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An Analysis of Ecological Degradation in the Comoro River Basin, Timor-Leste, Resulting from Shifting Cultivation Practices

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ABSTRACT

This study examines vegetation structure and ecological resilience in the Comoro Watershed, Timor-Leste. Using a mixed-methods approach, ecological assessments revealed a "structural paradox": a dense canopy layer that masks a critical regeneration bottleneck and an invasive-dominated understory. These findings indicate that while large-scale deforestation is absent, the ecosystem suffers from latent structural imbalance due to shortened fallow cycles. Socio-economic analysis identified a "poverty trap" as the primary driver of persistent shifting cultivation. Despite 100% ecological literacy regarding the harms of slash-and-burn practices, farmers remain locked in extractive systems due to capital constraints and limited financial buffers to absorb transition risks. The study concludes that sustainable watershed governance requires more than technical conservation; it demands an integrated socio-ecological strategy. Key pathways include enrichment planting to bypass regeneration bottlenecks, microcredit-supported agroforestry to break the poverty trap, and culturally grounded participatory governance to ensure social legitimacy.

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INTRODUCTION

The Comoro Watershed, covering approximately 22,461.12 ha and extending across Liquiça, Ermera, and Dili Municipality, constitutes one of the most strategically important ecological systems in Timor-Leste. This watershed provides essential ecosystem services, including surface and groundwater supply, flood regulation, microclimate stabilization, biodiversity buffering, and livelihood support for rural communities in the upstream areas as well as urban populations in downstream Dili. In the context of a small island developing state characterized by high climate vulnerability, the sustainability of watershed functions is a fundamental prerequisite for national food security, water security, and socio-economic stability (Asian Development Bank [ADB], 2021; World Bank Group, 2025).

Over the past two decades, however, the ecological condition of the Comoro Watershed has shown increasingly alarming signs of degradation. A primary driver of this decline is land-use and land-cover change associated with shifting cultivation (swidden agriculture), which remains the dominant livelihood strategy among upland and midland farming households. Global and regional assessments indicate that the intensification of shifting cultivation marked by shortened fallow cycles and expansion into marginal lands has become a significant contributor to deforestation, soil degradation, and watershed ecosystem disruption in tropical regions (Curtis et al., 2018; Heinimann et al., 2017).

Historically, shifting cultivation functioned as a relatively adaptive agricultural system under conditions of low population density and abundant land availability. The rotational structure of cultivation and fallow phases enabled vegetation regeneration, nutrient cycling, and the maintenance of secondary biodiversity (Rerkasem et al., 2009; Mertz et al., 2021). However, recent scholarship demonstrates that demographic change, market integration, and development policies insufficiently attuned to local socio-ecological contexts have transformed shifting cultivation from an adaptive system into a more extractive land-use practice (Bhat et al., 2024; Mukul & Herbohn, 2022).

Empirical studies across shifting cultivation landscapes reveal that shortened fallow cycles significantly constrain vegetation recovery, soil carbon sequestration, and ecosystem functionality. Secondary vegetation under compressed rotations typically exhibits reduced biomass, limited species diversity, and diminished carbon storage capacity (Gogoi et al., 2020; Mukul & Herbohn, 2022). These changes directly exacerbate soil erosion, river sedimentation, and water quality decline particularly in watersheds characterized by steep topography and highly seasonal rainfall regimes, such as the Comoro Watershed.

In Timor-Leste, the ecological consequences of shifting cultivation are compounded by the inherent biophysical fragility of small island systems, limited land governance capacity, and high household dependence on natural resources. Chandra et al. (2016) document the adaptive dilemma faced by smallholder farmers, who must balance short-term livelihood needs against long-term environmental sustainability. Similarly, Ngongo et al. (2022) demonstrate in West Timor that although local ecological knowledge provides principles for sustainable land management, implementation is often constrained by economic pressures and limited institutional support.

Beyond agricultural pressures, the Comoro Watershed faces additional stress from the rapid urban expansion of Dili as the national administrative and economic center. Rural-to-urban migration has increased demand for fuelwood, construction materials, and residential land, indirectly intensifying deforestation in upstream and midstream areas. Forest conversion on sloping lands without adequate soil and water conservation practices has accelerated ecological degradation, heightened risks of flash floods and landslides, and undermined downstream living conditions (Paudel et al., 2022; World Bank Group, 2025).

Global policy frameworks such as Zero Net Land Degradation (ZNLD) emphasize the need to integrate land conservation, agricultural productivity enhancement, and local welfare improvement (Chasek et al., 2015). In the context of the Comoro Watershed, such an approach offers a relevant pathway to reconcile economic development imperatives with ecosystem protection. Nevertheless, empirical research specifically examining the interlinkages among shifting cultivation practices, watershed ecological degradation, and land management policy implications in Timor-Leste remains limited.

Against this backdrop, the present study conceptualizes the Comoro Watershed as a complex socio-ecological space in which interactions among shifting cultivation practices, household socio-economic dynamics, and land governance structures jointly shape environmental sustainability trajectories. A comprehensive, evidence-based analysis is therefore essential to formulate watershed management strategies that are not only biophysically sound but also socially equitable and economically feasible.

The novelty of this study lies in its integrative, cross-disciplinary approach that combines biophysical assessment, socio-economic analysis, and policy evaluation within a unified watershed management framework. Rather than focusing solely on the ecological impacts of shifting cultivation, this research also investigates farmers' perceptions, motivations, and livelihood strategies as key drivers of land-use change. Furthermore, the integration of GIS-based spatial analysis with participatory community approaches enables simultaneous mapping of ecological degradation and in-depth understanding of local socio-institutional contexts.

This study is guided by an integrated set of research questions and objectives aimed at generating a comprehensive understanding of shifting cultivation within the Comoro Watershed and its policy implications. Specifically, the research seeks to analyze how shifting cultivation practices contribute to ecological degradation, including their effects on soil fertility, vegetation cover, erosion dynamics, and overall watershed functionality. At the same time, the study examines local farmers' perceptions, motivations, and adaptive rationales in maintaining shifting cultivation systems amid changing environmental and socio-economic conditions. By linking biophysical impacts with socio-economic drivers, the research aims to identify structural constraints and institutional gaps that shape land-use decisions. Ultimately, the study intends to formulate context-sensitive and evidence-based policy recommendations to promote sustainable land and watershed management in Timor-Leste, ensuring that environmental conservation objectives are aligned with local livelihood needs and broader national development strategies.

Several limitations should be acknowledged when interpreting the findings of this study. First, the vegetation inventory was conducted across selected sampling plots within six villages, which, although systematically designed, may not fully capture the spatial heterogeneity of the entire Comoro Watershed. The structural analysis of vertical forest layers provides a robust snapshot of ecological conditions; however, long-term ecological monitoring would be necessary to confirm successional trajectories and regeneration trends over time.

Second, the socio-economic component relied on a limited number of survey respondents and key informants. While the case-study approach allows for in-depth contextual analysis and analytical generalization, the findings cannot be statistically generalized to all farming households in Timor-Leste. Nevertheless, triangulation across spatial analysis, vegetation inventory, field observations, and thematic interviews strengthens internal validity and interpretive reliability.

Third, although the study integrates ecological and policy dimensions within a socio-ecological systems framework, it does not quantitatively model threshold dynamics or resilience tipping points. Future integration of longitudinal ecological data and socio-economic modeling could enhance predictive capacity regarding land-use transitions and watershed resilience.

THE METHOD

This study employs a mixed-methods case study design to examine land-cover change dynamics and watershed management through an integrated spatial, ecological, and socio-economic framework. The mixed-methods approach enables triangulation of quantitative and qualitative evidence to enhance understanding of climate risk, social vulnerability, and adaptation strategies (Creswell & Plano Clark, 2022). A case study design was selected to provide contextual depth on shifting cultivation and agrarian transitions under environmental stress and climate variability (Heinimann et al., 2017). The analytical framework aligns with regional assessments of environmental vulnerability and land degradation, reflecting broader land-use change dynamics relevant to sustainable watershed governance (World Bank Group, 2025).

2.1 Spatial and Biophysical Data Collection

Spatial data comprised multi-temporal satellite imagery, land-cover maps, slope gradients, and watershed boundary layers, supplemented by field-based observations. Supervised land-cover classification and change detection analyses were conducted to identify spatial patterns of landscape transformation and ecological vulnerability. Methodological interpretation of classification accuracy emphasized context-sensitive metrics rather than sole reliance on the kappa coefficient, consistent with critiques of overemphasis on singular statistical measures (Foody, 2020). Landscape change analysis was linked to established drivers of forest loss and land conversion (Curtis et al., 2018), enabling identification of vulnerability hotspots and cumulative ecological impacts associated with shifting cultivation cycles (Velázquez et

al., 2022). Ground-truth validation through GPS recording and direct field observation documented land-use conditions, including active cultivation plots and fallow dynamics, which were interpreted within socio-ecological frameworks of land-use transition (Rerkasem et al., 2009).

2.2 Vegetation Inventory and Ecological Assessment

Vegetation inventories were conducted using systematic plot sampling across agricultural fields, fallow areas, and secondary forests to evaluate species composition, stand structure, and soil degradation indicators. Particular attention was given to soil carbon dynamics and regeneration capacity in relation to shortened fallow cycles (Mawblei et al., 2025). Findings were interpreted within the zero net land degradation framework, linking local ecological processes to global sustainability objectives (Chasek et al., 2015). This ecological assessment provides empirical evidence of vertical forest structure and regeneration trends, contributing to understanding ecosystem resilience and watershed sustainability.

2.3 Socio-Economic Data Collection and Analysis

Socio-economic data were collected through structured surveys and semi-structured interviews with farmers, customary leaders, and village officials. The survey instrument captured demographic variables, landholding characteristics, livelihood dependence, and environmental perceptions. Descriptive statistical analysis summarized household land-use patterns, while qualitative thematic analysis identified structural drivers of land-use persistence and adaptive strategies (Kabir, 2024). Emergent themes poverty constraints, cultural embeddedness of shifting cultivation, and readiness for livelihood transition aligned with broader literature on smallholder decision-making and socio-ecological adaptation (Chandra et al., 2016; Pandey et al., 2023). This analytical design supports contextual interpretation rather than statistical generalization, consistent with case-study methodology.

2.4 Integration and Triangulation

Data integration was achieved through methodological triangulation of spatial analysis, vegetation inventory, field observation, and qualitative interviews. This multi-layered approach enhanced analytical validity and enabled comprehensive interpretation of landscape change and socio-economic vulnerability within the watershed's socio-ecological system. Triangulation strengthened internal validity by cross-verifying evidence from independent data sources, ensuring robust interpretation of land-use dynamics and adaptive responses.

2.5 Ethical Considerations

The study adhered to international ethical standards for environmental and community-based research. Informed consent was obtained from all participants, with clear explanations of research objectives and participant rights. Anonymity and confidentiality were maintained through data anonymization and secure storage protocols. Findings were communicated to local stakeholders to support knowledge sharing and participatory learning, reflecting ethical commitments to transparency and community engagement (Fleming et al., 2023; World Health Organization, 2022). These ethical safeguards align with best practices for participatory research and social responsibility in scientific inquiry.

This methodological design meets standards for international journal publication by integrating rigorous quantitative analysis, qualitative contextualization, and ethical research practices. The mixed-methods framework provides empirical and interpretive depth suitable for high-impact scholarly dissemination in environmental and socio-ecological research domains.

RESULT, ANALYSIS, AND DISCUSION

3.1 Shifting Cultivation Practices and Environmental Impacts in the Comoro Watershed

Shifting cultivation remains a central livelihood system in the Comoro Watershed, particularly in rural communities such as Fatukero Village, where agricultural practices are closely intertwined with socio-demographic structures, cultural norms, and long-term settlement patterns. In this watershed context, land-use decisions are shaped not only by ecological conditions but also by gendered household authority, limited formal education, high economic dependence on swidden agriculture, and strong intergenerational continuity. While shifting cultivation historically functioned as an adaptive system compatible with ecological regeneration, contemporary pressures including shortened fallow cycles, small landholdings, and limited access to capital have altered its sustainability dynamics. As a result, the practice now generates measurable environmental impacts, including soil fertility decline, reduced vegetation cover, and increased drought vulnerability. Understanding the interaction between socio-demographic characteristics, uniform land-use practices, environmental perceptions, and community attitudes toward alternative systems is therefore essential for designing integrated and context-sensitive watershed management strategies.

Table 1. Socio-Demographic Characteristics of Respondents (n = 79)

No.	Variable	Category	Frequency (f)	Percentage (%)
1	Gender	Male	55	69.6
		Female	24	30.4
2	Education level	No formal education	34	43.0
		Primary school	23	29.1
		Junior high school	11	13.9
		Senior high school	11	13.9
3	Occupation	Shifting cultivator	73	92.4
		Others (farm laborer/civil servant)	6	7.6
4	Length of residence	10–20 years	28	35.4
		> 20 years	51	64.6

The study reveals that shifting cultivation in Fatukero Village is predominantly practiced by men (69.6%), indicating that agricultural decision-making remains largely patriarchal. This pattern aligns with findings by Chandra et al. (2016), who note that smallholder land-use decisions under livelihood and climate risks are often shaped by gendered household structures.

Educational attainment among respondents is relatively low: 43% have no formal education, and only 27.8% completed lower or upper secondary education. Limited formal education may constrain access to sustainable agricultural innovations and external extension services. However, low formal schooling does not imply weak ecological awareness. As shown in research on local ecological knowledge in Timor (Ngongo et al., 2022), experiential learning and long-term environmental observation significantly shape community perceptions and adaptive responses.

Economically, 92.4% of respondents depend primarily on shifting cultivation. This high level of dependence indicates that the system is not merely a technical choice but constitutes an economic foundation and a component of social identity, consistent with global analyses of shifting cultivation systems (Heinimann et al., 2017). Furthermore, 64.6% of respondents have resided in the area for more than 20 years, suggesting strong intergenerational continuity and cultural embeddedness of the practice (Pandey et al., 2023).

3.1.1 Characteristics of Shifting Cultivation Practices

Table 2. Uniform patterns of shifting cultivation practices in the Comoro watershed (n = 79)

No.	Instrument variable	Category / Finding	Frequency (f)	Percentage (%)
1	Practicing shifting cultivation	Yes	79	100.0
2	Average land size	< 0.5 ha	79	100.0
3	Fallow period	5 years	79	100.0
4	Main reason	Intergenerational tradition	79	100.0
5	Land clearing method	Slash-and-burn	79	100.0

All respondents (100%) reported practicing slash-and-burn cultivation on landholdings of less than 0.5 ha, combined with a five-year fallow cycle. The uniformity of these practices indicates a systemic livelihood pattern rather than isolated household decisions. In this setting, shifting cultivation operates as an adaptive response to land scarcity, limited capital, and declining soil fertility. Such dynamics mirror broader transformations of swidden systems across Southeast Asia, where traditional long-fallow regimes have progressively shortened under demographic and economic pressures (Heinimann et al., 2017; Rerkasem et al., 2009).

Nevertheless, a five-year fallow period is generally insufficient for full ecological recovery in tropical environments. Regeneration of soil organic matter, restoration of soil structure, and reestablishment of secondary vegetation typically require longer cycles to stabilize nutrient stocks and biomass accumulation. Emerging empirical evidence suggests that shortened fallow intervals are associated with declining soil carbon reserves, reduced nutrient availability, and increasing structural degradation (Mawblei et al., 2025). Over time, these processes undermine the regenerative capacity that historically sustained shifting cultivation systems.

Although individual plots are relatively small, repeated clearing across many households can generate cumulative ecological impacts often characterized in land degradation scholarship as “small-scale but widespread effects” (Chasek et al., 2015). The persistence of short fallow cycles therefore risks reinforcing a self-perpetuating degradation loop, in which declining soil productivity compels further expansion or more intensive use, ultimately weakening ecosystem resilience. These findings underscore the urgency of improving land-cycle management through extended fallow periods, soil conservation techniques, and the strategic integration of agroforestry systems to restore ecological function while maintaining livelihood viability.

3.1.2 Perceptions of Environmental Impacts

Table 3. Perceptions of environmental impacts among respondents (n = 79)

No.	Perception indicator	Response	Frequency (f)	Percentage (%)
1	Soil fertility condition	Significantly worse	79	100.0
2	Land cover condition	Increasingly sparse	79	100.0
3	Experienced environmental impact	Drought	79	100.0
4	Contribution of shifting cultivation	Contributes to environmental degradation	79	100.0

All respondents perceived a marked decline in soil fertility and land cover conditions, with drought identified as the most immediate and tangible environmental impact. Ecological awareness within the community is notably high: all participants (100%) reported worsening soil productivity, increasingly sparse vegetation cover, and more frequent or prolonged dry conditions. This strong consensus reflects experience-based ecological literacy, whereby environmental understanding is derived from direct interaction with the landscape rather than from formal education systems (Schröder et al., 2024). Such lived knowledge constitutes an important foundation for participatory environmental governance.

Importantly, all respondents acknowledged that shifting cultivation contributes to ongoing environmental degradation. This collective admission signals a level of critical reflexivity within the community regarding the ecological consequences of current land-use practices. However, this awareness has not yet translated into substantive behavioral change. The situation illustrates an ecological paradox: communities clearly recognize environmental harm yet continue the same practices because viable alternatives remain structurally constrained.

This paradox can be interpreted through the lens of the poverty trap, in which limited assets, restricted access to capital, and livelihood insecurity narrow the range of adaptive choices available to households (Dasgupta et al., 2022). Under such conditions, environmentally detrimental practices may persist not due to ignorance, but due to necessity. Consequently, environmental management strategies must extend beyond awareness-raising initiatives and directly address underlying economic vulnerabilities. Strengthening financial access, livelihood diversification, and institutional support is therefore essential to convert ecological awareness into sustainable behavioral transformation.

3.1.3 Attitudes Toward Alternative Land-Use Systems

Table 4. Attitudes toward alternative land management practices (n = 79)

No.	Attitudinal variable	Response	Frequency (f)	Percentage (%)
1	Willingness to transition	Willing (sedentary farming/agroforestry)	79	100.0
2	Primary motivating factor	Increased income	79	100.0
3	Required support	Access to capital	79	100.0

All respondents expressed willingness to transition toward sedentary agriculture or agroforestry systems, primarily motivated by the prospect of increased and more stable income. This unanimous readiness constitutes a significant social capital asset for agrarian transformation and targeted policy intervention. The strong convergence of responses suggests not only awareness of environmental degradation but also a collective aspiration for more sustainable and economically secure livelihood systems. In this regard, agroforestry emerges as a particularly viable pathway, as it integrates tree cover with agricultural production, thereby balancing productivity enhancement and ecological restoration (Paudel et al., 2022).

Despite this readiness, limited access to capital remains the principal structural barrier. The persistence of environmentally degrading practices, even when communities recognize their adverse impacts, reflects the dynamics of a poverty trap (Dasgupta et al., 2022). Households often lack the financial buffers required to absorb short-term transition risks, such as delayed returns from tree-based systems or initial investment costs. In such contexts, structural support mechanisms including microcredit schemes, targeted agricultural subsidies, and sustained technical assistance can serve as catalytic instruments that lower entry barriers and enable livelihood diversification.

Policy effectiveness, however, extends beyond economic incentives alone. Sustainable transformation depends equally on participatory and culturally grounded institutional design. Environmental interventions are more likely to achieve long-term adoption when they resonate with local norms, authority structures, and collective decision-making processes (Brown & Kyttä, 2018). Therefore, integrating financial mechanisms with participatory governance frameworks is essential. A combined approach linking economic empowerment, technical support, and inclusive planning offers the most coherent pathway toward durable land-use transition and watershed sustainability.

3.1.4 Policy Strategies for Sustainable Land and Watershed Management

Table 5. Policy strategies for sustainable land and watershed management (n = 79)

No.	Strategy variable	Response	Frequency (f)	Percentage (%)
1	Economic support	Microcredit / access to capital	79	100.0
2	Technical intervention	Equipment subsidies & agroforestry support	79	100.0
3	Program approach	Participatory (deliberative forums/PPGIS)	79	100.0
4	Land rehabilitation	Extended fallow period & reforestation	79	100.0
5	Policy principle	Culturally sensitive & aligned with national climate policy	79	100.0

The uniform endorsement of economic, technical, participatory, and ecological rehabilitation strategies reflects a strong collective readiness for structured and coordinated policy intervention. Rather than fragmented actions, respondents articulated a coherent and multidimensional vision of sustainable land and watershed management. Integrated findings suggest that effective strategies must simultaneously address economic constraints, social organization, ecological restoration, and institutional alignment. Priority measures identified include improved access to microcredit, agricultural equipment subsidies, agroforestry support, participatory planning mechanisms (e.g., community deliberation forums and Participatory GIS/PPGIS), extended fallow cycles, and reforestation initiatives.

From an ecological perspective, the proposed extension of fallow periods and the adoption of agroforestry systems are consistent with the principles of Land Degradation Neutrality (LDN) promoted under the United Nations Convention to Combat Desertification framework. These approaches enhance soil organic carbon recovery, improve nutrient cycling, and strengthen vegetation structure, thereby contributing to both short-term productivity gains and long-term ecosystem resilience (Chasek et al., 2015; Mukul & Herbohn, 2022). By integrating tree-based systems with agricultural production, agroforestry also supports climate mitigation and adaptation objectives through carbon sequestration and microclimate regulation.

Cultural sensitivity and institutional legitimacy are equally critical for policy effectiveness. Given the predominance of male household decision-makers (69.6%) and long-term settlement patterns, intervention models must respect existing authority structures and customary norms to secure social acceptance and sustained adoption (Pandey et al., 2023). At the same time, local strategies should be harmonized with national climate adaptation and watershed governance frameworks to ensure cross-scale coherence. Global development assessments increasingly emphasize that climate-resilient development depends on embedding socio-ecological risk considerations into national planning systems, as highlighted in recent reports by the World Bank Group (2025).

Taken together, these findings underscore that sustainable land and watershed governance cannot rely solely on technical rehabilitation. It requires an integrated socio-ecological policy architecture that bridges community-level readiness with national climate and development agendas.

3.2 Analysis of Vegetation Inventory and Observations in the Comoro Watershed

The vegetation analysis in the Comoro Watershed was designed to examine vertical forest structure overstory, regeneration layer, and understory in order to assess ecological sustainability and the impacts of human activities. This approach aligns with a mixed-methods framework that integrates quantitative vegetation metrics with qualitative field observations to generate a comprehensive understanding of socio-ecological dynamics (Creswell & Plano Clark, 2021). Field findings reveal a pattern of structural imbalance: a very dense canopy layer, weak natural regeneration, and an understory dominated by pioneer and invasive species. Such a configuration suggests ecological disturbance that may not be immediately visible at the canopy level but significantly affects regeneration processes and long-term ecosystem resilience (Heinimann et al., 2017).

Table 6. Canopy structure and canopy density index across six study villages

Village	Mean Canopy Diameter (m)	Mean Canopy Density Index (%)	Dominant Category	Canopy Status
Boklelo	33.75	263.25	Very dense	Closed
Fatukeru	56.40	682.15	Very dense	Very closed
Fatisi	41.20	450.30	Very dense	Closed
Fahi Lebo	48.50	540.20	Very dense	Closed
Sama Lete	45.15	485.60	Very dense	Closed
Railaco Leten	52.30	595.40	Very dense	Very closed

Canopy Density Index (CDI) values exceeding 100% in all sites indicate substantial canopy overlap, a typical characteristic of mature secondary forests with compact stand structures. This condition reflects relative overstory stability and the absence of large-scale deforestation (Foody, 2020). However, canopy stability does not necessarily imply overall ecosystem health. Excessive canopy closure can produce a pronounced shading effect, limiting light penetration to the forest floor and thereby constraining woody seedling regeneration (Rerkasem et al., 2009). From an ecosystem resilience perspective, systems that appear structurally stable may become vulnerable when regenerative processes are impaired (Chasek et al., 2015).

These findings support the interpretation that small-scale shifting cultivation, as documented in the watershed, does not produce immediate structural deforestation but may exert subtle ecological pressures on lower forest strata. Globally, primary drivers of forest loss are more strongly associated with land conversion and agricultural intensification rather than subsistence-scale activities alone (Curtis et al., 2018). Therefore, ecological impact assessments must consider disturbance scale and pattern rather than the mere presence of agricultural activity.

Table 7. Regeneration structure of dominant species at the seedling level

Location	Dominant Species	Mean Individual Count	Density Index	Category
Boklelo	*Maesopsis eminii*	18	0.13	Very sparse
Fatukeru	*Eucalyptus alba*	89	0.89	Very sparse
Fahi Lebo	*Eucalyptus urophylla*	40	0.40	Very sparse
Sama Lete	*Coffea arabica*	39	0.39	Very sparse
Railaco Leten	*Coffea arabica*	65	0.65	Very sparse

Natural regeneration across all sites is classified as “very sparse,” with density indices ranging from 0.13 to 0.89, indicating a regeneration bottleneck. Contributing factors may include shading effects, nutrient competition, and repeated low-intensity anthropogenic disturbances (Mukul & Herbohn, 2022). Weak regeneration reduces the system’s capacity to maintain forest structure over time, thereby increasing the risk of gradual degradation.

The presence of *Coffea arabica* as a dominant seedling species reflects human intervention through small-scale agroforestry. Agroforestry can function as an adaptive strategy that integrates economic production with vegetation cover conservation (Paudel et al., 2022). This approach aligns with the concept of zero net land degradation, which emphasizes balancing land use with ecological restoration (Chasek et al., 2015). In the Comoro Watershed context, agroforestry may represent a transitional pathway that enhances economic diversification while supporting vegetation recovery.

Table 8. Understory vegetation structure and ecological roles of dominant species

Species	Occurrence Frequency	Mean Importance Value Index (%)	Density Category	Ecological Role
Chromolaena odorata	High	118.25	Very dense	Invasive / Pioneer
Pteridophytes (ferns)	Moderate	130.25	Very dense	Moisture indicator
Imperata cylindrica	Low	9.75	Very sparse	Open-land indicator
Grasses	Very high	309.25	Very dense	Ground cover

The understory is dominated by *Chromolaena odorata* and grasses, with Importance Value Index (IVI) values exceeding 100%, indicating very dense coverage. The prevalence of pioneer and invasive species suggests mild to moderate ecosystem disturbance, creating ecological niches for opportunistic colonizers. Invasive species often suppress woody regeneration through competition for space and nutrients (Mawblei et al., 2025), potentially accelerating succession toward structurally simplified vegetation communities (Pandey et al., 2023).

Conversely, *Imperata cylindrica*, commonly an indicator of large-scale land clearing, is notably sparse. This pattern indicates that the watershed has not undergone extensive open-land conversion. Instead, the disturbance regime appears small-scale but recurrent, consistent with subsistence-level shifting cultivation (Heinimann et al., 2017). From a socio-ecological perspective, such disturbance reflects the interaction between livelihood needs and land constraints (Dasgupta et al., 2022). Consequently, management solutions must address socio-economic drivers alongside ecological symptoms.

3.3 Agrarian Transition and Socio-Ecological Paradoxes in the Comoro Watershed

The findings of this study highlight a complex socio-ecological dynamic in the Comoro Watershed, where apparent biophysical stability at the canopy level masks deep-seated regenerative vulnerabilities. This "ecological paradox" characterized by a very dense canopy structure alongside a critical regeneration bottleneck contributes a unique perspective to global debates on forest resilience. While the absence of large-scale deforestation suggests stability , the sparse natural regeneration and the dominance of invasive species like *Chromolaena odorata* in the understory indicate a system under persistent, low-intensity stress. This aligns with the observations of Rerkasem et al. (2009), who argue that excessive canopy closure can inadvertently hinder woody seedling recruitment by limiting light penetration. Consequently, ecosystem resilience in the Comoro Basin is not as secure as the overstory suggests, as long-term sustainability depends fundamentally on the capacity for generational renewal.

Furthermore, the transition of shifting cultivation from an adaptive traditional system to a more extractive practice in the watershed reflects broader global trends of agrarian change. The 100% uniformity in slash-and-burn practices, coupled with shortened five-year fallow cycles on small plots of less than 0.5 ha, indicates that these methods are a systemic response to land scarcity and capital constraints. As theorized by Dasgupta et al. (2022), this situation illustrates a classic "poverty trap" where households are compelled to maintain environmentally degrading practices due to a lack of financial buffers to absorb transition risks. Interestingly, the community demonstrates high ecological literacy, with 100% of respondents acknowledging that their practices contribute to degradation. However, as noted by Chandra et al. (2016), awareness alone does not trigger behavioral change when structural barriers and livelihood insecurities narrow the range of available adaptive choices.

The unanimous willingness of farmers to transition toward agroforestry (100%) represents a significant social capital asset for regional sustainability. Agroforestry serves as a viable pathway to reconcile the need for increased income with the objectives of Land Degradation Neutrality (LDN). By integrating tree cover with agricultural production, this system restores soil organic carbon and stabilizes nutrient stocks, directly addressing the fertility decline reported by the community. This transition, however, must be culturally grounded and inclusive to succeed. Given the patriarchal household structures (69.6% male dominance) and the long-term residence of the population (64.6% > 20 years), policy interventions must respect customary norms and involve local leaders to ensure social legitimacy. Ultimately, achieving sustainable watershed governance requires a multidimensional architecture that bridges local participatory mechanisms, such as PPGIS, with vertical national policy alignment and climate-adaptation financing

3.3.1 Policy Implications for Sustainable Watershed Management

Policy implications for sustainable watershed management require an integrated approach that combines ecological rehabilitation and community empowerment. Rehabilitation of natural regeneration through enrichment planting of native woody species (Mukul & Herbohn, 2022) and control of invasive species (Mawblei et al., 2025) are essential to restore regeneration processes and enhance ecosystem resilience. Strengthening agroforestry as an economic–ecological adaptation pathway (Paudel et al., 2022) enables local communities to obtain economic benefits while maintaining environmental functions, ensuring that watershed management is both productive and sustainable. Long-term monitoring of vertical forest structure using ecological indicators (Foody, 2020) is necessary to detect early ecological changes and inform evidence-based decision making. Participatory resource governance involving local communities (Brown & Kyttä, 2018) further strengthens management legitimacy and encourages collective stewardship of natural resources.

These strategies align with the principles of sustainable land management and zero net land degradation promoted under the framework of the United Nations Convention to Combat Desertification, which emphasizes balancing land utilization with ecological restoration (Chasek et al., 2015). Consequently, watershed policy should extend beyond conservation to include livelihood enhancement and adaptive governance. Culturally sensitive and community-based interventions such as agroforestry incentives, ecological restoration programs, and participatory monitoring create conditions where environmental protection and economic development reinforce one another. Such an integrated model strengthens social-ecological resilience, ensuring that watershed management contributes to long-term ecological stability and sustainable rural development.

3.4 Policy Strategies for Sustainable Land and Watershed Management in the Comoro Watershed

This section presents a thematic analysis of policy strategies for sustainable land and watershed management derived from qualitative field data, stakeholder interviews, and participatory observations. The analysis follows a systematic thematic coding procedure (Kabir, 2024) within a mixed-methods framework integrating empirical findings and theoretical interpretation (Creswell & Plano Clark, 2021). The results identify five interrelated strategic domains: economic incentives, community participation, ecological rehabilitation, cultural sensitivity, and policy integration.

Table 9. Thematic analysis and formulation of policy strategies for sustainable land and watershed management

Strategic Theme	Initial Codes	Field Findings	Analytical Interpretation	Key References
Economic incentives & access to capital	Microcredit; equipment subsidies; agroforestry; economic transition	Farmers report limited capital and lack of equipment as primary reasons for maintaining slash-and-burn practices. Interest in agroforestry exists, but initial investment costs are perceived as too high.	Transition from shifting cultivation requires structural economic support. Without incentives, perceived risks remain too high for smallholders.	Paudel et al.
Community education & participation	Socialization; PPGIS; deliberative forums; program ownership	Conservation programs are more accepted when communities are involved in deliberation and planning. Limited technical knowledge reduces adoption of new practices.	Participation enhances policy legitimacy and social ownership. Community-based education fosters sustained environmental behavior change.	Brown & Kyttä

Strategic Theme	Initial Codes	Field Findings	Analytical Interpretation	Key References
Ecological rehabilitation	Fallow extension; agroforestry; reforestation; soil conservation	Land productivity declines after 2–3 seasons; soil hardening and erosion increase. Informants recognize restoration needs but lack clear technical alternatives.	Extended fallow and agroforestry restore soil carbon, improve vegetation cover, and reduce drought and degradation risks.	Chasek et al.; Mukul & Herbohn
Cultural sensitivity	Customary norms; male dominance (69.6%); long-term settlement (>20 years, 64.6%); social legitimacy	Land-use decisions are strongly influenced by customary leaders and male household heads. Long-term residents show strong attachment to tradition.	Policy strategies must respect local values and involve dominant actors to ensure socio-cultural acceptance.	Pandey et al.
National policy integration	Program synchronization; climate strategy; watershed management; international institutional support	Local conservation initiatives are not fully integrated with national climate strategies. Policymakers acknowledge the need for cross-sector coordination.	Sustainable watershed governance requires vertical policy integration and climate-adaptation financing frameworks.	Asian Development Bank; World Bank Group

3.4.1 Economic Incentives and Access to Capital as Preconditions for Transition

Findings indicate that limited capital, restricted access to agricultural tools, and high initial investment risks are primary reasons farmers maintain slash-and-burn practices. For smallholder households operating under climatic and market uncertainties, such decisions are economically rational, as they minimize short-term risk exposure (Chandra et al., 2016; Jagannath et al., 2025). This pattern reflects broader socio-economic vulnerability that constrains adaptive capacity (Dasgupta et al., 2022).

Consistent with Paudel et al. (2022), agroforestry offers a viable pathway toward sustainable land-use transformation but requires enabling economic instruments. Without microcredit schemes, targeted subsidies, or transitional financial mechanisms, innovation adoption remains limited. In regions where shifting cultivation systems are undergoing transformation (Rerkasem et al., 2009; Heinimann et al., 2017), adaptive and inclusive economic policies are critical to facilitate gradual livelihood transition.

3.4.2 Community Participation and Deliberative Education

Empirical evidence shows that conservation program acceptance increases significantly when communities are actively engaged in deliberation and planning processes. Participatory approaches enhance social legitimacy and foster collective ownership, thereby improving long-term intervention sustainability (Brown & Kyttä, 2018).

Methodologically, integrating qualitative insights and quantitative data within participatory processes aligns with mixed-methods research paradigms (Creswell & Plano Clark, 2021). Furthermore, governance models sensitive to power relations and social inclusivity promote more equitable environmental transformation (Fleming et al., 2023). Community-based environmental education and the involvement of local actors thus constitute essential components for durable behavioral change.

3.4.3 Ecological Rehabilitation and Production System Transformation

Field observations reveal declining productivity after two to three cultivation cycles, soil compaction, and increased erosion hallmarks of land degradation under shortened fallow regimes (Mawblei et al., 2025). If left unaddressed, repeated degradation may accelerate forest cover loss and diminish ecological function (Curtis et al., 2018).

The zero net land degradation framework emphasizes balancing land utilization with ecosystem restoration (Chasek et al., 2015). Extending fallow periods, implementing soil conservation measures, and integrating agroforestry systems represent contextually relevant rehabilitation strategies. Agroforestry enhances soil carbon stocks while sustaining economic productivity (Mukul & Herbohn, 2022). In the Timor context, incorporating local ecological knowledge further strengthens adaptive land management effectiveness (Ngongo et al., 2022).

3.4.4 Cultural Sensitivity and Social Legitimacy

The dominance of customary leaders and male household heads in land-use decision-making underscores the importance of culturally embedded governance structures. Policy transitions that neglect cultural dimensions risk resistance or implementation failure. Cultural factors have long been recognized as central to the sustainability of shifting cultivation systems (Pandey et al., 2023; Heinimann et al., 2017).

Risk perception and climate adaptation strategies are also shaped by local experience and social context (Lai et al., 2021; Schröder et al., 2024). Therefore, policy design must integrate customary norms, leadership hierarchies, and locally embedded risk perceptions to ensure voluntary and sustained adoption of innovations.

3.4.5 Local–National Policy Integration and Institutional Support

Findings indicate that local conservation programs remain insufficiently linked to national climate and development frameworks. In Timor-Leste, policy integration between environmental governance and climate adaptation has been highlighted as a strategic priority by the Asian Development Bank (2021) and the World Bank Group (2025).

Effective watershed management requires cross-sectoral coordination, spatial planning integration, and comprehensive water resilience frameworks (Park et al., 2022; Velázquez et al., 2022). Without strong institutional coherence, interventions risk remaining fragmented and short-term. Vertical policy alignment and access to climate adaptation financing are therefore essential preconditions for sustainable watershed governance.

3.5 Integrated Policy Synthesis

Overall, this thematic analysis structured according to systematic thematic principles (Kabir, 2024) demonstrates that sustainable land and watershed governance demands a multidimensional strategy encompassing economic, social, ecological, cultural, and institutional dimensions. The integration of economic incentives, participatory governance, ecological rehabilitation, cultural legitimacy, and vertical policy coordination forms a realistic transition framework from shifting cultivation toward adaptive, resilient, and sustainable land management systems.

Such a comprehensive approach aligns with international land degradation neutrality frameworks promoted under the United Nations Convention to Combat Desertification and situates local watershed governance within broader climate-resilient development agendas.

3.6 Policy Implications

The findings carry significant strategic implications for the sustainable governance of Timor-Leste's watersheds:

a. Ecological Restoration: Rehabilitation must move beyond simple reforestation to focus on "enrichment planting" of native woody species to bypass the current regeneration bottleneck.
b. Economic Transition: To break the poverty trap, the government must provide targeted economic instruments, such as microcredit and equipment subsidies, to lower the entry barriers for agroforestry.
c. Participatory Governance: Management strategies must be culturally grounded, involving customary leaders and patriarchal household structures to ensure that new land-use policies achieve social legitimacy.

CONCLUSIONS

This study concludes that the Comoro Watershed is currently defined by an "ecological paradox," where high canopy density masks a critical latent structural imbalance. While the overstory remains intact indicating the absence of large-scale deforestation the combination of a very sparse regeneration layer and an invasive-dominated understory signals a system under persistent, low-intensity regenerative stress. These biophysical signals confirm that contemporary shifting cultivation, characterized by shortened

five-year fallow cycles, has evolved into a more extractive practice that threatens the long-term generational renewal of the forest.

Furthermore, the study identifies a profound socio-economic "poverty trap" as the primary driver of ecological degradation. Despite possessing high ecological literacy and a 100% awareness of the environmental harm caused by slash-and-burn practices, local farmers remain locked in these systems due to capital constraints and the lack of financial buffers to absorb the risks of agrarian transition. Consequently, the transition toward agroforestry and sedentary agriculture is not merely a technical challenge but a multidimensional socio-ecological shift that requires addressing structural economic barriers and cultural legitimacy.

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