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Optimizing Restoration: Biophysical Suitability and Social Feasibility in the Nam Kading NBCA, Laos

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Abstract

The rapid expansion of hydropower infrastructure in the Lao People's Democratic Republic (Lao PDR) necessitates robust Forest Landscape Restoration (FLR) strategies to mitigate habitat fragmentation. However, a critical "implementation gap" persists between high-level policy mandates and on-the-ground execution, often resulting from generic restoration approaches that fail to account for site-specific biophysical constraints and complex socio-economic realities. This research bridges this gap by establishing a spatially explicit, empirically grounded restoration baseline for the Nam Kading National Biodiversity Conservation Area (NBCA). Utilizing a multi-scalar methodology, the study integrated remote sensing analysis via Google Earth Engine (GEE) and PlanetScope imagery with ecological ground-truthing and Participatory Rural Appraisal (PRA) in the strategic interface community of Namtek. Results characterize Land Use/Land Cover (LULC) dynamics, revealing that while the core protected area remains largely intact (65.7% forest cover), significant degradation is concentrated in valley floors, comprising 25.0% fallow and 7.6% bare land. A high-priority intervention zone of approximately 20,000 hectares was identified, distinguished by accessible terrain and fertile silty loam soils (pH 6.8) capable of supporting enrichment planting with high-value native species such as *Pterocarpus macrocarpus*. Crucially, socio-economic analysis identified that deforestation is primarily driven by a livelihood transition toward intensive cassava and rubber cultivation. However, the study posits that the local population, possessing high silvicultural proficiency, is an underutilized operational asset. The research concludes that sustainable restoration in the study area requires pivoting from strict exclusion to a participatory manage-

ment model. By formalizing "Conservation Labor Contracts" for nursery management and fire suppression, restoration initiatives can align local income streams with forest recovery, thereby ensuring the long-term operational viability of biodiversity offsets in the Greater Mekong Sub-region.

Keywords

Forest Landscape Restoration (FLR), Nam Kading NBCA, Remote Sensing, Participatory Rural Appraisal, Biodiversity Offsets, Lao PDR

1. Introduction

Hydropower expansion is driving economic growth in the Greater Mekong Sub-region, supporting Laos's vision to become the "Battery of Southeast Asia". While this energy development is pivotal for macroeconomic stability and poverty alleviation [1]-[4], it inevitably entails substantial ecological trade-offs, particularly the inundation of riverine habitats and the fragmentation of terrestrial ecosystems [5]. In response, the principles of the "mitigation hierarchy"—avoid, minimize, restore, and offset—have become codified in international lending standards and national environmental laws. Consequently, Forest Landscape Restoration (FLR) has emerged not merely as a conservation aspiration but as a mandatory compliance mechanism for hydropower operators, designed to offset residual biodiversity losses by rehabilitating degraded watersheds and establishing connectivity corridors in adjacent protected areas [1] [6] [7].

Despite the policy proliferation of biodiversity offsets, a critical implementation gap persists between high-level restoration mandates and on-the-ground ecological realities. Restoration initiatives in the tropics frequently fail to achieve their biodiversity and carbon sequestration targets due to a "one-size-fits-all" approach that neglects site-specific biophysical constraints [8]. Successful restoration is contingent upon precise matching of species to site conditions—specifically edaphic filters such as soil depth, pH, and hydrology, and an understanding of successional dynamics [9]. Furthermore, restoration in the Mekong region operates within a complex socio-ecological matrix where shifting cultivation and resource extraction are inextricably linked to local livelihoods [10]. Without a specific understanding of human impacts, projects risk "leakage", where replanting trees in one area accidentally pushes forest destruction into pristine zones. Therefore, the scientific challenge lies in moving beyond generic tree-planting targets to develop spatially explicit, ecologically stratified, and socially viable restoration master plans.

The primary objective of this research was to establish a comprehensive empirical baseline to inform the forest restoration efforts for the local authorities and national forest conservation section, under the PAFO/DAFO. Specifically, the study aimed to stratify the forest landscape into operational management units by

characterizing variations in forest cover and degradation levels to determine the optimal balance between active reforestation and assisted natural regeneration. Concurrently, the research sought to assess biophysical suitability, identifying limiting edaphic factors and selecting native tree species adapted to specific hydrological conditions. Furthermore, the study analyzed the socio-economic drivers of deforestation, particularly shifting cultivation, to integrate local livelihood strategies with sustainable restoration frameworks, thereby ensuring the long-term operational viability of conservation efforts within the Nam Kading NBCA.

2. Methodology

2.1. Study Area

The study site encompasses a total area of 20,000 hectares situated in the central province of Bolikhamxay, Lao PDR (see **Figure 1**). The project area is strategically located within a high-priority conservation landscapes: a central of the Nam Kading National Biodiversity Conservation Area (NBCA). The NBCA is one of the critical biodiversity hotspots in the Annamite Range, which is a significant ecosystem featuring the Nam Kading river and diverse tropical forests. Designated in 1993 as an IUCN Category VI site, the area protects rich wildlife diversity while permitting sustainable resource extraction for the livelihoods of local communities.

The landscape is defined by a complex mosaic of vegetation types driven by varied topography and anthropogenic history. The terrain is predominantly mountainous, with slopes ranging from 10% to 50%, interspersed with flat alluvial plains along stream corridors. Existing forest cover varies significantly across the study area. The study area is located closed to the Namtek village within a center of the Nam Kading NBCA. It exhibits a heterogeneous mix of dense mixed deciduous forest, old fallow lands (regenerating secondary forest), and active shifting cultivation plots including low-lying areas subject to seasonal inundation from the reservoir.

Access to the study sites is severely constrained, posing significant logistical challenges for restoration operations. The primary infrastructure consists of unpaved, legacy logging roads that deteriorate rapidly during the wet season (May–September), often becoming impassable for standard vehicles due to slippery clay surfaces and rock obstructions. The area is accessible via a single unpaved track from Namtek village, requiring 4WD vehicles. Some area is the most isolated, accessible primarily by foot, tractor, or boat along the Nam Kading river, rendering large-scale equipment transport difficult.

2.2. Remote Sensing and GIS Analysis

We employed a multi-scale remote sensing approach utilizing the Google Earth Engine (GEE) cloud computing platform to characterize land use and forest cover dynamics. Sentinel-2 Level-2A surface reflectance imagery was acquired for the dry season window of January to February 2023. This temporal selection mini-

mized cloud cover and optimized spectral classification between deciduous vegetation and evergreen forest patches. Pre-processing within GEE included cloud masking and topographic correction to account for the rugged terrain. The Normalized Difference Vegetation Index (NDVI) was computed using the near-infrared (Band 8) and red (Band 4) channels of a Sentinel-2 image. The NDVI is a metric used to quantify vegetative conditions. High positive indices correlate with robust vegetation, whereas values near or below zero denote barren features such as sand, or water bodies, as shown in Figure 2.

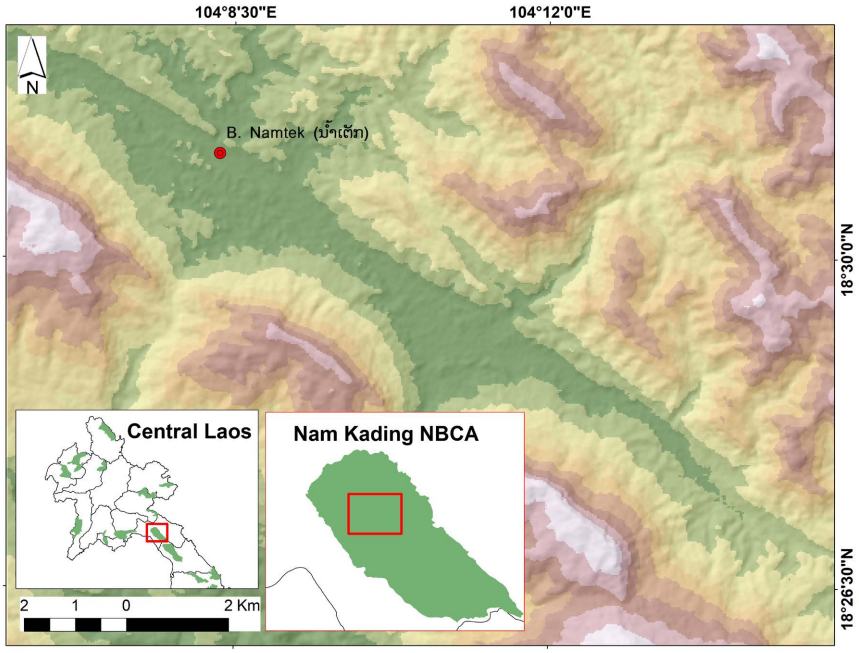

Figure 1. Study area, Nam Kading NBCA, Bolikhamxay province, Central Laos.

To classify pixels into the four distinct categories—dense forest, fallow land, bare soil, and water bodies—we employed the Random Forest (RF) machine learning algorithm within the GEE environment. The RF classifier was selected for its robustness in handling high-dimensional spectral data and its resistance to overfitting compared to single decision trees. The model was trained using a stratified random sampling of points derived from high-resolution PlanetScope reference imagery and field observations (70% for training, 30% for validation). The resulting LULC classification demonstrated high precision, achieving an Overall Accuracy of 94% and a Kappa Coefficient of 0.92, thereby validating the map's reliability for delineating complex boundaries between successional stages.

To further enhance classification accuracy, particularly within the heterogeneous landscape of shifting cultivation, we integrated high-resolution (5-meter) PlanetScope imagery acquired during the corresponding period (January-February 2023). The PlanetScope data were utilized to refine the interpretation of Sentinel-2 spectral signatures, specifically serving as high-fidelity reference data for training sample selection and accuracy assessment. Visual interpretation was applied

to delineate complex boundaries between "young fallow" and "degraded forest" classes. The resulting classification map was subsequently used to direct the stratified random sampling design for field transects.

2.3. Field Data Collection

The field campaign was executed over a comprehensive period from February 7th to February 26th, 2023, following a rigorous institutional coordination framework. Prior to ground deployment, an inception workshop was convened on February 7th at the Provincial Agriculture and Forestry Office (PAFO) in Paksan to align technical objectives with local administrative protocols. This was followed by tactical planning meetings with the Nam Kading NBCA Management Section on February 8th to ensure compliance with protected area regulations.

The core ground-truthing operations (February 9th - 22nd) involved the deployment of two specialized forestry teams (Team A and Team B) to ensure simultaneous coverage of the spatially distinct zones. These teams operated under a collaborative governance structure, integrating experts from the Faculty of Forest Science, National University of Laos. The field work was supported directly from the PAFO/DAFO of Bolikhan and Viengthong district. This multi-stakeholder presence facilitated access to restricted conservation zones and ensured the accurate identification of local flora through the integration of scientific taxonomy and indigenous knowledge.

1) Vegetation Sampling: Transect lines were established in each zone based on the remote sensing stratification. Data recorded included forest type, canopy density, and enumeration of tree species (DBH > 5 cm).

2) Soil Analysis: Soil pits were excavated to determine topsoil depth, texture class, structure, and pH levels using field kits.

3) Accessibility Assessment: Road networks and hydrological features were mapped to determine logistical feasibility for planting operations.

2.4. Field Data Collection

To gain a comprehensive understanding of the socio-economic conditions and anthropogenic pressures within the project area, a dedicated assessment was conducted over a one-week period. This component of the field mission was executed with direct logistical and technical support from the Provincial Agriculture and Forestry Office (PAFO), the District Agriculture and Forestry Offices (DAFO), and the Nam Kading Forest Conservation Office. The socio-economic landscape centers on Namtek village, a pivotal community of 882 residents (143 households) located within the Nam Kading NBCA restoration interface. Data collection was carried out during the February 2023 survey. We employed a mixed-method Participatory Rural Appraisal (PRA) framework, utilizing both quantitative and qualitative tools:

1) Structured Questionnaires: Distributed to households in Namtek and Phonmuang village to gather baseline data on demographics, income sources, and

agricultural practices.

2) Focus Group Discussions (FGD): Conducted with village chiefs, elders, and key community representatives to qualitatively explore historical land use changes, migration patterns, and local perceptions of forest conservation.

These interactions were critical for ascertaining current livelihood strategies (primarily cassava farming and livestock grazing) and evaluating the potential labor supply available within the community to support future restoration activities.

3. Key Findings

3.1. Spatial Distribution of Vegetation Cover

Figure 2 illustrates the spatial variability of vegetation density across the study area, derived from the Normalized Difference Vegetation Index (NDVI) analysis. The grayscale gradient represents vegetative health and density, where lighter pixels indicate dense canopy cover and darker pixels signify low vegetation biomass, bare soil, or water bodies. While the majority of the landscape—particularly the mountainous terrain in the northeast and southwest quadrants—exhibits high reflectance values consistent with dense, undisturbed forest cover, a distinct pattern of fragmentation is evident within the central valley system. The analysis identifies specific zones of low vegetation cover, highlighted by the orange ellipses, which contrast sharply with the surrounding protected forest matrix. The most significant cluster of low-NDVI values is geographically centered around the village of Ban Namtek. In this area, the vegetation cover exhibits a patchwork texture of dark grey and black pixels. This spatial configuration is characteristic of anthropogenic disturbance, suggesting that land-use activities such as small-scale agriculture, shifting cultivation, or infrastructure development are radiating outward from the settlement. A second, smaller cluster of reduced vegetation is observed further southeast along the valley floor, indicating a corridor of land-use change following the topographic depression. Additionally, the deep black feature in the southwest corner clearly delineates a water body (reservoir or river confluence), characterized by negative or near-zero NDVI values. These findings quantitatively confirm that while the Nam Kading NBCA remains largely intact, the valley floors inhabited by local communities are experiencing localized pressure on forest cover.

3.2. Land Use and Land Cover (LULC) Classification

The classification of the study area reveals four distinct land cover categories: forest, fallow, bare land, and water. Figure 3 illustrates the spatial distribution of these classes, while the quantitative assessment indicates that the landscape remains predominantly forested, though significant areas of anthropogenic modification are evident. Forest constitutes the dominant land cover class, occupying approximately 13,140 ha (65.7% of the total study area). This cover is primarily distributed across the rugged, higher-elevation terrain in the northeastern and southwestern quadrants of the NBCA, representing the intact core of the pro-

tected area. Conversely, agricultural and transitional landscapes comprise a substantial portion of the valley floor. Fallow land (vegetation in early regeneration stages) is the second-largest category, covering 5,000 ha (25%). Bare land (exposed soil or non-vegetated areas) accounts for 1,520 ha (7.6%). Spatially, these two classes are heavily clustered within the central lowlands, specifically surrounding the village of Namtek. As highlighted by the orange ellipses in Figure 3, this concentration of bare and fallow land suggests a zone of active land use and shifting cultivation radiating from the settlement. Finally, water bodies cover 340 ha (1.7%), located primarily in the southwest corner, corresponding to the reservoir system. The juxtaposition of the bare/fallow classes against the forest boundary clearly demarcates the extent of human encroachment within this section of the Nam Kading NBCA.

3.3. Prime Restoration Potential

Although the study area encompasses 20,000 hectares of high-priority conservation landscape, this entire extent is not designated for active intervention. The results delineate a specific operational zone of approximately 6,520 hectares—comprising fallow and bare land—where restoration activities are necessary and biophysically feasible. Conversely, the 13,140 hectares of existing forest cover are identified as preservation zones. This spatial stratification resolves the ambiguity between the total study area and the restoration targets, ensuring that silvicultural interventions are precisely directed at the degraded valley floors while the intact core remains under protective management.

Edaphically, this site is superior to all others; the terrain features deep topsoils (>80 cm on plains, 50 cm - 70 cm on slopes) composed of fertile silty loam with a subangular blocky structure.

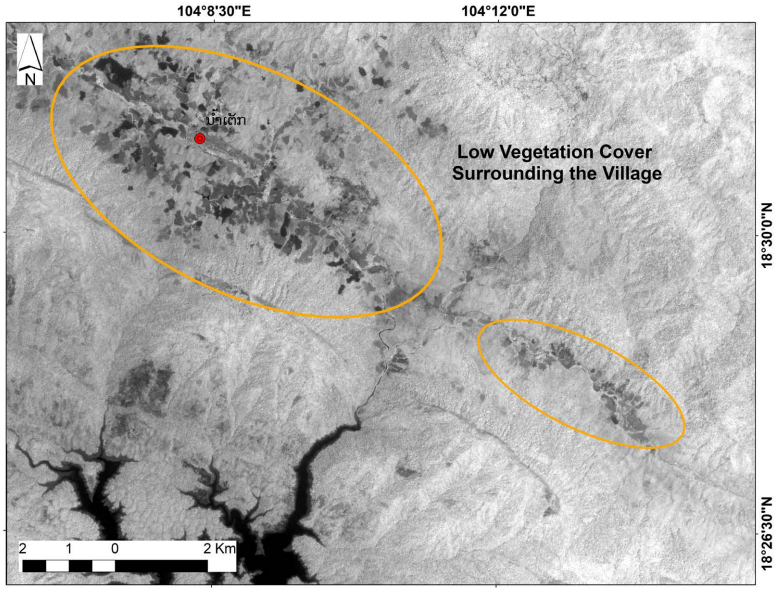

Figure 2. The spatial variability of vegetation density across the study area.

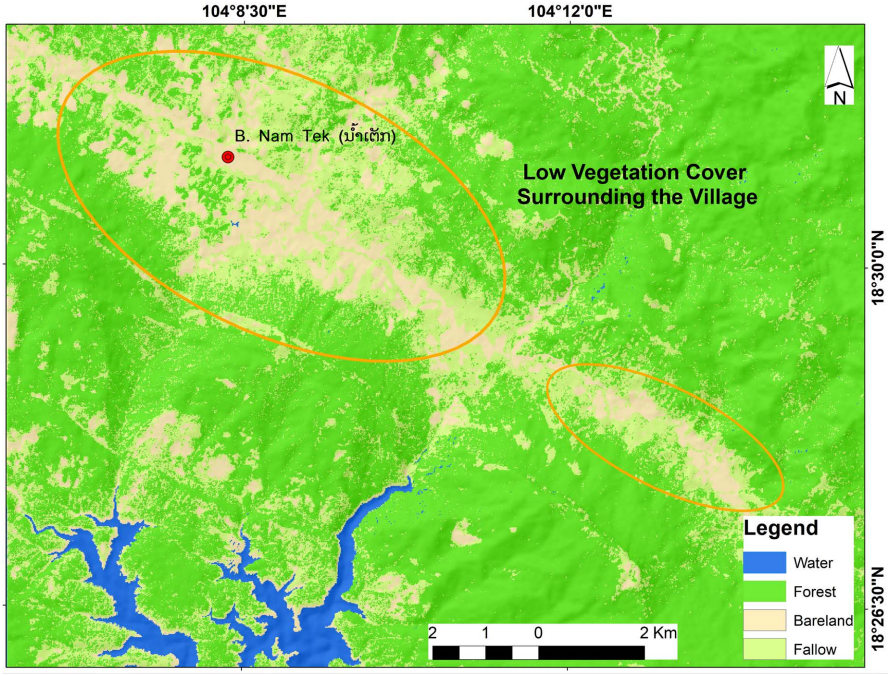

Figure 3. Land Use and Land Cover (LULC) classification.

These soils exhibit high porosity and neutral acidity (pH 6.8), creating optimal conditions for root development and moisture retention. This fertility supports a rich biological baseline of 54 native tree species, currently dominated by pioneer associations of *Cratoxylum maingayi* (>27% abundance) and *Terminalia corticosa* (9.92%). The existence of varied successional factors indicates that this location is well-suited for an immediate pilot implementation. Introducing valuable climax species, such as *Pterocarpus macrocarpus*, through enrichment planting is likely to succeed with high establishment rates and few operational difficulties.

This limits industrial exploitation but complicates the delivery of seedlings, labor, and monitoring equipment required for active restoration. Restoration in this landscape is not merely a compliance requirement but a critical ecological intervention. The targeted areas serve as vital buffer zones protecting the core biodiversity of the NBCA from encroaching edge effects (as shown in **Figure 4** and **Figure 5**). Rehabilitating these degraded corridors is essential to (1) Enhance Habitat Connectivity: Re-establishing forest cover to facilitate wildlife movement between fragmented forest blocks. (2) Secure Ecosystem Services: Stabilizing slopes to prevent erosion and regulating hydrological flows into the Nam Theun 1 reservoir, and (3) Mitigate Anthropogenic Pressure: Transitioning land use from expansive shifting cultivation to sustainable agro-forestry systems, thereby reducing the rate of deforestation in high-value conservation areas.

3.4. Socio-Economic Dimensions

The socio-economic landscape is anchored by Namtek village, a sentinel community of 882 inhabitants (143 households) situated directly within the restoration

interface of the Nam Kading NBCA. Demographically, the population is stratified between Hmong (108 households) and Mei (35 households) ethnic groups, whose livelihoods have transitioned from subsistence swidden agriculture to intensive cash-cropping. Cassava cultivation has emerged as the primary economic driver, yielding an average annual household income of 20,000,000 LAK (~$1,000 USD), yet this reliance fuels conflicting land-use dynamics, specifically the unauthorized expansion of rubber plantations and free-range livestock grazing into protected zones. Despite these anthropogenic pressures, the community represents a critical operational asset; the local workforce exhibits high physical fitness and silvicultural proficiency essential for difficult terrain operations. Additionally, the presence of a nearby military school offers a strategic reserve of disciplined labor for large-scale planting and patrolling. However, the absence of formal markets and the reliance on external traders for Non-Timber Forest Products (NTFPs) perpetuate an extractive economy. Therefore, the restoration strategy must pivot from pure conservation to a participatory model that formalizes labor contracts for nursery management and fire suppression, thereby aligning community income streams with forest recovery rather than clearance.

4. Discussion

Figure 4. Field photos of degraded areas for potential forest restoration.

This study aimed to bridge the "implementation gap" in the Nam Kading NBCA by moving beyond generic reforestation mandates to establish a spatially explicit operational baseline. The findings quantitatively confirm a sharp biophysical dichotomy: while the core protected area retains significant integrity (65.7% forest cover), degradation is structurally embedded in the valley floors, evidenced by the 25 % fallow and 7.6% bare land concentrated near settlement interfaces, as shown in **Figure 3** and **Figure 4**. This spatial non-randomness validates the hypothesis that degradation drivers are strictly tied to accessibility and proximity to infrastructure. Unlike many tropical restoration projects that falter due to poor site selection on highly degraded, acidic substrates [4] [8], our study area presents a rare "sweet spot" of logistical accessibility and edaphic resilience. The presence of deep, silty loam soils with a neutral pH of 6.8 suggests that restoration sites need not rely on robust but low-value pioneer species. Instead, the site conditions sup-

port an accelerated succession strategy using high-value framework species such as *Pterocarpus macrocarpus* and *Terminalia corticosa*. This empirically grounded site selection aligns with the framework species method advocated by Elliott *et al.* (2013), suggesting that careful site-species matching can significantly reduce the biological risks associated with FLR.

Figure 5. Drone's photo to capture the forest landscape with the study area.

The socio-economic analysis of Namtek village reveals a critical tension between development and conservation. The transition from subsistence swidden agriculture to intensive cash-cropping specifically cassava and rubber has generated an average household income of ~$1,000 USD. While this alleviates poverty, it introduces a high opportunity cost for conservation, creating a classic "leakage" risk where restoration in one area might simply displace agricultural clearance

into pristine forest frontiers [10]. The reliance on external traders for these commodities further entrenches an extractive economic model that bypasses local governance. However, our findings argue that viewing the local population solely as a threat is a strategic error. The community possesses distinct operational assets specifically, high physical fitness and deep silvicultural knowledge of the terrain that are unavailable in the commercial labor market. As Sodhi *et al.* note, excluding such communities from management plans in Southeast Asia invariably leads to enforcement failures. Therefore, the operational viability of restoring the study site depends on repurposing this existing labor force rather than displacing it.

To address these socio-economic drivers, we propose a pivot from exclusionary protection to a participatory management model anchored in "Conservation Labor Contracts". By formalizing local roles in nursery management, planting, and patrolling, the project can channel restoration funds directly into the local economy, effectively competing with the returns from cash crops. This approach transforms the restoration budget into a de facto Payment for Ecosystem Services (PES) mechanism. To operationalize this, we recommend a performance-based payment structure rather than a flat wage. Initial disbursements should cover planting labor, while subsequent payments—tiered over three to five years—would be contingent upon verified seedling survival rates exceeding 75%. This "survival dividend" creates a direct financial incentive for critical maintenance tasks, such as weeding and firebreak clearance, which are often neglected in standard planting schemes. By tying remuneration to biological outcomes, the contracts effectively align the community's short-term income goals with the long-term ecological stability of the restoration site. As Domingos *et al.* emphasizes community ownership is the most effective firebreak [11]. If local households derive stable income from the survival of trees, the incentive to burn for land clearance is structurally diminished. This model leverages the "stewardship" potential of the Hmong communities, aligning their economic self-interest with the biological recovery of the landscape.

Generic restoration mandates frequently fail in Nam Kading because they operate on the flawed assumption that degraded lands are economically idle. Our findings refute this, demonstrating that these "degraded" valley floors are actually high-yield agricultural assets, generating approximately $1,000 USD annually per household from cassava. This creates a quantifiable "implementation gap": a standard reforestation policy offers zero immediate return, whereas the status quo offers significant income. Therefore, any restoration intervention that ignores this high opportunity cost is structurally doomed to non-compliance. Success requires acknowledging that for local farmers, conservation is not an ecological choice but a financial trade-off that must be compensated. This confirms the existence of the "implementation gap" described in recent literature, where high-level policy mandates fail to materialize on the ground due to local livelihood conflicts [7] [12]-[15]. This indicates that the primary barrier to restoration is not a lack of ecological potential, but the economic dependence of Hmong households on swidden

agriculture and unauthorized plantation expansion. This aligns with the observations of [3], who noted that biodiversity losses in Southeast Asia are inextricably linked to poverty and the lack of economic alternatives. However, unlike studies that view local populations solely as drivers of degradation, our results highlight the community's high silvicultural proficiency and the strategic presence of the nearby military school as underutilized assets. This supports the argument by [16] that FLR success relies on stakeholder engagement that goes beyond consultation to active participation in implementation.

The divergence between the "pure conservation" model and the reality of the Nam Kading landscape suggests that a passive regeneration approach is insufficient. As researchers argues, second-growth forests hold immense promise, but their recovery is often arrested by recurrent anthropogenic disturbances—in this case, fire and grazing [4] [8]. Our proposed zoning strategy moves toward the "systematic approach" advocated by Stanturf *et al.* [12], advocating for a shift from exclusionary protection to a participatory labor model. By formalizing labor contracts for nursery management and patrolling, the restoration project can convert the economic driver of land clearance (cash crops) into an economic driver for forest recovery (wages for ecosystem services). This mechanism is essential to meet the objectives of the Lao PDR Forestry Strategy to 2035, which emphasizes the need for village-level participation in forest rehabilitation [17].

Several limitations warrant consideration. First, the remote sensing analysis utilized a dry-season snapshot (January - February 2023); while this minimized cloud cover, it may have led to the misclassification of some phenologically deciduous species as "degraded" or "fallow". This geographic restriction to Namtek village implies that our findings likely reflect the dynamics of "market-integrated" communities rather than the entire NBCA. In more isolated settlements lacking road access, livelihood drivers may differ significantly; without the option for intensive cassava cultivation, households might rely more heavily on subsistence hunting or timber extraction. Consequently, the proposed "Conservation Labor Contracts"—which compete with cash-crop income—may need calibration for remote zones where the opportunity costs of labor are lower but the reliance on direct forest extraction is higher. Future interventions must validate these socio-economic gradients before scaling. Future research should prioritize the establishment of permanent monitoring plots to assess the long-term survival rates of *Pterocarpus macrocarpus* across varying slope gradients. Additionally, a longitudinal study is required to track household income diversification following the implementation of labor contracts, ensuring that conservation wages effectively substitute, rather than merely supplement, income from forest encroachment.

5. Conclusion and Recommendations

This research underscores that effective FLR in the Nam Kading NBCA is unable to operate on generic national mandates but requires a spatially explicit, site-specific strategy. By bridging the gap between high-level policy goals and local eco-

logical realities, this study has delivered two critical operational baselines. First, the biophysical stratification identified a 20,000 hectare (study area), where the convergence of accessible terrain and fertile silty loam soils (pH 6.8) maximizes the biological potential for enrichment planting. Second, the socio-economic assessment reframed the local community not merely as agents of deforestation, but as the primary labor engine for recovery. The transition to intensive cassava cultivation in Namtek serves as a potent warning of "leakage" risks; however, it simultaneously highlights the availability of a skilled workforce capable of navigating complex terrain. Consequently, the sustainability of restoration efforts hinges on the implementation of "Conservation Labor Contracts". By monetizing forest stewardship through nursery management and fire suppression, project developers can align local economic incentives with biodiversity objectives, effectively turning the restoration budget into a sustainable livelihood mechanism. Ultimately, this study serves as a blueprint for hydropower mitigation across the Greater Mekong Sub-region. The evidence suggests that effective biodiversity compensation requires more than quantitative reforestation goals; it demands the precise alignment of edaphic conditions with social security frameworks. Future management plans must prioritize the rapid operationalization of the identified intervention zones, ensuring that the "Battery of Southeast Asia" recharges not only its energy grids but also the natural capital upon which its long-term stability depends.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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