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Multidimensional Inconsistency in Forest Ecosystem Representation: An NLP-Assisted Thematic Review

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Abstract

Forest ecosystem monitoring increasingly relies on multisensor remote sensing approaches integrating optical imagery, synthetic aperture radar (SAR), and LiDAR observations to assess biomass, degradation, and ecosystem condition. However, these systems frequently generate inconsistent representations of the same ecosystem due to differences in sensor sensitivity, ecological complexity, scale interactions, and recovery dynamics. This study conducted a natural language processing (NLP)-assisted structured thematic review to synthesize the dominant drivers, manifestations, and methodological responses associated with multidimensional inconsistency in forest ecosystem representation. A total of 500 publications were retrieved from the Dimensions database, of which 181 studies were retained following semantic relevance screening, thematic filtering, and manual verification.

Thematic synthesis showed that combined SAR and structural indicators dominated contemporary forest remote sensing literature, followed by ecosystem condition monitoring and multisensor fusion approaches. Ecological heterogeneity and terrain-related structural complexity emerged as the dominant drivers of inconsistency, accounting for 30.2% of all primary causes and occurring in 59.5% of all detected inconsistency pathways. Scale mismatch, sensor saturation, and benchmark instability also represented major sources of representational uncertainty. Biomass and carbon estimation uncertainty emerged as the most widespread manifestation, occurring in 94.0% of the reviewed studies. The review further demonstrated that spectral, structural, and functional ecosystem dimensions frequently become partially decoupled following disturbance, producing misleading representations such as spectrally recovered but structurally degraded “green deserts.” The study proposes a multidimensional inconsistency framework linking ecological, methodological, structural, and functional drivers of representational instability.

Keywords: Aboveground biomass, multisensor inconsistency, ecosystem representation uncertainty, multi-sensor fusion, spectral–structural divergence.

Introduction

Forests play critical roles in regulating global carbon dynamics, maintaining biodiversity, supporting hydrological processes, and sustaining ecosystem resilience under increasing anthropogenic and climatic pressures. Consequently, remote sensing has become fundamental for monitoring forest ecosystem condition, degradation, biomass dynamics, disturbance, and recovery across regional to global scales. Advances in Earth observation technologies, including optical imagery, synthetic aperture radar (SAR), LiDAR, and passive microwave observations, have substantially improved the capacity to characterize forest ecosystems beyond traditional land-cover mapping. In particular, the increasing availability of structural datasets from missions such as the Global Ecosystem Dynamics Investigation (GEDI) and ICESat-2 has accelerated efforts to integrate spectral, structural, and functional indicators for ecosystem monitoring (Cai et al., 2025; Gupta & Sharma, 2022).

Recent developments in multisensor integration have shifted forest monitoring toward increasingly multidimensional ecosystem representation frameworks. Optical sensors provide valuable information related to vegetation greenness, canopy condition, and productivity, while SAR and LiDAR systems offer complementary sensitivity to canopy structure, vertical complexity, biomass distribution, and forest architecture (Chen et al., 2021; Chen et al., 2022). Consequently, integrated remote sensing approaches combining optical, SAR, LiDAR, climatic, and topographic datasets are increasingly adopted for forest biomass estimation, degradation assessment, canopy height retrieval, and ecosystem condition monitoring (Tang et al., 2022; Cai et al., 2025).

Despite these advances, forest ecosystem representation remains affected by substantial inconsistencies across sensors, ecological conditions, spatial scales, and methodological frameworks. Different remote sensing systems frequently respond unevenly to canopy density, terrain complexity, disturbance gradients, vegetation heterogeneity, and ecological recovery processes, leading to divergent representations of forest structure, biomass, productivity, and ecosystem condition (Campbell et al., 2021; Wang et al., 2023). Optical vegetation indices such as NDVI and EVI are widely used because of their accessibility and long temporal coverage; however, they primarily capture canopy greenness and biochemical reflectance while often failing

to adequately represent vertical structure, biomass variability, canopy complexity, and ecological functioning, particularly in heterogeneous tropical forests (Campbell et al., 2021). Optical datasets also frequently exhibit saturation effects in high-biomass systems, cloud contamination, and mixed-pixel uncertainty, limiting their sensitivity to subtle degradation and structural disturbance

Structural observations derived from LiDAR and SAR provide complementary information by directly or indirectly capturing canopy height, biomass, vertical complexity, and forest architecture. Nevertheless, structural products also exhibit uncertainty associated with geolocation mismatch, terrain effects, sparse sampling, footprint–pixel scale discrepancies, benchmark disagreement, and model dependency (Campbell et al., 2021; Chen et al., 2022). Consequently, different remote sensing systems frequently produce inconsistent representations of the same ecosystem, where spectrally “healthy” forests may exhibit substantial structural degradation, biomass decline, or incomplete functional recovery. Similarly, biomass products generated using different calibration datasets, algorithms, or multisensor combinations may produce conflicting representations of ecosystem condition despite high reported model accuracies.

Emerging evidence increasingly suggests that spectral, structural, and functional indicators may exhibit divergent recovery trajectories can become spectrally, structurally, and functionally decoupled, leading to misleading interpretations such as “green deserts,” where canopy greenness masks persistent ecological degradation (Iheaturu et al., 2026). Several studies have demonstrated that rapid spectral recovery detected by optical imagery may not necessarily correspond to structural maturity, biomass recovery, compositional stability, or functional reintegration within recovering tropical forests (Iheaturu et al., 2026, Bejide et al., 2026). Similarly, large-scale biomass estimation frameworks integrating multisource remote sensing and deep learning have achieved strong agreement with remotely sensed structural products while still exhibiting substantial discrepancies relative to independent ground observations, highlighting persistent uncertainty in ecosystem representation (Cai et al., 2025).

These findings suggest that inconsistencies in forest ecosystem monitoring extend beyond isolated sensor limitations and instead reflect multidimensional interactions among ecological heterogeneity, scale mismatch, sensor sensitivity imbalance, benchmark instability, temporal recovery asynchrony, and structural–functional decoupling. Recent work by Bejide (2026) proposed a multidimensional framework for diagnosing inconsistencies in remote sensing-based

ecosystem assessment, demonstrating that inconsistencies may emerge simultaneously across scale, dimensional, and variable domains within forest monitoring systems. Such findings increasingly challenge the assumption that a single remotely sensed indicator or product can adequately represent the multidimensional ecological dynamics occurring within complex forest environments.

Although previous studies have investigated biomass estimation uncertainty, degradation monitoring, multisensor integration, and ecosystem assessment independently, limited attention has been given to synthesizing the broader drivers, manifestations, and methodological responses associated with multidimensional inconsistency in forest ecosystem representation. Existing reviews frequently emphasize algorithm performance or sensor-specific applications rather than the interacting ecological, structural, functional, and methodological processes that generate representational instability across remote sensing paradigms. Furthermore, the rapidly expanding and thematically fragmented forest remote sensing literature presents increasing challenges for conventional manual synthesis approaches.

This study therefore conducts a natural language processing (NLP)-assisted thematic review of multidimensional inconsistency in forest ecosystem representation. By combining automated thematic classification, semantic clustering, and conceptual synthesis, the study evaluates the dominant thematic domains, major drivers, manifestations, and methodological responses associated with ecosystem representation inconsistency across remote sensing-derived forest indicators and products. Specifically, the study aims to: (1) identify the dominant thematic patterns and monitoring dimensions in contemporary forest remote sensing literature; (2) examine the major drivers contributing to multidimensional inconsistency in forest ecosystem representation; and (3) develop a multidimensional inconsistency framework linking the drivers, manifestations, and methodological responses associated with ecosystem representation uncertainty.

Methodology

A structured literature review combined with natural language processing (NLP)-assisted thematic analysis was conducted to synthesize evidence of multidimensional inconsistency in forest ecosystem representation. The NLP-assisted workflow (Figure 1) was adopted to address terminology fragmentation and semantic overlap across remote sensing, ecology, forestry, and ecosystem monitoring literature, where similar concepts are often described using different

terminologies. Relevant publications were retrieved from the Dimensions database and exported in CSV format using the following search query:

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("forest degradation" OR "ecosystem condition") AND ("LiDAR" OR "GEDI" OR "canopy height") AND ("NDVI" OR "spectral index" OR "optical imagery") AND (disagreement OR inconsistency OR divergence OR mismatch OR uncertainty OR saturation)
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The initial database search retrieved 500 publications from the Dimensions database. Following semantic relevance screening, thematic filtering, duplicate removal, and manual verification of conceptual alignment, 181 publications were retained for detailed thematic synthesis and interpretation. Because publications could be classified into multiple thematic domains simultaneously, thematic frequencies exceeded the total number of retained studies.

The search primarily focused on studies published between 2018 and 2026, corresponding to the increasing adoption of spaceborne structural remote sensing systems such as GEDI and the growing integration of multi-sensor ecosystem monitoring approaches. The exported dataset containing titles, abstracts, and research-related keywords was processed in Python using a semi-automated NLP workflow. Titles, abstracts, and keywords were merged into a unified textual corpus following text preprocessing procedures including lowercase conversion, punctuation removal, whitespace normalization, and text cleaning to improve semantic consistency and reduce noise during thematic classification.

A dictionary-based thematic classification framework was developed to identify recurring concepts and thematic relationships across the literature. Six thematic domains were defined based on dominant conceptual patterns in contemporary forest remote sensing research: spectral indicators, structural and SAR-based indicators, divergence and inconsistency, ecosystem condition, functional indicators, and multi-sensor fusion. Each thematic category was represented using curated semantic dictionaries containing representative terms associated with LiDAR, GEDI, SAR, canopy height, biomass, NDVI, spectral indices, uncertainty, decoupling, ecosystem recovery, evapotranspiration, solar-induced fluorescence, and multi-sensor integration. Regular expression matching was subsequently used to automatically classify publications into one or multiple thematic domains based on semantic similarity and keyword occurrence.

To prioritize studies most relevant to multidimensional ecosystem representation, a weighted relevance scoring framework was implemented. Higher relevance scores were assigned to studies simultaneously addressing structural indicators, ecosystem inconsistency, multi-sensor integration, and ecosystem condition, reflecting the central conceptual focus of the review. Publications exceeding a predefined relevance threshold were retained for detailed thematic synthesis and interpretation. Automatically classified studies were subsequently manually reviewed to verify thematic relevance and conceptual alignment with multidimensional ecosystem representation.

Semantic pattern analysis was further conducted using bigram and trigram extraction from the screened textual corpus to identify recurring conceptual relationships and dominant thematic structures across the literature. Stopword removal and tokenization were applied prior to N-gram generation to improve phrase interpretability and thematic coherence. The retained studies were subsequently synthesized to identify recurring forms, drivers, and ecological implications of multidimensional inconsistency in forest ecosystem representation, including spectral–structural divergence, uncertainty propagation, sensor saturation, scale mismatch, product disagreement, and ecosystem recovery decoupling.

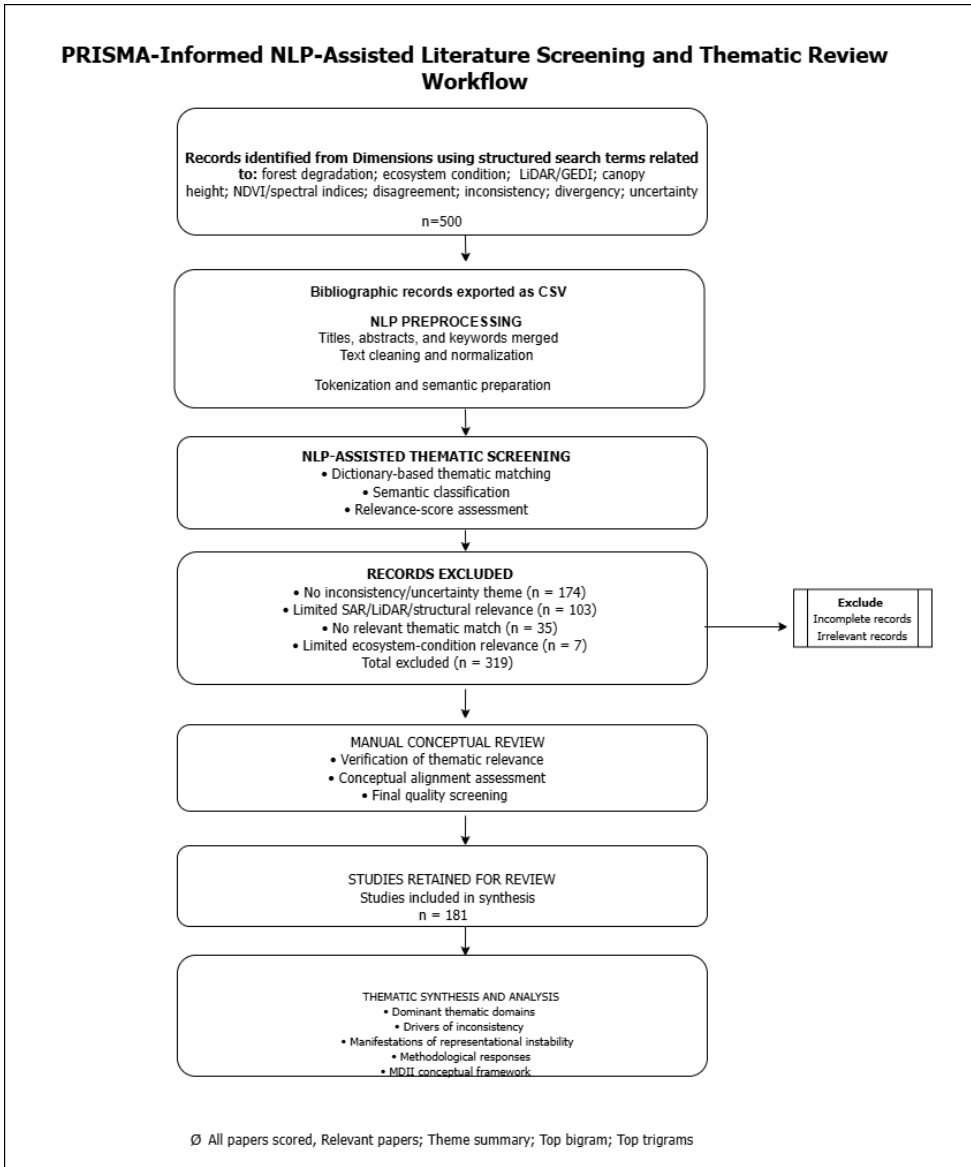


Figure 1. PRISMA-informed, NLP-assisted literature screening and thematic review workflow.

Results

4. Results and Thematic Synthesis

4.1 Dominant thematic domains in forest remote sensing literature

The thematic analysis showed that combined SAR and structural indicators were the most dominant themes in the reviewed literature, occurring in 176 studies, followed by ecosystem condition monitoring (165 studies) (Figure 2). This reflects the growing emphasis on structurally informed forest monitoring using integrated SAR, LiDAR, and optical datasets for biomass estimation, canopy structure assessment, and forest degradation monitoring.

Representation uncertainty and inconsistency-related themes were identified in 116 studies, indicating increasing attention to uncertainty propagation, benchmark disagreement, scale mismatch, and inconsistencies among remotely sensed forest representations. Multisensor fusion was also highly represented (107 studies), demonstrating the widespread adoption of integrated remote sensing approaches to improve ecosystem monitoring accuracy and reduce estimation uncertainty.

Spectral indicators occurred in 93 studies, showing the continued importance of vegetation indices such as NDVI and EVI in forest monitoring. However, functional indicators were comparatively underrepresented, appearing in only 21 studies. This suggests that current forest remote sensing research remains largely focused on structural and biomass-oriented ecosystem assessment, with relatively limited emphasis on functional ecosystem processes.

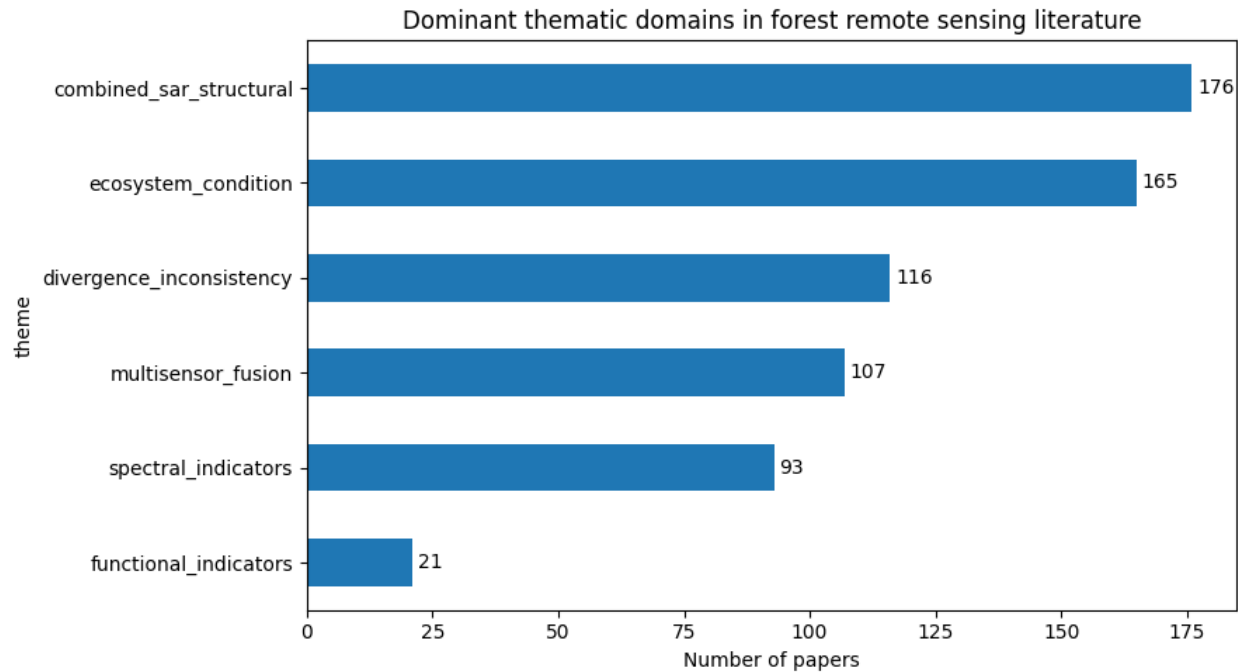


Figure 2: Thematic Analysis of forest remote sensing literature

4.2 Drivers of multidimensional inconsistency in forest ecosystem representation

4.2.1 Ecological heterogeneity and terrain/structural complexity

The drivers of multidimensional inconsistencies in forest ecosystem representation is presented in Table 1. Ecological heterogeneity and terrain-related structural complexity emerged as the most dominant drivers of inconsistency across the reviewed literature, representing approximately 30.2% of all primary causes and occurring in nearly 59.5% of all detected inconsistency pathways. The reviewed studies consistently demonstrated that heterogeneous canopy architecture, fragmented forest mosaics, disturbance gradients, variable stand density, and topographic complexity strongly influence the stability and reliability of remote sensing-based ecosystem representation.

Several studies have shown that environmental and structural heterogeneity remains a major challenge in forest remote sensing because terrain variability, vegetation density, and canopy structural differences influence sensor responses differently across optical, SAR, and LiDAR systems. Wang et al. (2023) demonstrated that topographic relief and vegetation cover degraded canopy-height retrieval accuracy, while Kanda et al. (2026) reported increased uncertainty in AGB estimation across spatially heterogeneous tropical forests despite Sentinel-1 and Sentinel-2

integration. Weber et al. (2025) further highlighted the growing reliance on multisensor deep-learning frameworks and uncertainty-aware modeling to improve the scalability and robustness of biomass, canopy-height, and canopy-cover estimation under diverse global forest condition

Ecological heterogeneity frequently intensified additional forms of inconsistency including scale mismatch, sensor saturation, and benchmark disagreement. Disturbance mosaics, forest fragmentation, and variable canopy closure altered spectral reflectance and radar backscatter differently across landscapes, thereby increasing uncertainty propagation during biomass estimation. These findings collectively indicate that ecological complexity remains a foundational source of multidimensional inconsistency because remote sensing systems respond unevenly to structurally diverse forest environments.

4.2.2 Scale mismatch and validation discrepancy

Scale mismatch and validation discrepancy represented another major source of inconsistency in forest ecosystem representation, accounting for approximately 19.8% of all primary inconsistency drivers and nearly 39.7% of all detected causes. The reviewed studies consistently demonstrated that inconsistencies emerge when field plots, LiDAR footprints, satellite pixels, and aggregated landscape units operate at different spatial supports, observational scales, and definitional frameworks.

A recurring issue involved spatial mismatch between spaceborne LiDAR observations and pixel-based optical or radar imagery. Chen et al. (2022) demonstrated that object-based approaches integrating GEDI and ICESat-2 with multisensor imagery improved biomass estimation relative to conventional pixel-based methods by reducing uncertainty associated with positional discrepancy and local heterogeneity in mountainous forests. Similarly, Campbell et al. (2021) showed that large GEDI footprints and coarse spatial resolution complicated woodland biomass estimation in dryland ecosystems characterized by sparse canopies and widely spaced trees.

Several studies further emphasized that forest representation and model performance remain highly sensitive to observational scale, environmental heterogeneity, and measurement uncertainty. Tang et al. (2019) demonstrated that field-, lidar-, and Landsat-based tree cover estimates diverged because of definitional discrepancies and estimation errors, particularly in sparsely vegetated mountainous environments. Similarly, Bejide et al. (2026a) showed that

satellite-derived forest classifications in rapidly urbanising tropical landscapes diverged substantially from GEDI-derived structural forest definitions, with agreement varying considerably across canopy-height thresholds and declining over time. Their findings demonstrated that spectrally derived forest extent frequently underestimated structurally defined forest, particularly at lower canopy-height thresholds, highlighting increasing divergence between spectral and structural forest representation over time. Wang et al. (2023) further showed that canopy-height retrieval accuracy was affected by topographic relief, vegetation cover, and spatially uneven uncertainty distributions, while Lahssini et al. (2024) highlighted the influence of GEDI geolocation uncertainty, sparse sampling, and signal saturation on canopy-height estimation in dense tropical forests.

Scale-related inconsistency was also evident in ecosystem productivity and carbon monitoring frameworks. Bejide et al. (2026b) operationalized multidimensional inconsistency by integrating scale, dimensional, and variable discrepancy metrics within a unified analytical framework. Their findings revealed persistent divergence between CASA-derived and MODIS-derived net primary productivity estimates, substantial mismatch between spectral and structural forest representations, and localized non-proportional changes between canopy height and aboveground biomass across heterogeneous tropical landscapes. The weak spatial correspondence between CASA and MODIS productivity estimates further demonstrated how ecosystem assessments may vary substantially depending on model structure, aggregation scale, and observational dimension.

Collectively, these findings indicate that scale mismatch, definitional inconsistency, and spatial uncertainty remain major drivers of representational instability in forest ecosystem monitoring because ecosystem properties are highly sensitive to observational scale, validation design, and representational framework.

4.2.3 Sensor saturation and sensitivity imbalance

Sensor saturation and sensitivity imbalance emerged as major causes of representational inconsistency, accounting for approximately 18.1% of all primary inconsistency drivers and 30.2% of all detected causes. The reviewed studies consistently demonstrated that optical, SAR, and LiDAR systems exhibit unequal sensitivity across vegetation density gradients, resulting in unstable ecosystem representation in structurally complex forests.

Optical saturation was among the most frequently reported limitations in forest biomass and canopy-structure estimation studies. Kumar and Aneesh (2025) noted that optical vegetation indices such as NDVI become saturated in dense forests, limiting their effectiveness in high-biomass environments. Jiang et al. (2020) similarly demonstrated that spectral saturation, cloud contamination, and mixed-pixel effects contributed substantially to biomass underestimation and uncertainty in MODIS-based carbon density estimation in the Brazilian Amazon. Zhang et al. (2025) further showed that canopy-height estimation accuracy declined during spatial extrapolation because of signal saturation, incomplete seasonal information, and variability in stand structure and species composition. Fayad et al. (2024) also highlighted that accurate estimation of tall tropical canopies remained challenging because of saturation effects in optical and radar sensors, persistent cloud cover, and lidar penetration limitations. Similarly, Akhtar et al. (2020) demonstrated that SAR backscatter reached saturation at high biomass levels and systematically underestimated AGB in dense subtropical pine forests, while optical spectral indices underestimated AGB at lower biomass conditions.

Collectively, these findings indicate that saturation effects and sensor-specific sensitivity constraints remain major sources of representational inconsistency in forest ecosystem monitoring because optical, radar, and LiDAR systems capture vegetation structure with varying effectiveness across biomass ranges, canopy conditions, and environmental gradients.

4.2.4 Reference/calibration and benchmark instability

Reference, calibration, and benchmark instability emerged as another major source of representational inconsistency, accounting for approximately 13.8% of primary causes and occurring in 32.8% of all detected pathways. Many studies demonstrated that differences in calibration datasets, harmonization procedures, and benchmark products frequently produced divergent biomass and canopy-structure estimates even within similar forest ecosystems. He et al. (2026) showed that models calibrated using INFyS inventory data consistently outperformed those calibrated using GEDI-derived biomass estimates, highlighting substantial variability among benchmark datasets used for biomass estimation in mountainous forests. George-Chacón et al. (2022) further demonstrated that limited field calibration data and uncertainty propagation constrained the robustness and transferability of multisensor biomass estimation frameworks outside calibration regions. Similarly, Knott et al. (2023) showed that temporal mismatch, spatial

mismatch, sampling protocols, and outlier handling substantially influenced biomass estimation outcomes during geospatial data harmonization workflows. Ferraz et al. (2020) additionally highlighted that uncertainty and estimation performance varied across structural scales and tree-height classes, emphasizing the importance of calibration strategy and scale-sensitive lidar methodologies. Wang et al. (2023) further demonstrated that canopy-height estimation performance and uncertainty distributions varied across multimodal fusion strategies and benchmark canopy-height products, particularly under complex topographic and vegetation conditions.

Collectively, these findings indicate that representational inconsistency is not solely driven by sensor limitations but also by instability among calibration references, harmonization protocols, and benchmark systems used to evaluate forest ecosystem properties.

4.2.5 Temporal and recovery asynchrony

Temporal and recovery asynchrony represented an important ecological driver of multidimensional inconsistency, accounting for approximately 7.8% of primary causes and occurring in 17.2% of all detected pathways. These studies demonstrated that ecosystem components frequently respond and recover at different rates following disturbance, resulting in temporal divergence among spectral, structural, and functional indicators.

Several studies showed that spectral or canopy-cover recovery may not accurately represent broader ecological recovery processes. Iheaturu et al. (2026) demonstrated that tropical forests may appear spectrally recovered despite incomplete structural, compositional, and functional recovery, thereby producing misleading “green desert” interpretations. Amaral et al. (2023) further showed that mangrove vulnerability and resilience varied substantially across regions and were strongly influenced by site-specific environmental conditions, pre-disturbance forest structure, and long-term climate trends. Similarly, Kozak et al. (2026) demonstrated that war-related forest disturbance produced substantial biomass decline and structural simplification, emphasizing the importance of multisensor monitoring frameworks for tracking post-disturbance ecosystem conditions.

Collectively, these findings suggest that ecosystem recovery cannot be reliably represented using a single observational dimension because structural, spectral, and functional ecosystem responses often operate over different temporal trajectories following disturbance.

4.2.6 Structural–functional decoupling

Structural–functional and structural–carbon divergence emerged as important ecological sources of representational inconsistency, accounting for approximately 5.2% of all primary causes and occurring in 17.2% of all detected pathways. The reviewed studies demonstrated that ecosystem functioning, carbon dynamics, and forest structure are often represented through different observational frameworks that capture distinct ecological properties and processes.

Several studies emphasized that structural indicators alone may not fully represent broader ecosystem functioning and carbon dynamics. Iheaturu et al. (2026) highlighted that multisensor integration is necessary to capture structural, compositional, and functional dimensions of tropical forest recovery, emphasizing that greenness-based indicators alone may overestimate ecosystem recovery. Similarly, Xiao et al. (2019) showed that remote sensing of the terrestrial carbon cycle relies on different observational approaches for estimating carbon stocks and carbon fluxes, including lidar, microwave sensing, vegetation indices, and solar-induced fluorescence, each representing different ecosystem processes and components. Brandt et al. (2018) further demonstrated that passive microwave vegetation optical depth (VOD) observations can effectively monitor climate-driven carbon dynamics and biomass variability across African drylands while avoiding saturation problems common in densely vegetated systems.

Empirical evidence of structural–carbon divergence was further demonstrated by Bejide et al. (2026), who showed that biomass decline in Southwestern Nigerian forests substantially exceeded canopy-height reduction between 2020 and 2025. Their structural–carbon decoupling index indicated that aboveground biomass declined approximately 1.8 times faster than canopy height, suggesting that canopy-height metrics alone may underestimate carbon loss in degrading tropical forests undergoing structural thinning rather than complete canopy removal.

Collectively, these findings indicate that structural, spectral, functional, and carbon-related ecosystem dimensions are not always represented consistently across remote sensing frameworks

because different sensors and indicators capture different components of ecosystem condition, degradation, and carbon dynamics.

4.2.7 Data coverage and sampling limitation

Data coverage and sampling limitation represented an additional source of inconsistency, accounting for approximately 3.4% of all primary drivers and occurring in 21.6% of all detected pathways. Several studies emphasized that incomplete spatial sampling, uneven observational coverage, and limited field calibration data constrained the reliability of biomass and structural estimation frameworks. Ometto et al. (2023) demonstrated that forest inventory data in the Brazilian Amazon covered only a small fraction of the region and were insufficient to ensure reliable interpolation and validation of biomass estimates. Similarly, Wu et al. (2022) showed that the spatially discrete nature of ICESat-2 LiDAR observations and the ecological variability of forest growth limited the effectiveness of generalized canopy-height models, requiring ecological zoning strategies to improve representation accuracy. Tang et al. (2019) further demonstrated that sparse vegetation conditions and definitional differences contributed to disagreement among remotely sensed tree-cover products.

Collectively, these findings indicate that incomplete spatial sampling and uneven ecosystem representation remain important sources of uncertainty in forest ecosystem monitoring, particularly in structurally complex and data-scarce environments.

Table 1: Drivers of Multidimensional Inconsistency

Primary Cause	Count	Share
Ecological heterogeneity and terrain/structural complexity	35	30.2%
Scale mismatch and validation discrepancy	23	19.8%
Sensor saturation and sensitivity imbalance	21	18.1%
Reference/calibration and benchmark instability	16	13.8%
Temporal/recovery asynchrony	9	7.8%
Structural–functional decoupling	6	5.2%
Data coverage and sampling limitation	4	3.4%
No explicit cause stated	2	1.7%

All Detected Causes	Count	Share
Ecological heterogeneity and terrain/structural complexity	69	59.5%
Scale mismatch and validation discrepancy	46	39.7%
Reference/calibration and benchmark instability	38	32.8%
Sensor saturation and sensitivity imbalance	35	30.2%
Data coverage and sampling limitation	25	21.6%
Temporal/recovery asynchrony	20	17.2%
Structural–functional decoupling	20	17.2%
No explicit cause stated	2	1.7%

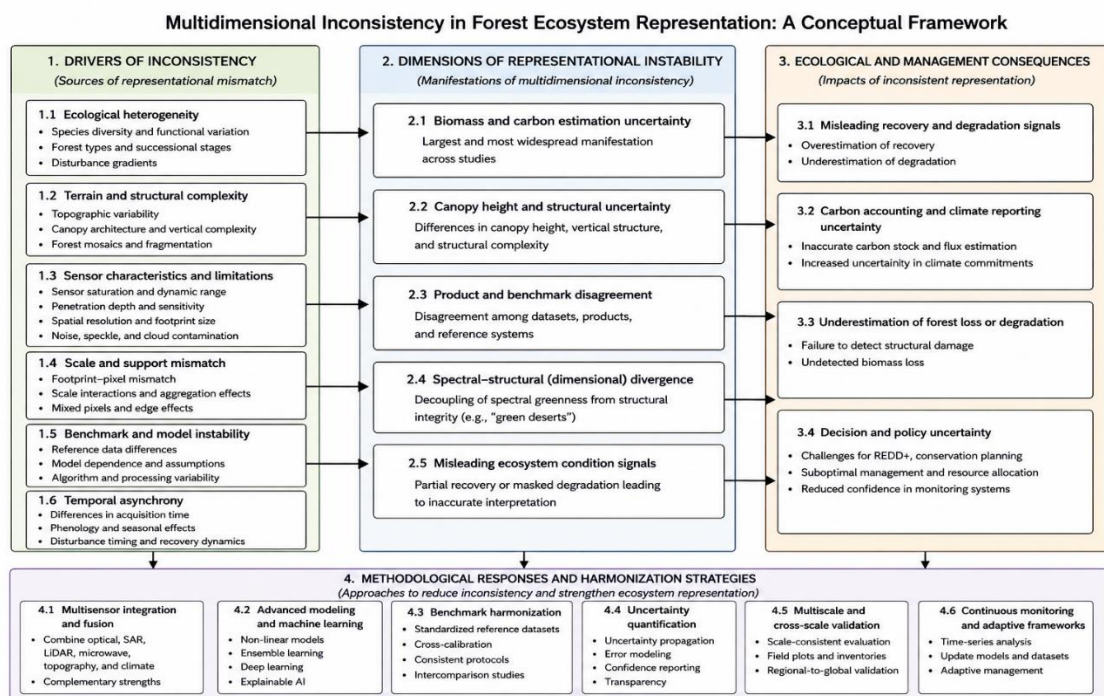


Figure 3. Conceptual framework linking the drivers, manifestations, consequences, and methodological responses associated with multidimensional inconsistency in forest ecosystem representation.

Figure 3: Multidimensional inconsistencies in forest ecosystem representation

4.3 Manifestations of multidimensional inconsistency in forest ecosystem representation

Biomass and carbon estimation uncertainty emerged as the dominant manifestation of multidimensional inconsistency, occurring in 94.0% of the reviewed studies (Table 2). Canopy height and structural estimation uncertainty were also highly represented (44.0%), particularly in heterogeneous forest environments affected by terrain effects, sparse LiDAR sampling, and scale mismatch. Product and benchmark disagreement occurred in 33.6% of studies, while explicit spectral–structural or dimensional divergence was comparatively less frequent (4.3%). These findings suggest that multidimensional inconsistency is more commonly expressed through uncertainty propagation and benchmark disagreement than through explicitly recognized divergence frameworks.

Table 2: Dominant manifestation of multidimensional inconsistency

Manifestations/Outcomes	Count	Share
Biomass/carbon estimation uncertainty	109	94.0%
Canopy height/structural estimation uncertainty	51	44.0%
Product/product benchmark disagreement	39	33.6%
Spectral–structural or dimensional divergence	5	4.3%

4.4 Methodological responses and harmonization strategies

Machine learning and ensemble modelling were the most common methodological responses, occurring in 50.9% of the reviewed studies (Table 3). Multisensor and data fusion approaches were similarly widespread (49.1%), reflecting increasing reliance on integrated remote sensing frameworks to improve ecosystem representation and reduce uncertainty. Additional responses included uncertainty propagation and benchmark validation (11.2%), as well as object-based and multiscale harmonization approaches (3.4%) aimed at reducing scale mismatch and positional inconsistency among ecosystem observations.

Table 3: Methodological responses and harmonization strategies

Mitigation/Responses	Count	Share
Machine learning/ensemble modelling	59	50.9%
Multisensor/data fusion	57	49.1%
Uncertainty propagation/benchmark validation	13	11.2%
Object-based or multiscale harmonization	4	3.4%

5. Discussion

5.1 Toward multidimensional ecosystem representation

The findings of this review demonstrate that inconsistencies in forest ecosystem monitoring extend beyond isolated sensor limitations and instead emerge through interacting ecological, structural, functional, and methodological processes. The reviewed literature consistently showed that optical, SAR, and LiDAR systems respond differently to canopy complexity, biomass density, disturbance history, and ecological recovery trajectories, resulting in multidimensional representational instability across forest ecosystems (Campbell et al., 2021; Chen et al., 2022; Bejide et al., 2026). These inconsistencies frequently manifested through biomass uncertainty, benchmark disagreement, structural underestimation, and spectral–structural divergence, particularly in heterogeneous and disturbance-prone environments.

The dominance of ecological heterogeneity, scale mismatch, and sensor sensitivity imbalance across the reviewed studies suggests that ecosystem representation uncertainty is fundamentally linked to the multidimensional nature of forest ecosystems themselves rather than solely to deficiencies in remote sensing technologies. Structurally complex forests often generate uneven spectral reflectance, radar backscatter, and LiDAR responses across spatial and temporal scales, thereby complicating attempts to derive consistent representations of ecosystem condition, biomass, and recovery dynamics from individual remotely sensed indicators.

The review further demonstrates that spectral, structural, and functional ecosystem dimensions may exhibit divergent or asynchronous responses following disturbance, degradation, or ecological transition. Several studies reported cases where spectrally recovered forests continued

to exhibit structural degradation, incomplete biomass recovery, or altered ecosystem functioning, producing misleading interpretations such as “green deserts.” These findings increasingly challenge the assumption that single-dimensional remotely sensed indicators can adequately represent ecosystem integrity within complex forest landscapes.

The widespread adoption of multisensor fusion, ensemble machine learning, benchmark harmonization, and multiscale validation approaches reflects growing recognition that no single remote sensing system can fully capture the multidimensional characteristics of forest ecosystems. Rather than treating ecosystem inconsistency solely as an error to be minimized, future remote sensing frameworks may increasingly benefit from explicitly diagnosing, quantifying, and interpreting multidimensional representational instability across spectral, structural, and functional domains.

Overall, this review highlights the need for ecosystem monitoring frameworks that move beyond isolated spectral or structural representations toward integrated multidimensional assessment strategies capable of capturing the interacting ecological processes governing forest condition, degradation, recovery, and resilience under rapidly changing environmental conditions.

Conclusion

This review demonstrates that inconsistencies in forest ecosystem representation arise from interacting ecological, structural, methodological, and scale-dependent processes rather than isolated sensor limitations. Ecological heterogeneity, scale mismatch, sensor saturation, benchmark instability, and temporal recovery asynchrony emerged as the dominant drivers of representational instability across contemporary forest remote sensing studies.

The findings further show that optical, SAR, and LiDAR systems frequently produce partially divergent representations of the same ecosystem because they respond differently to canopy structure, biomass density, disturbance, and recovery dynamics. Biomass and carbon estimation uncertainty emerged as the most widespread manifestation of inconsistency, while spectral–structural divergence highlighted the limitations of relying on single-dimensional ecosystem indicators.

Overall, the review emphasizes the need for integrated ecosystem monitoring frameworks that combine spectral, structural, functional, and carbon-related observations through multisensor

fusion, uncertainty-aware modelling, and multiscale validation approaches. The proposed multidimensional inconsistency framework provides a conceptual foundation for improving the reliability and ecological interpretability of remote sensing-based forest ecosystem assessment.

During the preparation of this work the author(s) used Google Gemini in order to correct the grammatical errors. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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