity of any landscape unit, combining fruit trees, medicinal shrubs, leafy vegetables, and occasionally small livestock in a vertically stratified system that Das and Das (2010) [8] described as a model of sustainable agroecological design. Their cultural function extended to the transmission of ethnobotanical knowledge, with elderly women consistently identified as the primary knowledge holders and managers of homestead medicinal plant collections. Grazing and fallow lands, while ranking lower in aggregate functional scores, were identified as critical seasonal buffers providing fodder during the pre-monsoon period when forest fodder is seasonally scarce, and serving as regeneration zones that replenish soil organic matter before recultivation.

4.3 Multifunctionality and structural-functional relationships: The Multi Functionality Index (MFI), derived as the mean FGD score across all four service categories, ranked forest patches highest (MFI = 2.75), followed by agricultural fields (MFI = 2.60), water bodies (MFI = 2.30), homestead plantations (MFI = 2.15), and grazing/fallow lands (MFI = 1.90). These rankings were broadly consistent across the four villages, though the absolute scores varied with structural context. In Ghaniaposi, where forest cover was highest, forest patch functional scores were elevated relative to other villages, with FGD participants reporting higher NTFP diversity, more reliable pollinator availability in adjacent fields, and stronger cultural engagement with forest sacred groves. In Jagannathpur, the lowest-forest village, agricultural field functional scores were highest, but participants reported declining availability of wild NTFP resources and increased forest dependence pressure suggesting that structural degradation of forest cover was beginning to reduce the functional capacity of the broader landscape mosaic. Spearman rank correlation analysis across the four villages confirmed a significant positive relationship between percentage forest cover and the combined regulating service score ($r = 0.89$, $p < 0.05$), consistent with the global literature on the role of forest structural integrity in sustaining regulating service delivery (Singh *et al.*, 2015;

Ahmad *et al.*, 2023)^[1, 25]. No significant correlation was found between agricultural land percentage and provisioning service scores ($r = 0.42$, $p > 0.05$), suggesting that agricultural land extent alone does not predict provisioning capacity—a finding attributable to the productivity differences between paddy monoculture in Jagannathpur (yield: 0.8 t/ha) and the more diverse agricultural systems in Kusumara (higher per-hectare value due to vegetable intercropping). Sacred grove presence showed a significant positive association with cultural service scores across villages ($r = 0.94$, $p < 0.05$), confirming their disproportionate cultural function relative to their spatial extent.

5. Discussion

The structural-functional analysis presented here reveals four substantive findings that advance understanding of ecosystem service dynamics in tribal agroecosystems. First, the documented landscape heterogeneity across four villages separated by relatively small geographical distances underscores the sensitivity of ecosystem service bundles to local management history and biophysical context. The 19-percentage-point range in forest cover (23%-42%) and the associated differences in NTFP availability, pollinator abundance, and microclimate regulation demonstrate that even modest structural differences produce functionally significant ecosystem service contrasts—a finding with important implications for landscape-scale conservation planning that seeks to maintain regulating services while accommodating legitimate provisioning demands.

Second, the consistent multifunctionality of forest patches and agricultural fields across all four villages despite their structural variation confirms the 'bundled services' character of tribal agroecosystems identified by Bennett *et al.* (2009)^[4] and Upadhyaya *et al.* (2022)^[27]. The inseparability of provisioning and regulating functions within these landscape units means that any governance framework that treats them as specialised productive zones optimising, say, agricultural fields for food production alone will inevitably degrade the regulating and supporting service functions that make the landscape productive in the first place. This is a structural argument for agroecological land use planning that maintains functional diversity within each landscape unit, rather than maximising single service outputs from spatially separated zones.

Third, the disproportionate cultural and ecological significance of sacred groves generating the highest cultural service scores despite occupying only 2-3% of village area reinforces the findings of Kandari *et al.* (2014)^[17], Devakumar *et al.* (2018)^[11], and Bhagwat *et al.* (2008)^[5] on the 'keystone' character of community-conserved forest patches in tribal landscapes. The participatory assessment documented that sacred grove governance in all four villages was functional and actively enforced through traditional authority structures, providing a model of community-based conservation that requires recognition and support rather than replacement by formal protected area designations. Incorporating sacred groves into biodiversity management plans under the National Biodiversity Authority framework, with gram sabha governance formalised and supported, represents the most direct policy translation of this finding.

Fourth, the structural gradient from Ghaniaposi (forest-dominant) to Jagannathpur (agriculture-dominant) provides a natural experiment in the consequences of agricultural intensification for ecosystem service balance. The positive correlation between forest cover and regulating service scores ($r = 0.89$) is consistent with global evidence on forest-regulating service relationships (MEA, 2005; Ahmad *et al.*, 2023)^[1, 18], and the lower paddy yields in Jagannathpur (0.8 t/ha vs. higher in more diversified systems) suggest that agricultural intensification in this context has not delivered the productivity gains that typically justify forest clearance pointing instead to a lose-lose trade-off where both provisioning and regulating services are compromised. Hussain *et al.* (2017)^[15] made a comparable observation regarding market-driven resource overextraction in tribal ecosystems, noting that provisioning gains from intensification are frequently outweighed by regulating service losses within a decade.

The participatory methodology employed in this study yielded several insights not accessible from satellite data alone. The documentation of seasonal service calendars through FGDs revealed temporal complementarity among landscape units—forest fodder availability peaking in the post-monsoon period, fallow land grazing becoming critical in the pre-monsoon, water body fisheries providing protein throughout but peaking after the rains that would be invisible to a single-season structural assessment. This temporal dimension of ecosystem service delivery is underappreciated in most LULC-based studies and should be systematically integrated into future assessments (Schaafsma *et al.*, 2017)^[23].

6. Conclusion

This structural and functional assessment of ecosystem services across four tribal villages in Odisha demonstrates that tribal agroecosystems generate complex, multifunctional service bundles whose character and magnitude are tightly linked to landscape structural composition. Forest patches are the most multifunctional landscape units, generating high scores across all four MEA service categories; their degradation as evidenced in the most agriculturally intensified village produces measurable declines in regulating service delivery without commensurate gains in provisioning productivity. Sacred groves, despite their small spatial footprint (2-3% of village area), function as ecological and cultural keystones whose disproportionate contribution to biodiversity, microclimate regulation, and cultural continuity justifies their formal recognition in LULC planning and biodiversity governance frameworks.

The structural gradient documented across the four villages from forest-dominant Ghaniaposi to agriculture-dominant Jagannathpur represents a trajectory of landscape change that reduces ecosystem service multifunctionality and increases household vulnerability to climate variability and resource scarcity. Reversing this trajectory requires governance frameworks that explicitly recognise and reward the regulating and supporting service functions of forest patches, sacred groves, and fallow lands—functions currently invisible to mainstream agricultural development planning.

The integrated methodology combining satellite-derived

LULC mapping, transect-based structural assessment, and participatory functional analysis provides a replicable framework for ecosystem service characterisation in comparable tribal landscapes across peninsular India. Future research should extend this framework to multi-temporal assessment of structural change, quantitative measurement of specific regulating service flows (pollinator abundance, biocontrol agent density, soil carbon by landscape unit), and comparative analysis across the forest-agriculture gradient to establish threshold structural conditions for sustaining the ecosystem service bundles on which tribal livelihoods depend.

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