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High-Resolution Mapping of Decadal Forest Cover Change in the Phou Pha Nang NBCA, Central Laos

Chittana Phompila[1*], Kethsa Nanthavongduangsy[2], Vongphet Sihapanya[2], Saengmany Boutthavong[3]

[1]The Faculty of Forest Science, National University of Laos, Vientiane, Laos
[2]Faculty of Land Resource Engineering, Kunming University of Science and Technology, Kunming, China
[3]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China
Email: *c.phompila@nuol.edu.la

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Abstract

The surge in state-promoted land concessions across Laos since the mid-2000s has accelerated the expansion of monoculture timber plantations. This transition has resulted in widespread deforestation and posed a severe, systemic threat to the region's rich biodiversity. Monitoring these dynamics is historically complex due to persistent cloud cover and the spectral similarities between commercial plantations (such as Rubber, Acacia, and Eucalyptus) and secondary natural forests. This study aims to quantify decadal forest cover changes and produce high-resolution distribution maps for the Phou Pha Nang National Biodiversity Conservation Area (NBCA) across a 2015-2025 timeframe. Utilizing the Google Earth Engine platform, we processed high-resolution (4.77 m) Planet NICFI satellite imagery. An automated Random Forest machine learning classifier, trained using reference data derived from the ESA WorldCover, was applied to generate annual binary forest masks to track spatiotemporal deforestation patterns. The analysis reveals a severe and accelerating trajectory of habitat loss within the NBCA. While initial deforestation manifested as isolated, fragmented pockets, a definitive shift toward extensive, contiguous canopy clearing occurred later in the decade. The protected area experienced an unprecedented surge in forest loss between 2023 and 2025, peaking at 7367.28 hectares in 2023 alone. This massive conversion is heavily concentrated in the central and lower-middle corridors, indicating systematic anthropogenic encroachment rather than minor localized disturbances. Accelerated landscape fragmentation within this vital forest ecosystem not only destabilizes its intrinsic ecological integrity but also undermines national conservation mandates. While the structural drivers precipitating this abrupt escalation in forest loss require further elucidation, comprehensive field-based validation and high-fidelity carbon stock assessments remain imperative to fully parameterize the environmental consequences. Ultimately, the accelerating rate of habitat conversion documented in this study underscores a critical window of opportunity to optimize existing conservation frameworks and bolster resource management strategies before the ecological integrity of Phou Pha Nang is irreversibly compromised.

Keywords

Deforestation, High-Resolution Imagery, Random Forest, Land-Use Change, Phou Pha Nang NBCA, Laos

1. Introduction

Tropical forests in Southeast Asia are experiencing unprecedented rates of land-use and land-cover change, driven primarily by aggressive agricultural expansion and economic development initiatives (Estoque et al., 2019; Liu et al., 2025). In the Lao People's Democratic Republic (Laos), land concessions have been promoted since the mid-2000s to attract foreign direct investment and stimulate the rural economy (Hirsch & Scurrah, 2015; Kenney-Lazar, 2012; Phompila et al., 2017). This promotion has catalyzed a massive surge in the establishment of industrial tree plantations—predominantly Rubber (*Hevea brasiliensis*), *Eucalyptus* spp., and *Acacia* spp. (Phompila et al., 2017; Smith et al., 2021). While these mono-cultural plantations contribute significantly to national economic growth, their rapid expansion often occurs at the direct expense of native Mixed Deciduous and Dry Dipterocarp forests. The conversion of these highly diverse natural ecosystems raises profound concerns regarding the loss of critical biodiversity habitats, the disruption of local hydrological cycles, and significant fluctuations in terrestrial carbon stocks (Estoque et al., 2019; Liu et al., 2025; Warren-Thomas et al., 2015; Xiao et al., 2019). Consequently, protected ecological refuges, such as the Phou Pha Nang NBCA, are increasingly vulnerable to relentless anthropogenic pressures. Evidence suggests that rather than experiencing random, isolated disturbances, these critical conservation zones are facing systematic border encroachments that threaten to deeply penetrate core watershed regions.

To mitigate these severe ecological impacts and successfully enforce conservation boundaries, precise and continuous spatial monitoring is essential. Satellite remote sensing offers a viable solution for tracking large-scale forest transitions; however, accurately mapping deforestation and distinguishing specific industrial plantation species from natural secondary forest regrowth presents a significant technical challenge (Azizan et al., 2021; Hansen et al., 2013; Phompila et al., 2017; Phompila et al., 2026; Wagner et al., 2023). Morphologically, young Acacia and Eucalyptus stands exhibit spectral signatures in standard optical imagery that are nearly indistinguishable from regenerating natural vegetation (Anuar et al., 2022; Goebel & Iwaszczuk, 2023; Gomat et al., 2024). While researchers have successfully leveraged phenological variations—such as Rubber's deciduous "wintering" phase or Acacia and Eucalyptus's varied physiological responses to dry-season water stress in the Short-Wave Infrared (SWIR) spectrum, most studies have focused strictly on regions like Xishuangbanna, China (Wagner et al., 2023; Xiao et al., 2019), or Northern Laos (Xiao et al., 2020). Significant knowledge gaps remain regarding the highly complex spatial mosaic of Central and Southern Laos, where pulpwood plantations densely coexist with natural forests. Furthermore, tracking continuous degradation is historically hindered by the persistent cloud cover endemic to tropical regions, limiting the effectiveness of traditional medium-resolution sensors (Dalagnol et al., 2023; Phompila et al., 2015). Although recent advancements in Deep Learning show promise, they remain computationally prohibitive and demand extensive manual labeling (Zhao et al., 2025). Therefore, a critical need remains for a scalable, cloud-resilient framework capable of detecting fine-scale canopy fragmentation—such as the agglomeration of small non-forest patches into expansive core clearings, before systematic land-use conversion irrecoverably damages protected areas (Ma et al., 2024).

Addressing these critical knowledge gaps, this study aims to quantify the spatiotemporal dynamics of forest loss and systematic habitat fragmentation within the Phou Pha Nang NBCA over the last decade (2015-2025). By utilizing high-resolution imagery from the Planet Norway's International Climate and Forests Initiative (NICFI) using the Google Earth Engine (GEE) cloud-computing platform, this research seeks to uncover the fluctuating but ultimately escalating trajectory of anthropogenic encroachment. Specifically, the objectives of this research are to: 1) classify binary forest and non-forest cover using a Random Forest machine learning classifier; and 2) produce a high-resolution (4.77 m) baseline distribution map alongside an annual deforestation trajectory map. Ultimately, this study intends to pinpoint the geographic loci of severe forest loss, providing actionable spatial intelligence to inform and reassess future conservation enforcement policies.

2. Materials and Methods

2.1. Study Area

The study focuses on the Phou Pha Nang National Biodiversity Conservation Area (NBCA), located in the Vientiane Prefecture of Laos (**Figure 1**). This conservation area is critical for maintaining regional biodiversity and watershed integrity. The boundary of the study region was defined using available public spatial data from K4D Laos: https://lo.data.k4d.la. The region is characterized by a mix of dense tropical forest, topography varying in elevation, and increasing pressure from anthropogenic land-use changes, making it a suitable candidate for high-resolution monitoring.

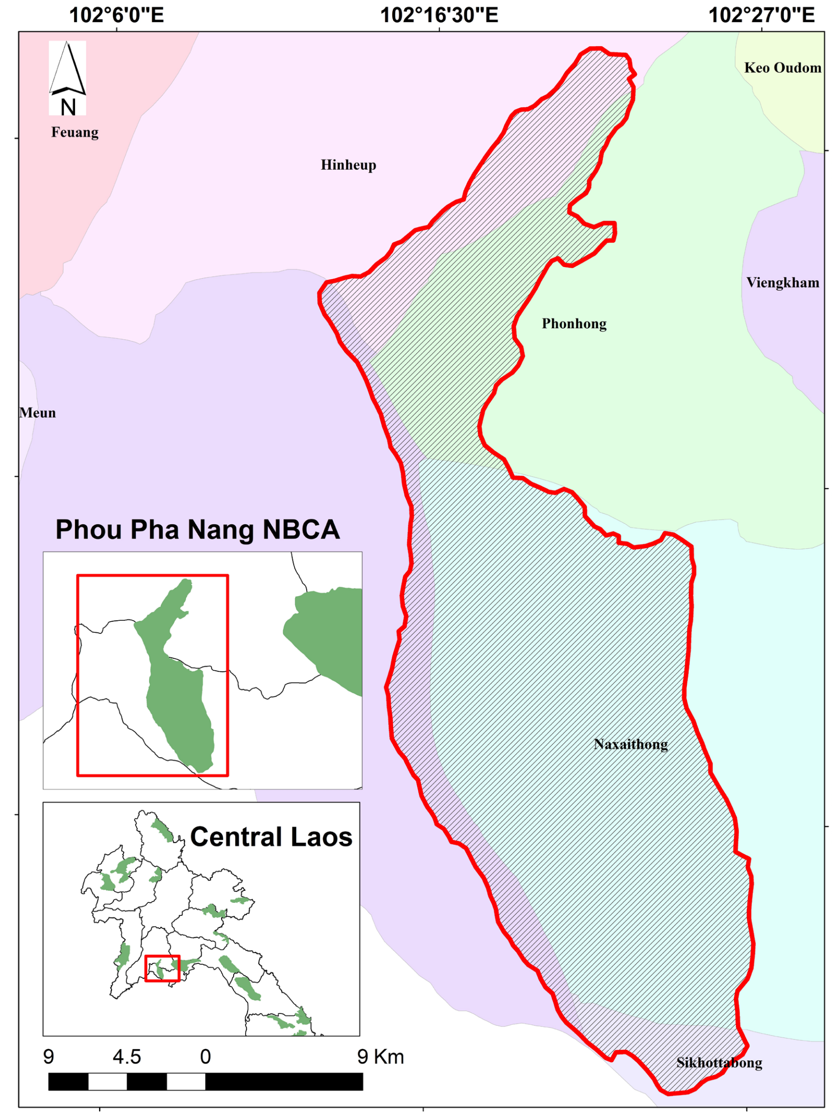

Figure 1. The study area, Phou Pha Nang NBCA, Central Laos.

2.2. Datasets

2.2.1. Planet NICFI Satellite Imagery

To capture fine-scale deforestation events that may be missed by medium-resolution sensors (e.g., Landsat or Sentinel-2), this study utilized high-resolution satellite imagery provided by the Planet Norway's International Climate and Forests Initiative (NICFI) program. The dataset consists of normalized analytic basemaps for Asia, offering a spatial resolution of approximately 4.77 meters, four-band (RGB-NIR) PlanetScope imagery for tropical ecosystem monitoring. Evaluating these continuous, monthly surface-reflectance basemaps is particularly advantageous during the January-to-March tropical dry season. In remote sensing, tropical optical imagery is frequently hindered by persistent cloud cover. However, the January-to-March period yields reduced precipitation and cloud interference, maximizing high-fidelity, clear-sky pixels. This temporal window enables researchers to fully leverage the dataset's monthly cadence to detect small-scale forest disturbances typically obscured during wet seasons. Specifically, we utilized the standard biannual mosaics available prior to September 2020, and the monthly cadence mosaics available thereafter, which yielded exactly 3 mosaics per January-March dry season for the years 2021-2025.

Furthermore, this dry period coincides with accelerated anthropogenic forest degradation—such as logging, mining, and agricultural clearing—due to improved terrain accessibility, alongside a peak in fire prevalence. Utilizing the multispectral data, particularly the Near-Infrared band for vegetation indices, allows scientists to accurately track burn scars and rapid canopy loss, making these specific monthly mosaics indispensable for precise deforestation assessments. The imagery includes four spectral bands: Blue (465 - 515 nm), Green (500 - 590 nm), Red (690 - 670 nm), and Near-Infrared (NIR) (780 - 860 nm). The high spatial resolution of this dataset allows for the detection of small-scale logging activities and canopy gaps consistent with the fragmentation often observed in tropical protected areas.

2.2.2. Validation Data

For the automated generation of validation data, high resolution imagery from Google Earth was employed. A total of 500 points was visually interpreted. This dataset served exclusively as an independent ground-truth reference to conduct a formal accuracy assessment of the classification outputs, separate from the model training process.

2.3. Data Preprocessing and Compositing

All image processing was conducted within the Google Earth Engine (GEE) cloud computing platform. The temporal scope of the study spanned from 2015 to 2025. To mitigate the influence of cloud cover, shadows, and seasonal phenological variations (e.g., leaf-off phases in deciduous species), we generated annual median composites.

For each year in the sequence 2015, 2025, the collection was filtered from January 1st to March 31st to align with the tropical dry season. A median reducer was applied pixel-wise across the temporal stack. This approach prioritizes the most representative pixel value for the year, effectively filtering out transient noise such as clouds or aerosols, resulting in a cloud-free, four-band (R, G, B, N) composite for each year. 2015 was established as the baseline reference year for forest cover, with subsequent years analyzed for cover change.

2.4. Machine Learning Classification

2.4.1. Algorithm Selection

While recent studies have successfully employed Deep Learning architectures like U-Net for tropical forest mapping, such methods often require extensive manual labeling and external GPU processing. To implement a scalable, computationally efficient workflow entirely within GEE, we adapted the classification strategy to use a Random Forest (RF) classifier. Random Forest is a non-parametric ensemble learning method that is robust against overfitting and handles high-dimensional spectral data effectively.

2.4.2. Training Sample Generation

To mitigate subjective interpreter bias and minimize manual digitization efforts, we implemented an automated training data extraction protocol. The European Space Agency (ESA) WorldCover 2021 product was utilized as the reference baseline. We reclassified the study area into a binary stratification scheme: “Tree Cover” (WorldCover Class 10) and “Non-Tree Cover” (an aggregation of all remaining thematic classes). Based on this stratification, a total of 2000 reference points were generated across the Phou Pha Nang boundary using a stratified random sampling design for model training. At each point location, spectral reflectance features were extracted from the 2021 Planet NICFI composite. The 2021 temporal baseline was specifically selected to synchronize the predictor variables with the ESA reference labels, thereby minimizing temporal discrepancies and ensuring robust label consistency.

2.4.3. Model Training and Application

The Random Forest classifier was initialized with 50 decision trees. The model was trained using the extracted spectral properties (Red, Green, Blue, and NIR) as predictors and the binary class (Forest/Non-Forest) as the response variable. Once trained on the 2021 data, this classifier was applied to the entire time series of annual dry-season composites (2015-2025). This temporal extension was justified under the premise that the broad spectral distinction between forest and non-forest classes remains sufficiently stable across dry-season mosaics for robust inter-annual loss mapping. This process yielded a binary forest_mask for every year, where a value of 1 represents forest cover and 0 represents non-forest.

2.5. Deforestation Detection and Quantification

2.5.1. Temporal Change Logic

In this study, deforestation is operationalized as the unidirectional transition of a pixel from a “Forest” to a “Non-Forest” land cover class between consecutive observation years. To quantify these transitions, we employed a post-classification comparison trajectory approach. For any given spatial unit (pixel) i and year t (where t € [2016, 2025]), a discrete deforestation event, denoted as $L_{i,t}$, is mathematically defined as:

$$L_{i,t} = \begin{cases} 1, & \text{if } \left(C_{i,t-1} = \text{Forest}\right) \wedge \left(C_{i,t} = \text{Non-Forest}\right) \\ 0, & \text{otherwise} \end{cases}$$

where $C_{i,t}$ represents the classified land cover state of pixel i at time t. This strict Boolean logic ensures the isolation of definitive forest removal events. Consequently, our methodology quantifies gross forest loss; while subsequent secondary forest regrowth or afforestation may occur in later years, this analysis intentionally isolates the primary deforestation event to prevent the conflation of forest loss and recovery dynamics.

2.5.2. Area Estimation

To quantify the extent of deforestation, pixel counts of the detected loss areas were converted to area units (hectares). The area calculation was performed using the ee.Image.pixelArea() function, which accounts for the area distortion inherent in projected coordinate systems. We utilized the reduceRegion function with a summation reducer at the native scale of the Planet imagery (approximately 4.77 m) to ensure high precision in the statistical output.

2.5.3. Spatiotemporal Mapping

A "Year of Loss" map was generated to visualize the spatiotemporal progression of deforestation. An iterative algorithm was applied to the time series, assigning the pixel value equal to the year in which the deforestation event occurred. If a pixel underwent deforestation in 2018, for example, its value in the final map would be 2018. Pixels that remained stable forest throughout the decade (2015-2025) or were non-forest at the baseline (2015) were masked out to isolate disturbance events.

2.6. Validation and Export

An independent accuracy assessment was performed using the 500 visually interpreted Google Earth points to calculate a confusion matrix for the classification outputs. Additionally, visual inspection was conducted against the high-resolution 2024 Planet composites to verify the coherence of the deforestation patterns. The final outputs, including annual deforestation statistics (CSV), the cumulative Year of Loss map (GeoTIFF), and forest cover maps for the baseline (2015) and final (2025) years, were exported for further analysis. The statistical results provided the annual rate of forest loss in hectares, enabling an assessment of deforestation trends within the protected area over the last decade.

3. Results

3.1. Spatiotemporal Dynamics of Deforestation in Phou Pha Nang NBCA

The analysis of the Random Forest classified land cover datasets from 2015 to 2025 reveals a pronounced and accelerating trajectory of habitat loss within the Phou Pha Nang NBCA in the Vientiane Prefecture of Laos. The classification achieved an Overall Accuracy of 94% and a Kappa coefficient of 0.96. The detailed confusion matrix is presented in **Table 1**, demonstrating robust performance for both the Forest and Non-Forest classes. For the purpose of this analysis, deforestation was strictly defined as the discrete conversion of a spatial pixel from a "Forest" state (classified by the RF model) to a "Non-Forest" state between consecutive years. Applying this pixel-level conversion metric, our results demonstrate a severe contraction and fragmentation of the protected area's forest canopy over the decadal timeframe.

Table 1. Confusion matrix and class-level accuracy metrics ($n = 500$).

Classes	Forest	Non-forest	User's Accuracy
Forest	245	12	95.3%
Non-forest	18	225	92.6%
Producer's Accuracy	93.2%	94.9%	**Overall Accuracy: 94%**

As illustrated in Figure 2, the spatial distribution and density of non-forest areas—represented by the dark pixels—have expanded dramatically. In the baseline year of 2015, the forest matrix (indicated by grey pixels) remained largely contiguous. Early indicators of deforestation were relatively isolated, primarily manifesting as small, fragmented pockets sparsely distributed across the central and southern regions, alongside minor edge-effect disturbances near the eastern boundaries.

By 2025, the landscape structure had fundamentally shifted. The comparative classification map highlights a massive proliferation and agglomeration of non-forest pixels. The previously isolated patches observed in 2015 have noticeably coalesced into expansive, continuous tracts of cleared or severely degraded land, deeply penetrating the core of the reserve. This concentrated pixel transition is most aggressive throughout the central and lower-middle corridors of the NBCA, indicating systematic encroachment and sustained land-use conversion rather than random, localized ecological disturbances. While the northernmost tip of the protected area exhibits greater resilience and retains a more cohesive forest cover, it is increasingly threatened by the advancing fragmentation migrating from the south.

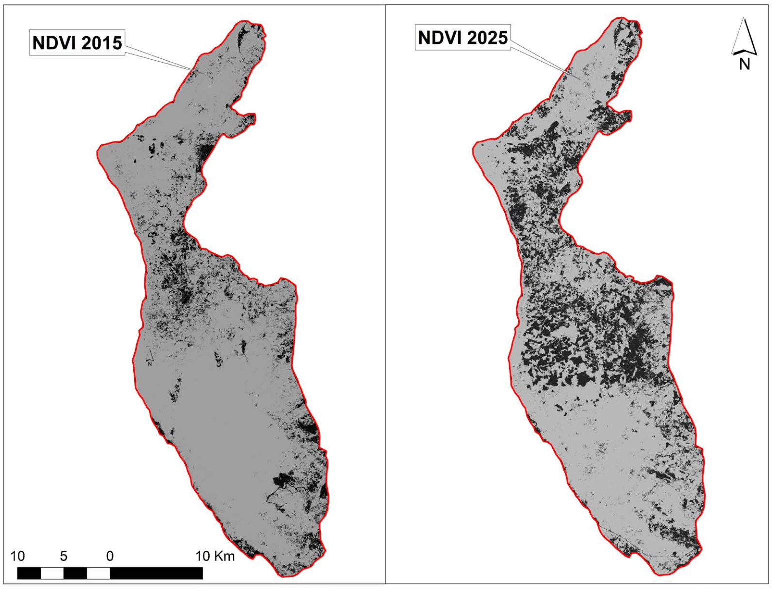

Figure 2. The spatial distribution forest and non-forest areas in 2015 and 2025.

Given that the Phou Pha Nang NBCA is a critical ecological refuge essential for maintaining regional biodiversity and watershed integrity, this extensive transition from "Forest" to "Non-Forest" states represents a severe environmental compromise. The spatial footprint of the 2025 data explicitly shows that the central watershed regions have borne the brunt of this deforestation. The pronounced vegetative loss observed over this ten-year period strongly underscores the urgent need for reassessing current conservation enforcement strategies within this vital Laotian protected area.

3.2. Annual Deforestation Trends and Spatial Distribution (2016-2025)

To further elucidate the temporal progression and geographic distribution of forest loss, annual deforestation events were quantified and mapped from 2016 to 2025 (**Figure 3**). The quantitative analysis of the deforested area reveals a highly fluctuating but ultimately escalating trend in habitat conversion over the study period. In 2016, an initial high deforestation extent of 6181.43 hectares was recorded. However, this was followed by a marked deceleration, dropping to 2918.29 hectares in 2017 and reaching its lowest point of 2256.65 hectares in 2018. Following this minimum, a localized spike reached 3848.19 hectares in 2019, before stabilizing temporarily at 2668.24 hectares in 2020 and 2804.59 hectares in 2021.

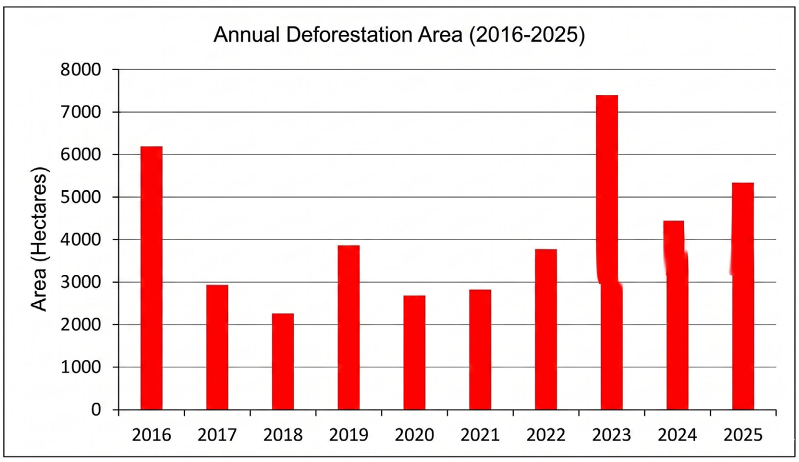

Figure 3. The Annual Deforestation Areas (Hectares) from 2016 to 2025. This illustrates significant fluctuations in forest cover loss within the Phou Pha Nang National Biodiversity Conservation Area (NBCA) over a decadal period. Deforestation peaked in 2016, followed by a general decline in 2018. However, a sharp resurgence occurred in 2023, marking the highest recorded loss during the study period. While a subsequent decrease was observed in 2024, the rate climbed again to over 5000 hectares in 2025.

A dramatic and alarming shift occurred in the latter half of the decade. Following a steady increase to 3761.28 hectares in 2022, the annual deforestation area surged significantly, peaking in 2023 at an unprecedented high of 7367.28 hectares—the most severe singular year of forest loss recorded in this analysis. Although the rate temporarily decreased in 2024 to 4428.05 hectares, it climbed again to 5327.79 hectares by 2025. This sustained elevation in the concluding years of the study underscores a renewed and intensifying pressure on the NBCA's ecosystems.

The accompanying spatial map of annual deforestation further contextualizes these statistical trends by illustrating the specific geographic loci of these conversion events. The spatial distribution clearly indicates that the massive forest losses observed during the peak years of 2023, 2024, and 2025 (represented by the orange, magenta, and prominent yellow-orange hues, respectively) are heavily concentrated within the central and lower-middle sectors of the protected area. Rather than occurring as dispersed, isolated patches, the recent deforestation fronts appear to expand contiguously from previously degraded zones, creating expansive clearings that dissect the core forest matrix. Conversely, the extreme northern tip and certain eastern peripheral regions remained relatively unimpacted during these peak years. This distinct spatiotemporal pattern—characterized by escalating annual rates concentrated in the reserve's core—highlights critical ecological vulnerabilities and points to systematic, large-scale anthropogenic drivers operating within the central watershed regions of the Phou Pha Nang NBCA.

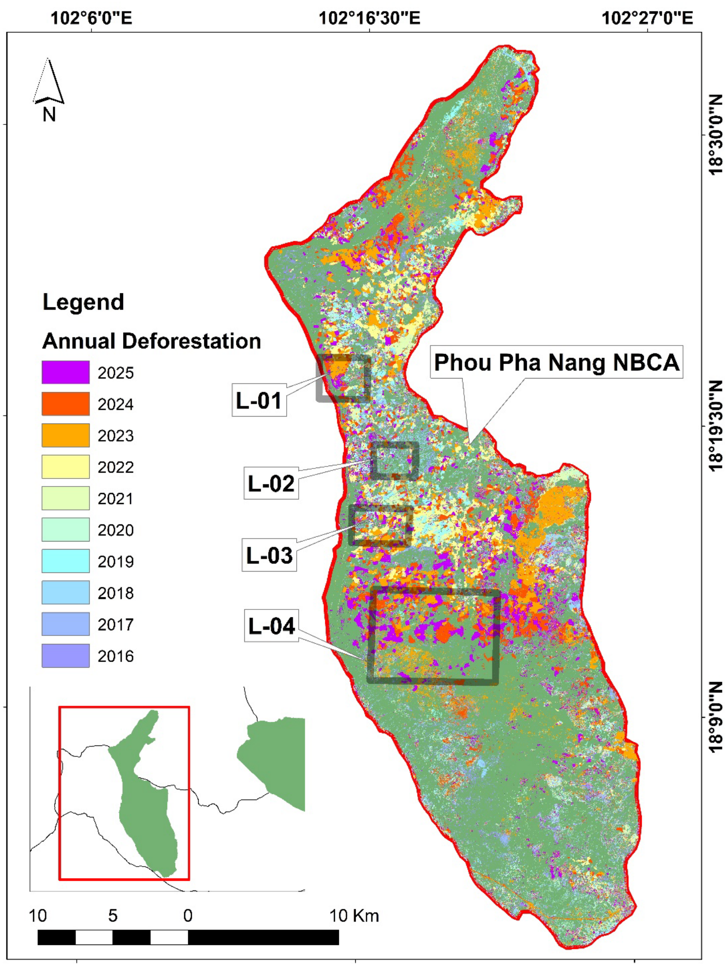

Figure 4. The annual deforestation distribution from 2016 to 2025.

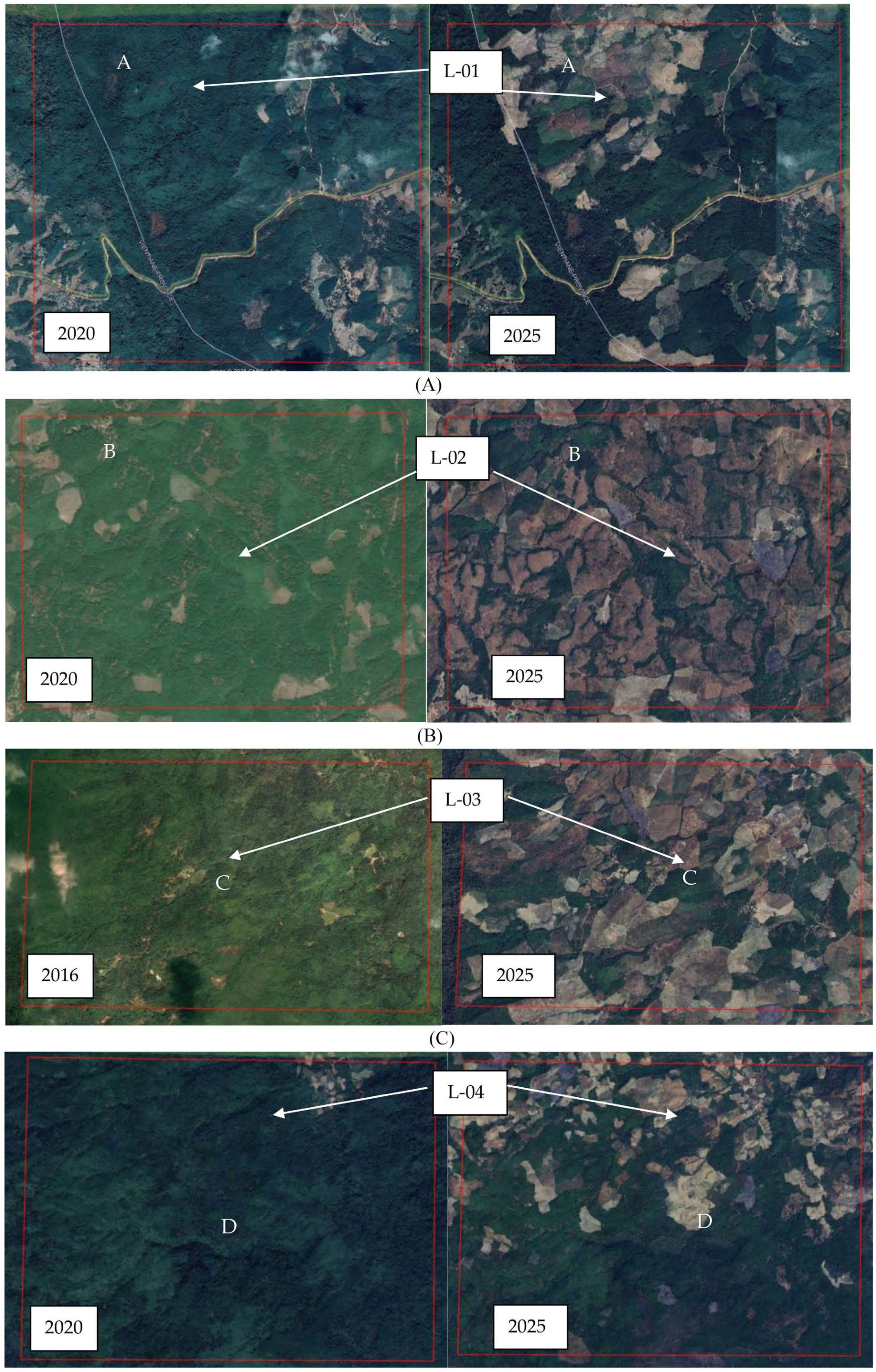

Figure 5. (A) Images from Google Earth indicating Deforestation between 2020 and 2025, L-01; (B) Images from Google Earth indicating Deforestation between 2020 and 2025, L-02; (C) Images from Google Earth indicating Deforestation between 2016 and 2025, L-03; (D) Images from Google Earth indicating Deforestation between 2016 and 2025, L-04.

The provided high-resolution Google Earth time-series imagery reveals a stark and concerning temporal progression of deforestation within the Phou Pha Nang NBCA in Laos. By conducting a comparative analysis of multi-temporal satellite data across four distinct geographic locations (L-01 through L-04 in **Figure 4**) between 2016 and 2025, a pronounced trajectory of habitat fragmentation, canopy degradation, and anthropogenic encroachment is highly evident.

Location 1 (**Figure 5(A)**): Early-Stage Disturbance in Figure A (L-01), the temporal transition from 2020 to 2025 captures the rapid onset of forest disturbance. The 2020 baseline exhibits a relatively homogenous, closed-canopy forest characterized by low surface reflectance (dense, dark green vegetation). However, the 2025 imagery reveals an increasing frequency of high-albedo, irregular patches. These spectral shifts signify localized clear-cutting and the perforation of continuous forest cover, serving as early spatial indicators of human encroachment penetrating the protected zone.

Location 2 (**Figure 5(B)**): Severe Landscape Fragmentation Figure B (L-02) demonstrates a drastic land-cover transformation over the same five-year epoch. The imagery exposes severe landscape fragmentation, shifting from a contiguous forest matrix to a highly interspersed "patchwork" topology. The widespread emergence of pale, barren tracts indicates exposed soils with high spectral reflectance. This spatial pattern is a classic remote sensing signature of systemic land use and land cover change, strongly correlated with slash-and-burn agriculture, illicit logging, or the aggressive expansion of monoculture plantations compromising the NBCA's borders.

Location 3 (**Figure 5(C)**): Longitudinal Canopy Erosion Figure C (L-03) provides an extended longitudinal perspective, contrasting the ecosystem's baseline state in 2016 with its degraded condition in 2025. The 2016 optical data establish a baseline of a robust, primary forest canopy with negligible anthropogenic disturbance. Over the nine-year temporal baseline, the imagery captures the insidious and cumulative erosion of this vital green infrastructure. Initial, small-scale spatial incisions have steadily coalesced into extensive tracts of degraded land and secondary growth.

Location 4 (**Figure 5(D)**): Large-Scale Contiguous Clearing Figure D (L-04) further corroborates this alarming trend by illustrating widespread, intensive canopy loss. Comparing the dense, uniform forest cover of the baseline imagery against the highly heterogeneous 2025 landscape, there is a pronounced spatial shift from natural forest to cleared, mosaic agricultural plots. The scale and geometric nature of these recent clearings suggest highly organized or mechanized land conversion, presenting a direct and immediate threat to the core conservation zones of the region.

Collectively, these multi-temporal datasets provide empirical, irrefutable visual evidence of accelerating anthropogenic forcing on the Phou Pha Nang NBCA. The systematic transition from closed-canopy biomes to fragmented, high-reflectance exposed earth emphasizes the critical necessity for continuous, high-cadence spatial monitoring, automated deforestation alerting systems, and stringent ground-level conservation enforcement to mitigate the irreversible loss of this vital biodiversity hotspot.

4. Discussion

Our decadal analysis (2015-2025) of the Phou Pha Nang NBCA reveals an alarming and accelerating trend of deforestation, culminating in unprecedented forest loss between 2023 and 2025. Utilizing high-resolution Planet NICFI imagery and Random Forest classification, we identified a definitive shift from isolated, fragmented disturbances to extensive contiguous clearings, heavily concentrated within the central and lower-middle corridors of the protected area.

These findings align with broader regional dynamics in Southeast Asia, where state-promoted land concessions and foreign direct investment have historically catalyzed the conversion of natural forests into industrial tree plantations, notably rubber, acacia, and eucalyptus (Azizan et al., 2021; Estoque et al., 2019; Gomat et al., 2024; Liu et al., 2025). The dramatic surge in forest clearance observed from 2023 onwards suggests a severe intensification of anthropogenic pressures. This acceleration could be driven by post-pandemic economic recovery initiatives or expanding cross-border agricultural demands (Sperling et al., 2022). Furthermore, the contiguous and aggressive nature of the recent canopy loss indicates large land conversion rather than localized small-scale subsistence farming.

The profound fragmentation of the Phou Pha Nang core poses critical threats to regional ecological integrity. As a vital biological refuge, the rapid erosion of continuous natural canopy jeopardizes endemic biodiversity and compromises essential watershed services. If this trajectory continues unabated, the ecological resilience of the region will be permanently undermined, directly challenging Laos's national carbon sequestration and biodiversity conservation targets (Estoque et al., 2019; Kenney-Lazar, 2012; Ma et al., 2024).

Despite the robustness of our high-resolution methodology, this study acknowledges certain limitations. The primary constraint is the binary "Forest vs. Non-Forest" classification paradigm. While highly effective for tracking initial clearing, this metric struggles to differentiate between intact natural forests and mature, full-canopy industrial plantations that exhibit similar spectral reflectance over time (Ferrer Velasco et al., 2022; Xiao et al., 2024). Furthermore, reliance exclusively on optical imagery means persistent wet-season cloud cover could obscure critical, transient phenological phases needed for finer species differentiation.

Future research must address these technical gaps by integrating Synthetic Aperture Radar (SAR) data, such as Sentinel-1, with dense optical time series to bypass cloud cover issues and capture structural canopy differences. Enhancing the classification model to definitively separate natural mixed deciduous forests from specific commercial plantations using advanced harmonic analysis is critical (Jiao et al., 2022; Romano, Ricci, & Gentile, 2025). Finally, extensive field-based ground-truthing is urgently recommended to translate these remote sensing findings into actionable, targeted enforcement policies for the NBCA.

5. Conclusions

This decadal analysis (2015-2025) highlights a critical and escalating ecological crisis within the Phou Pha Nang NBCA. By leveraging high-resolution Planet NICFI imagery and cloud-based machine learning, this study provides empirical evidence of severe, contiguous canopy loss, particularly surging between 2023 and 2025. The spatial patterns indicate a systematic anthropogenic encroachment into the core of the protected area, deeply compromising its integrity as a vital regional watershed and biodiversity refuge. While our binary classification approach successfully quantified the spatial extent of these disturbances, future monitoring efforts must incorporate multi-sensor data, such as SAR, to reliably distinguish natural forest matrices from expanding industrial plantations or small agriculture. Additionally, integrating socio-economic spatial modeling is necessary to identify the localized, underlying drivers of the recent deforestation surge. Comprehensive field-based ground-truthing and subsequent carbon stock assessments will also be vital to fully quantify the environmental toll. The increasing pace of habitat loss shown here highlights an urgent need to improve current conservation efforts and resource management before the ecosystem of Phou Pha Nang suffers permanent damage.

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Conflicts of Interest

The authors declare no conflicts of interest.

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