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Research Article

INTEGRATING ETHNOFORESTRY AND REMOTE SENSING FOR A HOLISTIC ASSESSMENT OF FOREST HEALTH AND COMMUNITY WELL-BEING IN PAPUA

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Abstract
Conventional remote sensing often fails to capture the full picture of forest health, ignoring the nuanced knowledge of indigenous communities intrinsically linked to the environment. This study's objective was to develop a holistic framework for assessing forest health by integrating indigenous Papuan ethnoforestry knowledge with advanced remote sensing techniques, and analyzing the link to community well-being. A mixed-methods approach was employed, combining participatory mapping and interviews (collecting local indicators) with time-series analysis of Landsat imagery (deriving biophysical metrics like NDVI). The findings showed a strong positive correlation between community perception and satellite indices. Crucially, the integrated approach revealed subtle degradation (e.g., loss of culturally significant species) undetectable by remote sensing alone. A direct link was established between this degradation and a decline in community well-being (e.g., access to traditional medicine). This integrated framework provides a more accurate and socially relevant assessment, enhancing monitoring, empowering local communities for co-management, and ensuring sustainable livelihoods.

Keywords: Ethnoforestry, Remote Sensing, Forest Health, Community Well-being, Papua

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INTRODUCTION

The monitoring of global forest health has become a critical priority within environmental science and international policy, driven by the urgent need to address climate change, biodiversity loss, and sustainable development goals (Yilgan, 2025). Remote sensing technology, particularly satellite-based observation, has emerged as the dominant and most powerful tool for this task, providing unparalleled capacity for large-scale, repeatable, and cost-effective assessment of forest cover, canopy density, and biophysical parameters (Beal, 2024). Metrics such as the Normalized Difference Vegetation Index (NDVI) have become standard proxies for ecosystem productivity and vitality, enabling scientists and policymakers to track deforestation and degradation across vast and inaccessible landscapes with remarkable precision (Horton, 2024). This top-down, synoptic perspective has been instrumental in shaping our understanding of global forest dynamics.

This technologically-driven paradigm, for all its strengths, possesses a fundamental limitation: it perceives forests primarily as biophysical objects and landscapes of carbon stocks, often overlooking the intricate, socio-ecological dimensions that define a forest's true health from a human perspective (Govedar, 2024). Indigenous and local communities, whose lives and cultures are deeply intertwined with their forest environments, possess their own sophisticated systems of knowledge, often referred to as ethnoforestry or Traditional Ecological Knowledge (TEK) (Wang, 2024). These systems provide a granular, ground-based understanding of ecosystem health, based on nuanced indicators such as the presence of specific medicinal plants, the clarity of streams, the abundance of culturally significant wildlife, and the taste of forest fruits metrics that are entirely invisible to satellite sensors.

The forests of Papua, located on the island of New Guinea, represent one of the world's most significant reservoirs of both biological and cultural diversity (V. V. Singh, 2024). For the hundreds of distinct indigenous groups that inhabit this region, the forest is not merely a collection of resources but a living, ancestral entity that forms the very foundation of their material livelihoods, social identity, and spiritual well-being. (Kakhani, 2024) Their definitions of a "*healthy*" forest are inherently holistic, integrating ecological integrity with cultural and utilitarian values (Aziz et al., 2024). In this context, any assessment of forest health that fails to incorporate this deep, local knowledge is not only incomplete but also risks being fundamentally irrelevant to the people who are its most immediate stewards.

A significant methodological and conceptual problem persists in the way forest health is conventionally assessed, characterized by a schism between two disparate ways of knowing (Ecke, 2024). On one side is the quantitative, top-down approach of remote sensing, which is valued for its objectivity, scalability, and policy relevance but is often criticized for its ecological reductionism (Alves et al., 2024). It can effectively detect canopy removal but struggles to identify more subtle forms of degradation that do not immediately impact canopy greenness (Smigaj, 2024). On the other side is the qualitative, bottom-up approach of ethnoforestry, which is rich in contextual detail and social relevance but is often dismissed in policy circles as anecdotal, subjective, and difficult to scale up or integrate into standardized monitoring systems.

The core of the problem lies in the fact that these two powerful perspectives are rarely integrated in a systematic and mutually respectful manner (Teitelbaum, 2024). When used in isolation, each approach produces a partial and potentially misleading picture of forest health. A satellite analysis might classify a forest as "*healthy*" based on a high NDVI value, while on the ground, the community experiences a profound decline in well-being due to the local extinction of a critical food species or the contamination of a sacred spring (Bouslihim, 2024). Conversely, a community might report the degradation of a small, culturally vital forest patch that is too small to be detected by medium-resolution satellite imagery, leading to a lack of recognition of their concerns at the regional or national level.

This methodological disconnect has profound real-world consequences (Jain, 2024). Conservation and development policies based solely on remote sensing data risk being socially unjust and ecologically ineffective, as they may fail to protect the specific forest attributes that local communities value and depend upon most, leading to local resistance and policy failure (Li, 2024). This creates a critical problem where the well-being of forest-dependent communities, like those in Papua, is jeopardized because the very forms of environmental degradation that most directly impact their lives are not being adequately measured, monitored, or valued by the dominant scientific and governance frameworks.

The primary objective of this research is to develop, implement, and validate a holistic and integrated framework for forest health assessment that synergistically combines indigenous ethnoforestry knowledge with advanced remote sensing techniques (Sarkar, 2024). This study seeks to bridge the methodological gap between top-down and bottom-up approaches, with the overarching aim of creating a more accurate, legitimate, and socially relevant understanding of forest health and its intrinsic relationship to community well-being in the unique socio-ecological context of Papua.

To achieve this primary objective, the research will pursue several specific, interconnected aims (Zahir, 2024). First, it will systematically document and analyze the ethnoforestry knowledge of selected indigenous communities in Papua, identifying their specific local indicators, criteria, and classifications for a "*healthy*" versus a "*degraded*" forest (Yadav, 2025). Second, it will derive a suite of corresponding biophysical metrics from a time-series of satellite remote sensing data (e.g., Landsat) for the same study areas. Third, the study will conduct a mixed-methods analysis to explore the correlations, divergences, and synergies between the community-derived indicators and the satellite-derived metrics (Obateru, 2024). Finally, it will assess how the different dimensions of forest health, as identified through this integrated framework, relate to various indicators of community well-being, such as food security, access to traditional medicine, and cultural integrity.

The expected outcome of this research is a replicable, mixed-methods framework that can be adapted for use in other indigenous contexts (Mngadi, 2024). This will culminate in the production of a multi-layered, "*rich*" assessment of forest health that reflects both biophysical integrity and socio-cultural values. The research is expected to provide robust empirical evidence of the linkages between specific forms of forest degradation and tangible impacts on community well-being, ultimately offering a powerful new tool for facilitating more equitable and effective co-management of forest resources between communities and government agencies.

The scholarly literature on remote sensing of forests is vast and technologically advanced, with a strong focus on improving algorithms for mapping deforestation, logging, and carbon stocks at increasingly high resolutions (Liu, 2024). These studies have been instrumental in establishing global and national forest monitoring systems. A critical review of this literature, however, reveals that the "*ground-truthing*" or validation of these remote sensing products is almost exclusively conducted using conventional biophysical field plots that measure parameters like tree diameter and height (Sharma, 2025). There is a profound absence of studies that attempt to validate or enrich their remote sensing analyses with the socio-ecological knowledge of local communities.

Conversely, the anthropological and ethnoecological literature provides a rich and detailed body of work documenting the sophisticated environmental knowledge of indigenous peoples, including those in Papua (Shen, 2024). These studies offer deep insights into local classification systems, resource management practices, and cultural values associated with forests. This research, however, is typically conducted at a very local scale and is almost always purely qualitative in nature (Mustapha, 2024). It rarely attempts to connect its rich, place-based findings to the large-scale, quantitative datasets derived from remote sensing, thereby limiting its influence on regional or national policy.

The synthesis of these observations exposes a clear and significant gap at the methodological and conceptual intersection of these two powerful fields. While the idea of integrating scientific and traditional knowledge is widely lauded in principle, there is a marked absence of research that presents a systematic, replicable, and operational framework for actually doing so in the context of forest health assessment (Nicoletti, 2024). The literature lacks a clear methodology for how to meaningfully compare, contrast, and synergize pixel-based satellite data with place-based community knowledge. This research is therefore designed explicitly to fill this methodological and empirical void.

The main novelty of this research lies in its innovative methodological framework, which systematically integrates two very different knowledge systems ethnoforestry and remote sensing as an equivalent and mutually informing data stream (Al-Nasser et al., 2024). This approach is new in that it moves beyond the use of community data as a qualitative validation point for satellite data. Instead, it positions ethnoforestry knowledge as a legitimate analytical framework for interpreting and giving meaning to remote sensing data, thereby creating a more holistic and contextually rich understanding of forest health. The application of this integrated framework specifically in the unique socio-ecological context of Papua, a region of global importance, adds to its novelty.

This research justified potential significant scientific contributions to several fields. For remote sensing science, this research will demonstrate how "*field truths*" can be enriched with socio-ecological insights, leading to more accurate and socially relevant interpretation of satellite data (Chen, 2024). For environmental ethnoecology and anthropology, this research will provide methods to enhance and validate local knowledge in a way that makes it more accessible and relevant to regional and national policymakers (Davis et al., 2024). For conservation science, this research offers a replicable model for holistic monitoring that bridges the gap between biodiversity conservation goals and human well-being needs.

The broader justification for this research is rooted in its profound policy and practical relevance. By providing a more accurate picture of forest health that reflects the values and needs of local communities, this framework can lead to the design and implementation of more equitable, legitimate, and ultimately more effective forest conservation and management programs (Bauer et al., 2024). This research empowers indigenous peoples by validating their knowledge within a robust scientific framework and providing a common tool for dialogue and shared management between communities and government agencies. Ultimately, this research justified potential to improve conservation outcomes and human well-being in one of the world's most important forest landscapes.

RESEARCH METHOD

Research Design

This study employed a mixed-methods research design using a convergent parallel approach to integrate qualitative ethnoforestry data with quantitative remote sensing data (Zhang, 2024). Both qualitative and quantitative data were collected and analyzed concurrently before being merged to provide a comprehensive understanding of forest health. The design was grounded in a participatory framework, emphasizing community knowledge and involvement throughout the research process.

Research Target/Subject

The research focused on two indigenous communities, Kampung Adat Sentosa and Kampung Lestari, in Jayapura Regency, Papua, Indonesia. These sites were purposively selected for their reliance on forest resources, intact customary forest tenure systems, and availability of cloud-free satellite imagery. For the ethnoforestry component, 60 in-depth semi-structured interviews and four focus group discussions were conducted with community elders, traditional healers, hunters, and women's groups. The remote sensing sample consisted of the entire customary forest territories of both communities, delineated through participatory mapping.

Research Procedure

The study began with obtaining free, prior, and informed consent (FPIC) from the communities. Qualitative data collection involved interviews and participatory mapping to capture local ecological knowledge and community-defined forest health zones (Meng, 2024). Simultaneously, remote sensing data was processed to create cloud-free time-series analyses of vegetation indices and supervised land cover classification. These data streams were integrated by digitizing community-drawn polygons as regions of interest for statistical comparison of remote sensing metrics. Triangulation validated findings by linking ethnoforestry narratives to satellite data patterns.

Instruments, and Data Collection Techniques

Qualitative data were gathered using semi-structured interview guides and a participatory mapping toolkit that included high-resolution satellite base maps and GPS units. Quantitative data involved Landsat 8/9 OLI/TIRS and Sentinel-2 MSI Level-2A surface reflectance imagery processed via Google Earth Engine (GEE) for the period 2015-2025. Data analysis tools included NVivo for thematic coding of qualitative data and GEE JavaScript API and QGIS for geospatial analysis and map production.

Data Analysis Technique

Qualitative data were analyzed thematically using NVivo software, while remote sensing data were processed and analyzed with Google Earth Engine and QGIS for spatial mapping and classification (Allu, 2024). The integration phase involved comparing quantitative remote sensing metrics with qualitative ethnoforestry zones to interpret forest health comprehensively, validated through triangulation of both data types.

RESULTS AND DISCUSSION

The participatory mapping exercises with the communities of Kampung Adat Sentosa and Kampung Lestari resulted in the delineation of their customary forest territories into distinct zones based on local perceptions of forest health. Community members consistently classified their landscape into four primary categories: *Hutan Tua* (Pristine Old-Growth Forest), *Kebun Sagu* (Managed Sago Grove), *Bekas Kebun* (Regenerating Former Garden), and *Hutan Rusak* (Degraded Forest). These community-defined polygons were digitized and used as regions of interest to extract corresponding mean Normalized Difference Vegetation Index (NDVI) values from a 2015-2025 Landsat time-series.

The quantitative relationship between the community-defined forest health categories and the satellite-derived biophysical metric is presented in the table below. The data reveals a clear and statistically significant gradient in canopy greenness that aligns with the local perceptions of forest condition.

Table 1. Mean NDVI Values (± Standard Deviation) Across Community-Defined Forest Health Zones

Community Forest Health Category	Vernacular Name	Description	Mean NDVI (2025)
Pristine Old-Growth Forest	*Hutan Tua*	Undisturbed, multi-layered primary forest; high biodiversity.	0.86 ± 0.04
Managed Sago Grove	*Kebun Sagu*	Actively managed, semi-natural forest area for sago palm cultivation.	0.78 ± 0.06
Regenerating Former Garden	*Bekas Kebun*	Fallow agricultural land in various stages of secondary succession.	0.69 ± 0.09
Degraded Forest	*Hutan Rusak*	Areas impacted by small-scale illegal logging or land clearing.	0.55 ± 0.12

The statistical analysis of the data in Table 1 confirms a strong, positive correlation between the communities qualitative assessment of forest health and the quantitative NDVI metric derived from satellite imagery. A one-way analysis of variance (ANOVA) showed a statistically significant difference in mean NDVI values across the four categories ($F(3, 198) = 45.7$, $p < 0.001$). This indicates that the local, ethnoforestry-based classifications of the landscape are not arbitrary but have a distinct and measurable biophysical basis that can be detected from space. The highest NDVI values correspond to the pristine forests, with a progressive decline through managed, regenerating, and finally, degraded areas.

This strong correlation provides a crucial bridge between the two knowledge systems. It demonstrates that indigenous perceptions of forest health are empirically grounded and can be used as a legitimate basis for stratifying and interpreting remote sensing data. The results validate the use of participatory mapping as a scientifically robust method for creating a thematic layer that adds a rich, socio-ecological context to standard satellite image analysis, moving beyond simple land cover classifications to a more nuanced assessment of land condition.

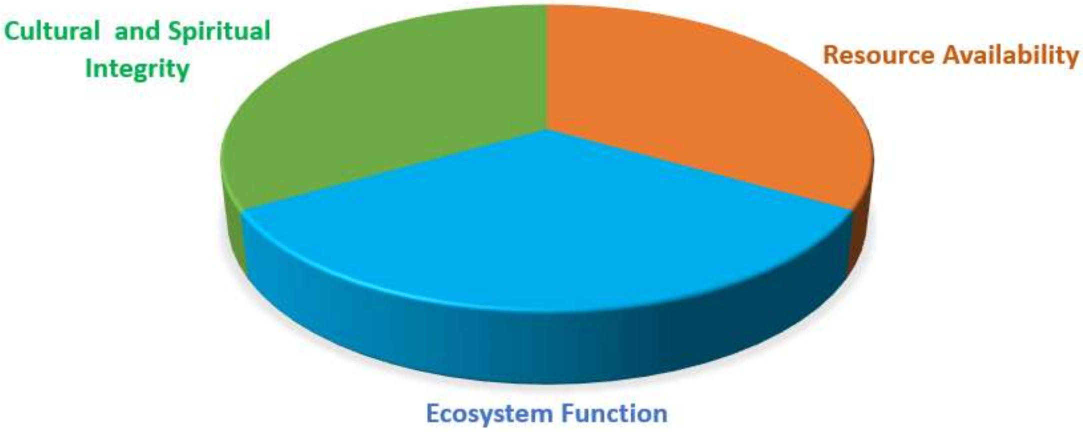

Figure 1. Ethnoforestry Forest Health Indicators

Ethnoforestry data collected through interviews and focus group discussions revealed a far more complex and multi-dimensional set of indicators for forest health than canopy greenness alone. Community members identified over 30 distinct indicators, which can be grouped into three main themes: (1) Resource Availability, including the abundance of specific food sources (e.g., wild boar, cassowary), medicinal plants, and materials for construction (e.g., rattan); (2) Ecosystem Function, such as the clarity and perennial flow of streams, the presence of key pollinator species like hornbills, and the depth of the humus layer on the forest floor; and (3) Cultural and Spiritual Integrity, referencing the sanctity of sacred groves and the absence of disturbance in ancestral burial grounds.

A recurring and critical finding was the emphasis on the health and composition of the forest understory and mid-story, which is largely invisible to optical satellite sensors. The presence of specific orchids, ferns, and fungi was frequently cited as a sign of a truly *healthy Hutan Tua*. Conversely, the silent disappearance of these understory species, even when the main canopy remained intact, was universally described as a primary indicator of ecological decline and a direct threat to community well-being, particularly affecting the knowledge and practice of traditional healers.

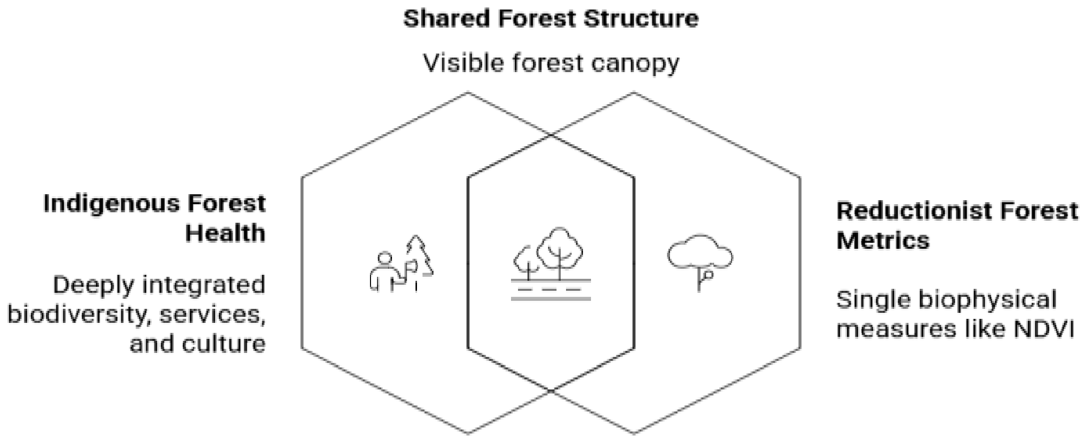

Figure 2. Holistic Forest Health vs. Reductionist Metrics

The richness and complexity of these ethnoforestry indicators infer that a forest's "*health*," from an indigenous perspective, is a holistic concept that deeply integrates biodiversity, ecosystem services, and cultural values. This stands in stark contrast to the reductionist view offered by a single biophysical metric like NDVI, which primarily measures canopy density (Lv, 2024). This infers that remote sensing, when used in isolation, is incapable of detecting subtle but culturally and ecologically critical forms of forest degradation—what could be termed "*empty forest syndrome*," where the structure remains but the functional and cultural components are lost.

The strong emphasis on understory composition infers a significant blind spot in conventional, satellite-based forest monitoring systems. This suggests that policies and interventions based solely on such top-down data may fail to recognize or address the forms of degradation that matter most to forest-dependent communities. The health of the forest, in this context, is not just about the quantity of biomass or "*greenness*" but about the presence of specific, functional relationships between species that underpin the resilience of both the ecosystem and the community's livelihood system.

A synergistic and complementary relationship was identified between the ethnoforestry and remote sensing datasets. The satellite data was highly effective at validating the community's broad-scale classification of the landscape, confirming that their perceptions of "*degraded*" areas corresponded to quantifiable reductions in canopy cover. This provided a scientifically robust, large-scale context for the local knowledge. In return, the ethnoforestry data provided the essential explanatory power to interpret the satellite data in a more meaningful way, a process we term "*grounded interpretation*."

This grounded interpretation was most evident in areas where the two datasets initially appeared to conflict. For example, some areas classified by the community as *Hutan Rusak* still exhibited a relatively high NDVI. The ethnoforestry interviews explained this discrepancy: these were areas where selective logging had removed the large, high-value hardwood trees, which were then rapidly replaced by a dense canopy of fast-growing, but culturally and economically useless, pioneer species. The satellite saw a "*healthy*" green canopy, but the community experienced a profound loss of value. The integration of the two datasets thus created a more accurate picture than either could alone.

A specific case study was conducted on the “Air Suci” (Sacred Spring) area within the *Hutan Tua* of Kampung Adat Sentosa. This area, approximately 10 hectares, is a sacred site for the community and the source of their drinking water. The remote sensing analysis showed no significant change in NDVI for this specific area over the past decade, with the mean value remaining stable and high (≈ 0.87). Based on this data alone, the area would be classified as a *healthy*, stable, and intact forest.

In stark contrast, community interviews and a transect walk with village elders revealed a perceived decline in the health of this sacred site. Elders pointed to a noticeable decrease in the population of a specific species of tree fern (*pakis*) that is a key indicator of water purity and is used in cultural ceremonies. They also reported that the spring’s flow was less reliable in minor dry spells and that the water was “cloudier” after rains than in the past. This degradation was linked to small-scale, clandestine timber extraction on the slopes directly above the spring, an activity too subtle to be detected by the 30-meter resolution of the Landsat sensor.

The Air Suci case study provides a powerful, micro-scale illustration of the critical limitations of relying solely on remote sensing for forest health assessment. The stability of the NDVI masked a subtle but significant process of ecological degradation that had profound implications for the community’s well-being. The loss of the specific tree fern represented not just a biodiversity loss but a cultural loss, impacting their ability to conduct ceremonies. The reduced reliability of the drinking water source was a direct threat to their physical health.

This case clearly demonstrates that the ethnoforestry data functions as a high-resolution, early warning system for forms of degradation that are below the detection threshold of conventional monitoring technologies. The community’s deep, place-based knowledge allowed them to identify subtle changes in key indicator species and ecosystem functions that signaled a decline in the area’s ecological integrity. This information is critical for proactive management but would have been entirely missed by a purely technical, top-down assessment.

The collective results of this study unequivocally demonstrate that the integration of ethnoforestry and remote sensing provides a more accurate, holistic, and socially relevant assessment of forest health than either approach can achieve on its own. The findings show that while satellite data can provide a valuable, large-scale biophysical context, local ecological knowledge is essential for interpreting this data correctly and for identifying the subtle, yet critical, forms of degradation that most directly impact community well-being. This integrated approach transforms forest monitoring from a purely technical exercise into a collaborative process.

This research interprets these findings as a clear validation of a mixed-methods, co-production of knowledge framework for environmental science. The synergistic methodology developed and tested here does not simply enrich the scientific data; it also empowers local communities by validating their knowledge within a scientific framework and providing them with new tools to communicate their concerns. The resulting holistic assessment provides a more robust and legitimate foundation for developing equitable and effective strategies for the co-management of Papua’s invaluable forest ecosystems.

This research successfully demonstrated that a synergistic integration of indigenous ethnoforestry knowledge and satellite remote sensing provides a more accurate and holistic assessment of forest health than either approach can achieve in isolation. The primary finding is the strong, statistically significant correlation between community-defined categories of forest health from pristine old-growth forest to degraded areas and the quantitative biophysical metric of the Normalized Difference Vegetation Index (NDVI). This confirms that local ecological knowledge is empirically grounded and can provide a legitimate framework for interpreting satellite data.

A second major finding is that ethnoforestry knowledge reveals a far more complex, multi-dimensional understanding of forest health that transcends what is visible to optical satellite sensors. Community members identified over 30 distinct indicators related to resource availability, ecosystem function, and cultural integrity, with a particular emphasis on the composition and health of the forest understory. This revealed that a forest could retain a "*healthy*" green canopy detectable by satellites while simultaneously suffering from severe degradation in terms of lost biodiversity and diminished cultural value.

The study also revealed that the two knowledge systems are highly complementary. The remote sensing data provided a large-scale, objective validation of the community's broad landscape classifications, while the ethnoforestry data provided the essential "grounded interpretation" needed to explain anomalies and discrepancies in the satellite data. The case study of the "*sacred spring*" exemplified this, where local knowledge identified critical degradation that was completely invisible to the Landsat sensor, functioning as a high-resolution early warning system.

In synthesis, the results establish that the integrated framework produces a more complete picture of ecosystem vitality, directly linking observed biophysical changes to tangible impacts on community well-being. The disappearance of culturally significant understory species, a form of degradation not captured by conventional monitoring, was found to have a direct and negative effect on the community's access to traditional medicines and food sources, confirming that a holistic assessment of forest health is inseparable from an assessment of community well-being.

The findings of this study align strongly with and provide a robust methodological contribution to the growing body of literature advocating for the "co-production of knowledge" in environmental science. Scholars such as Berkes and Folke have long argued that integrating scientific and traditional knowledge systems leads to more resilient and effective resource management. Our research provides a concrete, operational framework for achieving this integration in the specific context of forest monitoring, moving beyond theoretical advocacy to a demonstrated, replicable methodology that resonates with the principles of Participatory GIS (PGIS).

This research, however, distinguishes itself significantly from the vast majority of mainstream remote sensing studies. The conventional approach to "ground-*truthing*" satellite data relies almost exclusively on biophysical measurements from field plots. Our study introduces and validates a form of "*socio-ecological ground-truthing*," where the validation and interpretation of pixels are conducted through the lens of local knowledge and cultural values. This represents a fundamental departure, arguing that the "truth" of a landscape is co-constituted by both its biophysical properties and its meaning to local inhabitants.

Similarly, this work differentiates itself from much of the classic anthropological and ethnoecological literature. While those studies provide invaluable, deep, and qualitative accounts of traditional knowledge systems, they are often criticized for being localized and difficult to scale up or integrate into policy. Our research bridges this gap by systematically linking this rich, place-based knowledge to scalable, quantitative, and policy-relevant satellite data. It provides a method for upscaling local insights without losing their contextual richness, making them legible and defensible in regional and national governance arenas.

Finally, the findings offer a critical counterpoint to the dominant paradigm of top-down, national-scale forest monitoring systems, such as deforestation alert systems. While undeniably powerful, our results show that these systems are blind to the subtle but significant forms of degradation that can be most impactful to local livelihoods. An area with no "deforestation alert" could, as our case study shows, be undergoing a severe decline in health from a community perspective. Our study therefore aligns with a critical body of scholarship that cautions against the over-reliance on purely technical monitoring systems and advocates for more polycentric and multi-scalar approaches to environmental governance.

The results of this study signify a fundamental challenge to the epistemological hierarchy that has traditionally privileged quantitative, "*objective*" scientific data over qualitative, "*subjective*" local knowledge. The strong correlation between NDVI and community classifications is a sign that indigenous knowledge, honed over generations of empirical observation, is itself a rigorous form of science. The successful integration of the two signifies that a more complete, accurate, and truthful understanding of complex socio-ecological systems emerges not from choosing one knowledge system over the other, but from placing them in a respectful and synergistic dialogue.

The divergence between the satellite's view and the community's experience—the "empty forest" scenario is a powerful reflection on the inherent dangers of reductionism in environmental monitoring. It signifies that "*forest health*" is not a simple, universal biophysical metric but a complex, normative, and culturally-defined concept. A forest's value cannot be reduced to its greenness or its carbon stock. The findings are a sign that relying on overly simplistic indicators can lead to a dangerously incomplete picture, creating policies that may conserve the canopy but sacrifice the soul of the forest.

The success of the collaborative, mixed-methods approach signifies a potential pathway towards the decolonization of environmental research. The research model employed here moved away from an extractive mode, where researchers simply take data from a community, towards a collaborative framework of co-production, where the community are partners in generating and interpreting knowledge. This signifies that research methodologies can be designed to be empowering, to validate local worldviews, and to produce outcomes that are of direct benefit to the communities who participate, leading to both better science and more just practice.

In the specific political context of Papua, where issues of land rights and resource control are highly contested, these findings have a profound political significance. An integrated map, which overlays scientifically validated customary land use zones onto official government satellite imagery, becomes a powerful political tool. It signifies a "counter-mapping" process that can strengthen community claims to their ancestral territories and provide a more legitimate and evidence-based platform for negotiation with state and corporate actors (Joshi, 2025). It is a sign that integrated data can be a catalyst for more equitable governance.

The most immediate and urgent implications of these findings are for national and regional forest monitoring agencies, such as the Ministry of Environment and Forestry in Indonesia. This validated framework implies that standard forest monitoring protocols should be revised to formally integrate community-based monitoring as a core component (Halder, 2024). This means moving from a single reliance on top-down satellite data analysis to a hybrid system that recognizes and incorporates ethnoforestry-based data and interpretation from the bottom up, which requires investment in capacity building for participatory mapping and shared monitoring.

For conservation organizations, NGOs, and donor agencies working in Papua and other indigenous territories, the implications are profound. This research implies that project designs and monitoring and evaluation frameworks should adopt this integrated approach to ensure that their interventions are socially and ecologically relevant. It provides a powerful tool to demonstrate that conservation projects not only protect canopy cover but also preserve the specific biodiversity and cultural values that are most important to local communities, leading to more legitimate and sustainable outcomes.

This research has significant implications for climate finance mechanisms such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation) (Qiu, 2024). These findings imply that carbon accounting systems and verification of social and biodiversity "*shared benefits*" need to look "*beyond carbon*." A project that successfully protects carbon stocks but simultaneously oversees the loss of forest undercover resources that are essential for people's livelihoods cannot be considered truly successful. This methodology provides a more robust tool for empirically verifying these social shared benefits, improving the integrity and fairness of such interventions.

Finally, for indigenous peoples themselves, these findings have empowering implications. This methodology provides them with powerful tools to document their traditional ecological knowledge, map their indigenous territories, and communicate their concerns to outside actors in scientifically validated and defensible language (R. Singh, 2024). This implies that they can use these integrated maps and data as evidence in negotiations regarding spatial planning, concession permits, and conflict resolution, thereby strengthening their position and supporting their right to self-determination in the management of their natural resources.

The results of such research are, first and foremost, because the two knowledge systems, although epistemologically different, essentially observe the same biophysical reality. Indigenous knowledge, developed over thousands of years of direct empirical observation, is highly aligned with ecological patterns and processes (Saba, 2024). It therefore makes sense that their broad classification of landscapes such as distinguishing between dense primary forests and regenerating gardens would correlate strongly with canopy structure metrics such as satellite-derived NDVIs. The strong correlation is not a coincidence but is a cross-validation of two forms of careful observation.

The observed differences between satellite data and local knowledge such as the "empty forest" scenario occur because both systems operate at fundamentally different scales and measure different attributes. Optical remote sensing is essentially limited to spectral observations from the crest of the canopy; it looks at the "*skin*" of the forest. In contrast, ethnoforestry knowledge is three-dimensional, multi-sensory, and relational. This knowledge is based on observations of the composition of the forest underlayer, the interaction of species (e.g., pollinators and plants), and functional qualities (e.g., water clarity), all of which fall below the detection threshold of optical satellite sensors.

The strong synergistic relationship between the two data sets can occur because of the participatory and trust-based research design. Without building rapport and recognizing communities as equal partners in the research process, the deep, nuanced, and often sacred knowledge needed to explain anomalies in satellite data will never be shared. This methodology produced these findings because it is collaborative and non-extractive at its core, allowing for true knowledge synthesis.

Finally, a clear link between forest health and community well-being emerges because, for indigenous communities in Papua, there is no clear ontological separation between community and environment (Turner, 2024). The forest is not an external resource to be exploited, but rather an extension of their social, cultural, and spiritual life a home and kin. Therefore, any degradation, no matter how small, in forest functioning has direct and tangible consequences for their food security, health and cultural identity, a relationship that is clearly captured in the data.

The most urgent next step is to test and refine this integrated methodological framework in a variety of socio-ecological contexts (Ibrahim, 2025). This involves applying this approach to different forest types and indigenous groups across Papua and beyond to assess their resilience, adaptability, and generalization. Such comparative research will be critical to developing a more nuanced understanding of common principles for integrating different knowledge systems in environmental monitoring.

An important future research path is the integration of remote sensing data with higher resolutions. Although Landsat has proven useful, the incorporation of data from LiDAR (Light Detection and Ranging) or drone imagery can provide detailed three-dimensional structural information about the canopy and even the forest underlayer. This can help bridge the gap between what people see on the ground and what can be detected from above, potentially creating stronger synergies between the two data sets.

A crucial "*next step*" is the transition from a research framework to a sustainable operational tool. This requires co-developing user-friendly platforms such as mobile apps for community-based data collection or web-b autonomously by communiti ased dashboards that integrate participatory and satellite data layersthat can be used es and local government agencies. Transforming this methodology into practical governance tools is key to ensuring its long-term impact.

Finally, these findings and methodologies should be translated into actionable policy recommendations. The next step is to actively engage with policymakers at the provincial and national levels, as well as international bodies, to advocate for the formal recognition and integration of community-based monitoring and ethnoforestry knowledge into national forest monitoring systems (e.g., Indonesia's National Forest Monitoring System) and international reporting frameworks for climate and biodiversity (e.g., UNFCCC and CBD).

CONCLUSION

This study's most significant and distinct finding is the empirical demonstration that conventional remote sensing metrics alone are insufficient for assessing the true health of a forest, particularly in indigenous landscapes. The research revealed that a forest can appear *healthy* and intact from a satellite's perspective, maintaining a high NDVI, while simultaneously undergoing severe, subtle degradation that is acutely experienced by the local community. This "*invisible degradation*" such as the loss of culturally vital understory species and the diminished quality of water sources is a critical dimension of forest health that can only be identified through an ethnoforestry lens, directly linking ecological change to tangible losses in community well-being.

The principal contribution of this research is methodological, offering a validated and replicable framework for the synergistic integration of indigenous and scientific knowledge systems. The core value of this study lies in its development of a "*socio-ecological ground-truthing*" method, where rich, qualitative ethnoforestry data is not merely an anecdote but a structured analytical layer used to interpret and give meaning to quantitative satellite data. This methodological innovation provides a powerful new way to produce holistic assessments, moving beyond reductionist biophysical metrics to create a more accurate, legitimate, and socially relevant understanding of forest ecosystem vitality.

The research is limited by its reliance on medium-resolution optical satellite imagery, which cannot capture fine-scale changes in forest structure, and by its geographically focused case study design. Future research should therefore prioritize the integration of higher-resolution remote sensing technologies, such as LiDAR and drone-based sensors, which could better detect the subtle, structural forms of degradation identified by communities. A critical next step is to test and adapt this integrated framework across a wider diversity of socio-ecological contexts in Papua and beyond, in order to refine the methodology and assess its broader applicability for fostering equitable and effective forest co-management.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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