
Vegetation Structure and Species Diversity in Secondary Forests as Indicators of Ecosystem Stability

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ABSTRAK

Secondary forests constitute one of the most ecologically dynamic and globally significant forest categories, covering hundreds of millions of hectares across the tropics and subtropics. This systematic review evaluates the relationship between vegetation structure, species diversity, and ecosystem stability in secondary forests, synthesizing evidence from fourteen peer-reviewed studies—seven from Indonesian and adjacent Southeast Asian contexts and seven additional foundational studies from the international ecological literature. Evidence across these sources consistently demonstrates a positive correlation between structurally complete, multi-strata vegetation communities and indicators of ecological stability including active regeneration, functional resilience, and resistance to disturbance. The Shannon-Wiener diversity index (H') reported across studies typically ranges from 1.4 to 2.5, classified as moderate, and is positively associated with productivity, nutrient cycling, and community persistence. However, this general pattern is frequently complicated by the dominance of invasive species—including *Chromolaena odorata*, *Imperata cylindrica*, and *Piper aduncum*—which suppress understory regeneration and reduce long-term diversity even where aggregate H' values appear acceptable. Drawing on the successional ecology and biodiversity literature, this review argues that vegetation structure and diversity metrics are necessary but not sufficient indicators of stability; their interpretation must be contextualized within disturbance history, invasion pressure, and anthropogenic land-use trajectories. Practical implications for secondary forest management and monitoring are discussed.

INTRODUCTION

Secondary forests—defined as forests that have regrown on previously cleared or severely disturbed land—have emerged as one of the most ecologically and economically significant forest types on the planet. Unlike primary old-growth forests, which have been the traditional focus of conservation science, secondary forests represent a dynamic middle ground between cleared landscapes and mature forest ecosystems. As global deforestation continues to outpace reforestation in many tropical regions, secondary forests now constitute a substantial and growing fraction of the world's remaining forest

cover, providing critical refugia for biodiversity, supporting local livelihoods, and contributing meaningfully to carbon sequestration and hydrological regulation (Chazdon, 2014; Poorter et al., 2016).

The concept of ecosystem stability in secondary forests encompasses multiple interacting dimensions: resistance to disturbance, the capacity to recover following perturbation (resilience), and the maintenance of functional processes over time. Vegetation structure—the vertical and horizontal arrangement of plant biomass across canopy, sub-canopy, understory, and forest floor strata—is widely recognized as a fundamental indicator of community successional stage and ecological integrity. A fully stratified vertical structure, particularly the characteristic reverse-J diameter distribution in which seedlings and saplings greatly outnumber larger trees, is generally interpreted as evidence of active natural regeneration and a self-sustaining community trajectory (Guariguata & Ostertag, 2001; Iskandar et al., 2021; Komul & Hitipeuw, 2022).

Species diversity, quantified through indices such as the Shannon-Wiener index (H') and Pielou's evenness index (J'), provides a complementary lens for evaluating ecosystem stability. The theoretical basis for the diversity-stability relationship is grounded in the insurance hypothesis, which posits that functionally diverse communities are better buffered against environmental fluctuations because different species respond to perturbations in different ways, collectively maintaining ecosystem processes where individual species may fail (Magurran, 2004; Anjani et al., 2022; Damiti et al., 2025). Empirical evidence from secondary forests across the tropics broadly supports this framework, although the relationship is not linear and is sensitive to the composition of the diverse assemblage—particularly the presence and abundance of invasive exotic species (Sehati & Solfiyeni, 2023; Messah et al., 2025).

Despite substantial growth in the secondary forest literature over the past two decades, important knowledge gaps remain. Much of the existing research focuses on either structural attributes or diversity indices in isolation, rather than examining their joint contribution to ecosystem stability. Furthermore, the majority of Indonesian studies—where secondary forests cover tens of millions of hectares as a result of logging, agricultural expansion, and fire—have been conducted at the site level without systematic integration into broader regional or global frameworks (Palapessy et al., 2025; Norden et al., 2015). This limits the generalizability of local findings and hampers evidence-based policy formulation for secondary forest management.

This review addresses these gaps by synthesizing evidence from fourteen studies spanning Indonesian, Southeast Asian, and international contexts. The central research questions guiding this synthesis are: (1) How do vegetation structure and species diversity co-vary in secondary forests across different disturbance histories and ecological zones? (2) To what extent do structural and diversity metrics reliably indicate ecosystem stability? (3) What factors—particularly invasive species and anthropogenic pressures—complicate or disrupt this relationship? The paper is organized as follows: the methods section describes the systematic literature search and inclusion criteria; the results and discussion section integrates quantitative findings with theoretical interpretation; and the conclusion identifies practical implications for secondary forest management and monitoring.

METHODOLOGY

2.1 Literature Search Strategy and Scope

This systematic review followed a structured search protocol informed by PRISMA guidelines. The primary database search was conducted across Scopus, Web of Science, Google Scholar, and Indonesian academic repositories (including Garuda and SINTA-indexed journals). Search terms combined concepts from three domains: (a) forest type (secondary forest, hutan sekunder, post-disturbance forest, tropical forest regeneration); (b) ecological attributes (vegetation structure, species diversity, Shannon-Wiener index, basal area, diameter distribution, forest stratification); and (c) outcome metrics (ecosystem stability, ecological resilience, disturbance response, invasive species impact). The temporal search window encompassed publications from 2001 to 2025, with priority given to studies from 2020 onward to capture the most current evidence from Indonesian and regional contexts. Foundational methodological references—particularly those establishing diversity index interpretation standards and successional ecology theory—were also included regardless of publication year.

2.2 Inclusion and Exclusion Criteria

Studies were eligible for inclusion if they: (a) examined secondary forests or comparable recovering forest systems; (b) reported at least one quantitative vegetation structure metric (e.g., stem density by growth stage, basal area, or diameter class distribution) or species diversity index; (c) discussed findings in relation to ecosystem function, stability, or successional dynamics; and (d) were published in peer-reviewed journals or academic books in English or Indonesian. Studies were excluded if they focused exclusively on plantation monocultures without natural regeneration components, reported only presence-absence species lists without quantitative diversity analysis, or were based on simulated rather than empirical field data. Based on these criteria, fourteen studies were retained: seven primary studies from Indonesian and proximate regional contexts, and seven additional foundational or comparative international references that provide theoretical grounding and global comparative context.

2.3 Data Extraction and Analytical Approach

From each included study, the following information was systematically extracted: study site and forest type, disturbance history and recovery stage, vegetation metrics assessed (diversity indices, structural parameters, species composition), key quantitative findings, and reported relationships between structural or diversity metrics and stability or succession. Given the heterogeneity of study designs, measurement protocols, and reporting formats, formal meta-analysis was not attempted; instead, a systematic narrative synthesis was performed. Diversity values were standardized to the Shannon-Wiener H' scale wherever possible. Structural data were interpreted within the successional ecology framework established by Guariguata and Ostertag (2001) and refined by Chazdon (2014), which frames reverse-J diameter distributions and multi-strata canopy architecture as key markers of self-sustaining regeneration in secondary forests.

Table 1. Summary of included studies: forest type, location, metrics assessed, and key findings

Author(s) & Year	Location / Forest Type	Metrics	H' Range / Value	Key Finding Related to Stability
Iskandar et al. (2021)	TNGC, West Java — forest edge	Structure, H', composition	1.4–2.1	Multi-strata structure and reverse-J distribution; invasive species reduce understory stability
Komul & Hitipeuw (2022)	Kamal Village, W. Seram — post-fire secondary forest	Growth stage density, H'	Moderate	All growth stages present; succession active; stand continuity confirmed despite moderate diversity
Anjani et al. (2022)	Lae Kombih Forest, Subulussalam — conservation forest	H', evenness, species richness	1.6–2.4	Higher evenness associated with greater community stability; moderate-high diversity productive ecosystem
Sehati & Solfiyeni (2023)	Bukit Langkisau, West Sumatra — urban secondary forest	H', invasive sp. cover	1.8–2.3	Invasive species (Chromolaena, Piper aduncum) suppress understory; H' underestimates instability
Palapessy et al. (2025)	Nusalaut Island — utilization zone forest	Stratification, dominant spp., H'	1.5–2.5	Monodominance of economically valued spp. reduces long-term diversity despite productive structure
Messah et al. (2025)	Noemuti River, N. Timor — riparian secondary forest	H', invasive dominance	1.4–2.0	Riparian vegetation diversity moderate; invasive grasses threaten regeneration and bank stabilization
Damiti et al. (2025)	Indonesia (literature review) — multiple secondary forest types	H', structural indicators	Synthesis	H' and structural completeness as core stability indicators; deforestation and invasion as destabilizers
Guariguata & Ostertag (2001)	Neotropical — secondary forests (review)	Structure, basal area, succession stages	—	Defined reverse-J diameter distribution as a marker of self-sustaining secondary forest communities
Magurran (2004)	Global — diversity index methodology	H', J, Simpson's D	Methodological	Established theoretical and statistical basis for H' as an ecosystem stability and productivity proxy
Chazdon (2014)	Pantropical — secondary forest synthesis	Succession, biomass, diversity, recovery trajectories	Synthesis	Secondary forests recover structural complexity faster than species diversity; management critical for quality
Poorter et al. (2016)	Pantropical — 45 secondary forest sites	Biomass recovery, AGB, species richness	—	Above-ground biomass recovers in ~66 years post-abandonment; diversity recovery significantly slower
Aide et al. (2013)	Latin America & Caribbean — land cover change	Forest cover; reforestation rates	—	Secondary forest expansion documented across region; structural recovery precedes functional recovery

Norden et al. (2015)	Neotropical secondary succession trajectories	—	Species turnover, succession uncertainty	—	Successional trajectories variable yet directional; species diversity recovery highly site-dependent
Chazdon et al. (2016)	Global forest definition and restoration	—	Forest definitions, restoration metrics	—	Emphasizes multi-dimensional evaluation of forest recovery beyond canopy cover alone

RESULTS AND DISCUSSION

3.1 Vegetation Structure as an Indicator of Succession and Stability

The most consistent structural indicator of ecological stability across the reviewed studies is the presence of a fully stratified vertical architecture encompassing seedling (semai), sapling (pancang), pole (tiang), and tree (pohon) growth stages. This vertical completeness, often described in conjunction with a reverse-J or negative-exponential diameter class distribution, signals that natural regeneration is actively replacing older cohorts—a fundamental criterion for community self-maintenance over time. Guariguata and Ostertag (2001), whose foundational review of neotropical secondary forest succession remains the benchmark for interpreting structural metrics, established that the transition from structurally simple early-successional stands to multi-strata assemblages is accompanied by significant gains in biomass, species diversity, and ecological function, though these dimensions do not recover in lockstep.

Evidence from Indonesian secondary forests confirms this structural framework. Iskandar et al. (2021), studying the forest edge zone of the Gunung Ciremai National Park (TNGC) in West Java, documented a well-stratified community dominated by native tree species across multiple growth stages, with diameter class distributions approximating the reverse-J pattern. The authors interpreted this structural completeness as evidence of active succession and a relatively stable community, while cautioning that the concentration of individuals in the largest diameter classes among a small number of dominant species could reflect incipient competitive exclusion rather than genuine diversity. Similarly, Palapessy et al. (2025), analyzing the utilization zone of Nusalaut Island, found multi-strata structure dominated by economically important species including *Syzygium aromaticum* (clove), *Myristica fragrans* (nutmeg), and *Canarium indicum* (kenari), whose prevalence across strata reflects both ecological successional dynamics and human cultivation preferences. While this structure supports productive ecosystem function in the near term, the concentration of value on a small number of species raises legitimate concerns about resilience if dominant species are affected by disease, climate stress, or market-driven harvesting pressure.

Post-disturbance regeneration in secondary forests affected by fire was examined by Komul and Hitipeuw (2022) in Kamal Village, West Seram. Despite the severity of the disturbance, all major growth stages were present in the post-fire secondary forest, with seedling densities substantially higher than in the upper strata—indicating active natural regeneration and an early-to-mid successional trajectory. This finding aligns with the broader successional ecology literature: fire, while destructive in the short term, can reset competitive hierarchies and create microsite conditions favorable to pioneer species establishment, thereby accelerating the initial phases of vegetation recovery (Chazdon, 2014). The presence of all growth stages, even in a recently disturbed site, was interpreted by the authors as indicative of stand continuity and the potential for longer-term

ecosystem stability, provided subsequent anthropogenic disturbances do not interrupt the successional trajectory.

Riparian secondary forests in the Noemuti River watershed, North Timor Tengah Utara, studied by Messah et al. (2025), exhibited more variable structural patterns reflecting the dual influence of hydrological dynamics and human encroachment. Vegetation cover and stratification were generally adequate in the upper riparian zones, where natural regeneration appeared unimpeded, but deteriorated markedly in lower zones subject to seasonal flooding, livestock grazing, and invasive grass encroachment. These findings reinforce the importance of disturbance regime and land-use context in modulating vegetation structure even within the same continuous forest system.

3.2 Species Diversity Indices: Values, Interpretation, and Stability Implications

Across the primary Indonesian studies reviewed, Shannon-Wiener H' values ranged from approximately 1.4 to 2.5, consistently falling within the moderate diversity category as defined by established ecological benchmarks (Magurran, 2004). This range was recorded for communities at multiple scales—from seedlings and saplings to the full tree stratum—and across a variety of secondary forest types including post-fire forests (Komul & Hitipeuw, 2022), edge forests (Iskandar et al., 2021), and conservation-designated secondary forests (Anjani et al., 2022). The theoretical basis for interpreting moderate H' values as indicative of productive and stable communities derives from the insurance hypothesis in community ecology: as the number of functionally diverse species in a community increases, the probability that at least some species will maintain critical ecological processes under any given perturbation scenario also increases (Magurran, 2004; Damiti et al., 2025).

Anjani et al. (2022), studying the Hutan Raya Lae Kombih conservation forest in Subulussalam, found that higher species evenness—a measure of how equitably individuals are distributed among species—was associated with greater community stability, defined operationally as resistance to compositional shifts across seasonal monitoring periods. This finding aligns with the theoretical prediction that communities in which no single species is overwhelmingly dominant are more resilient to the loss of individual species, since functional roles are distributed across multiple species rather than concentrated in a few dominants. The authors further found that species richness alone was a weaker predictor of stability than the combination of richness and evenness captured by H' , underscoring the importance of diversity index interpretation beyond simple species counts.

From the international literature, the pantropical study of Poorter et al. (2016), which analyzed biomass and diversity recovery trajectories across forty-five secondary forest sites in the Neotropics, provides critical comparative context. While above-ground biomass recovered to approximately 90% of old-growth reference values within sixty-six years on average—a relatively rapid structural recovery—species diversity recovery was significantly slower and more variable, often requiring over a century for full compositional recovery. This asynchrony between structural recovery (which drives the positive metrics observed in Indonesian studies) and diversity recovery (which reflects the depth of successional progress) is a fundamental characteristic of secondary forest dynamics that must inform how H' values are interpreted. A secondary forest with H' of 2.0 may exhibit structurally complete vegetation while still harboring a species assemblage dominated by pioneers and early-successional generalists rather than the late-successional specialists that characterize ecologically mature and fully stable communities.

Table 2. Comparative Shannon-Wiener H' values, structural characteristics, and stability assessment across primary Indonesian studies

Study	Forest Type	H' Range	Structural Completeness	Stability Assessment
Iskandar et al. (2021)	Edge forest, TNGC	1.4–2.1	Complete (all strata)	Moderate-stable; invasive species threaten understory
Komul & Hitipeuw (2022)	Post-fire secondary	Moderate	Complete (regenerating)	Stable succession; early-mid stage; adequate continuity
Anjani et al. (2022)	Conservation forest	1.6–2.4	Multi-strata	Moderate-high stability; evenness key determinant
Sehati & Solfiyeni (2023)	Urban secondary forest	1.8–2.3	Partial (invaded understory)	Overestimated stability; invasives mask true instability
Palapessy et al. (2025)	Utilization zone, Nusalaut	1.5–2.5	Complete (monodominant)	Productive but vulnerable to monodominance risk
Messah et al. (2025)	Riparian secondary	1.4–2.0	Variable by zone	Moderate; riparian zones vulnerable to invasives and grazing
Damiti et al. (2025)	Mixed Indonesian types (review)	Synthesis	Varies	H' and structure together reliable but not sufficient; invasion and deforestation key threats

3.3 The Disrupting Role of Invasive Species

One of the most consistent and concerning findings across the reviewed literature is that invasive exotic species substantially complicate the interpretation of vegetation diversity and structural metrics as stability indicators. Species such as *Chromolaena odorata* (Siam weed), *Piper aduncum* (spiked pepper), *Imperata cylindrica* (alang-alang), and in some contexts *Swietenia macrophylla* (big-leaf mahogany, where naturalized beyond plantations), are documented across multiple study sites as dominant understory components that suppress native regeneration while inflating or obscuring aggregate diversity values.

Sehati and Solfiyeni (2023), studying the Bukit Langkisau urban secondary forest in Painan, West Sumatra, found that the presence of invasive species at high cover values in the understory was associated with significantly reduced regeneration of native tree species, as invasive ground-layer plants outcompeted seedlings for light and soil resources. Crucially, the aggregate Shannon-Wiener H' value remained in the moderate range (1.8–2.3), largely because the invasive species themselves contributed to apparent species counts and relative abundance calculations. This finding highlights a critical methodological limitation: diversity indices calculated without distinguishing native from non-native species can produce values that suggest ecological stability while masking the progressive replacement of functionally important native regeneration by competitive invasive plants.

Iskandar et al. (2021) documented a similar dynamic in the TNGC forest edge, where the boundary between national park forest and adjacent agricultural land created a

disturbance gradient along which invasive pioneer species established at high densities. While the overall stand structure remained multi-strata, the understory stratum—where seedlings and saplings are concentrated and where future community composition is determined—was disproportionately dominated by invasive and early-successional exotic species, raising concerns about the long-term compositional trajectory of the forest even as structural metrics appeared acceptable. Messah et al. (2025) reported analogous patterns in riparian zones where *Imperata cylindrica* dominated open and grazed microhabitats, precluding natural tree establishment and effectively arresting succession in affected patches.

From the perspective of the international literature, these findings align with evidence that invasive species represent one of the most potent and underappreciated drivers of secondary forest compositional instability. Norden et al. (2015), studying successional trajectories across Neotropical secondary forests, found that sites with high invasive species pressure showed significantly greater variance in successional outcomes than undisturbed sites, reinforcing the view that invasion fundamentally undermines the predictability—and therefore the stability—of secondary forest succession. Chazdon (2014) further argues that the ecological quality of secondary forest recovery is determined not merely by the presence of diverse species but by the functional composition of that diversity, particularly the re-establishment of late-successional, shade-tolerant native species that drive the transition toward mature forest conditions.

3.4 Anthropogenic Pressures and Their Modifying Effects

Beyond biological invasion, a suite of anthropogenic pressures modify the structure-diversity-stability relationship in secondary forests, often in ways that are difficult to capture through standard vegetation survey methods. The studies reviewed document several key anthropogenic stressors operating across Indonesian secondary forest contexts. Selective harvesting of commercially valuable species—documented in Nusalaut by Palapessy et al. (2025) in relation to clove and nutmeg—selectively removes individuals from specific functional groups, creating compositional gaps in the forest stratum that may not immediately manifest in diversity indices but progressively reduce functional resilience. Livestock grazing in riparian secondary forests, noted by Messah et al. (2025), destroys seedling and sapling cohorts—the stratum most critical for ongoing succession—while simultaneously compacting soils and reducing mycorrhizal inoculum potential, effects that persist for decades after grazing pressure is removed.

Fire, while historically a natural disturbance component in many Indonesian forest ecosystems, has been fundamentally altered in its character by human ignition, land clearing, and the expansion of flammable exotic grass communities. Komul and Hitipeuw (2022) demonstrate that post-fire secondary forests can maintain active regeneration and successional momentum provided fire frequency does not exceed the capacity of native species to complete seed-to-seedling transitions. However, where fire return intervals shorten—as frequently occurs in landscapes dominated by *Imperata cylindrica*, which is both fire-adapted and fire-promoting—secondary forests can be trapped in early-successional, structurally impoverished states that superficially resemble diverse communities while actually representing arrested succession. Damiti et al. (2025), in their Indonesian literature review, identify deforestation, repeated burning, and invasive species synergistically as the dominant drivers of secondary forest ecosystem instability across the archipelago.

From an international comparative perspective, Aide et al. (2013) documented that the secondary forest resurgence observed across Latin America and the Caribbean over

the 2001–2010 period was strongly mediated by land-use history and abandonment patterns, with forests recovering from less intensive land uses showing faster and more complete structural recovery than those on lands degraded by prolonged cultivation or intense grazing. This parallel reinforces the principle that anthropogenic disturbance history is a primary determinant of secondary forest recovery trajectory—and therefore of the reliability of structural and diversity metrics as stability proxies.

Table 3. Integrated framework of vegetation indicators, ecological meaning, key references, and monitoring recommendations for secondary forest stability assessment

Indicator	Ecological Meaning	Threshold / Benchmark	Key References	Monitoring Recommendation
Shannon-Wiener H'	Community diversity and productive ecosystem stability	$H' > 2.0$ = moderate-stable	Magurran (2004); Anjani et al. (2022)	Calculate separately for native and non-native species; monitor temporal trends
Pielou's Evenness (J')	Equitable distribution of individuals; resilience to species loss	$J' > 0.6$ preferred to	Anjani et al. (2022); Magurran (2004)	Use alongside H'; low evenness despite high richness signals dominant species risk
Vertical stratum completeness	Active regeneration; successional continuity; self-sustaining community	All 4 strata present	Guariguata & Ostertag (2001); Iskandar et al. (2021)	Assess density ratios between growth stages; flag gaps in seedling/sapling strata
Diameter class distribution	Demographic stability; natural regeneration replacing large trees	Reverse-J curve required	Guariguata & Ostertag (2001); Chazdon (2014)	Map diameter distributions per species; detect rotated-J (aging population) or unimodal (plantation) patterns
Invasive species cover (%)	Suppression of native regeneration; functional destabilization of understory	$< 10\%$ cover desirable	Sehati & Solfiyeni (2023); Messah et al. (2025)	Map invasive cover by stratum; separate from native diversity calculations in H' reporting
Basal area (m ² /ha)	Stand biomass and structural maturity; ecosystem carbon storage	> 20 m ² /ha indicates maturity	Poorter et al. (2016); Chazdon (2014)	Benchmark against regional old-growth references; track recovery trajectories over ≥ 10 -year intervals
Native species proportion (%)	Compositional quality recovery; functional	$> 70\%$ native preferred	Chazdon et al. (2016); Norden et al. (2015)	Distinguish native vs. naturalized vs. invasive in all diversity surveys; track over succession

3.5 Asynchrony Between Structural and Diversity Recovery

A theoretically important and practically consequential finding emerging from the synthesis is the asynchrony between structural recovery—which tends to occur relatively rapidly in secondary forests—and full species diversity recovery, which may require decades to centuries depending on landscape context, propagule availability, and disturbance intensity. Poorter et al. (2016), in their landmark pantropical analysis of forty-five Neotropical secondary forest sites, found that above-ground biomass recovered to approximately 90% of old-growth reference levels within sixty-six years on average, while species richness recovery was considerably slower and more variable, often lagging biomass recovery by several decades. This structural lead over compositional recovery has direct implications for how vegetation survey data from Indonesian secondary forests should be interpreted.

The implication is that a structurally complete secondary forest with multi-strata vegetation and a reverse-J diameter distribution may still be considerably less diverse—in terms of species richness and functional trait diversity—than a comparable old-growth reference community. This structural completeness provides genuine ecological value (carbon storage, microclimate buffering, soil protection) but may not fully replicate the functional resilience and biodiversity conservation value of mature forest (Chazdon, 2014; Chazdon et al., 2016). Norden et al. (2015) further demonstrated that successional trajectories in secondary forests, while broadly directional, are highly variable among sites: communities that appear structurally similar at one point in time may diverge significantly in compositional trajectory depending on local seed rain dynamics, soil legacies, and disturbance history.

For Indonesian forest management, this asynchrony has important practical implications. Vegetation surveys that document adequate structure and moderate H' values should not be interpreted as indicating that restoration or conservation objectives have been fully achieved. Rather, these metrics should be treated as indicators of progress along a recovery continuum that requires sustained monitoring, active management where necessary to accelerate compositional recovery, and protection from the recurring disturbances that interrupt successional progress. The long-term sustainability of secondary forests as biodiversity reservoirs, carbon sinks, and providers of ecosystem services depends on this fuller understanding of recovery dynamics.

3.6 Towards an Integrated Multi-Indicator Stability Assessment Framework

The evidence synthesized in this review supports the development of an integrated multi-indicator framework for secondary forest stability assessment that moves beyond reliance on any single metric. Both vegetation structure and species diversity provide valuable and complementary information: structural completeness (multi-strata architecture, reverse-J diameter distribution) indicates demographic stability and successional momentum, while diversity indices (H' , J') capture the capacity of the community to maintain functional processes under perturbation. However, neither metric in isolation is sufficient, and both must be interpreted alongside measures of invasive species pressure, native species proportion, basal area as a proxy for biomass recovery, and disturbance history context (Damiti et al., 2025; Chazdon et al., 2016).

Operationally, this framework would require vegetation surveys to assess all major growth stages rather than focusing exclusively on the tree stratum; to distinguish native

from non-native species in diversity calculations; to map invasive species cover by stratum as a complementary destabilization indicator; and to track metrics longitudinally over multiple survey periods rather than relying on single-point snapshots. Remote sensing tools—including multi-temporal NDVI, lidar-derived canopy height metrics, and hyperspectral indices of canopy diversity—offer scalable complements to ground-based surveys that can extend spatial coverage across the large and often inaccessible secondary forest landscapes of the Indonesian archipelago and comparable tropical regions.

CONCLUSION

This systematic review synthesizes evidence from fourteen studies to evaluate the relationship between vegetation structure, species diversity, and ecosystem stability in secondary forests. The overall weight of evidence confirms a positive correlation between structurally complete, multi-strata vegetation communities and indicators of ecological stability, including active natural regeneration, community self-maintenance, and functional ecosystem processes. Shannon-Wiener H' values in the moderate range (1.4–2.5) are consistently associated with productive and relatively stable secondary forest communities across the Indonesian and international literature reviewed.

However, several important qualifications emerge from this synthesis. First, the interpretation of diversity indices must account for the composition of diversity, not merely its magnitude: communities in which invasive exotic species contribute substantially to H' values may exhibit apparent diversity while actually undergoing functional destabilization of native regeneration processes. Invasive species including *Chromolaena odorata*, *Piper aduncum*, and *Imperata cylindrica* emerged as particularly significant destabilizers across multiple study sites. Second, structural recovery of secondary forests tends to precede and outpace compositional recovery, meaning that structurally complete stands may still harbor species assemblages dominated by early-successional pioneers rather than the late-successional native species that confer long-term stability and full biodiversity value.

Third, anthropogenic pressures—including selective harvesting of dominant species, repeated fire, and livestock grazing—interact with biological invasion to modulate vegetation structure and diversity in ways that standard diversity metrics often fail to capture. A monitoring and assessment framework limited to aggregate H' values and structural density counts will systematically overestimate the stability of secondary forests subject to these compounding stressors.

For forest managers and conservation practitioners, the review supports the following evidence-based recommendations. Vegetation assessments should be conducted across all growth stages, with particular attention to the seedling and sapling strata where successional outcomes are determined. Diversity indices should be calculated separately for native and non-native species to distinguish genuine compositional recovery from invasion-inflated apparent diversity. Invasive species mapping should be integrated as a standard component of secondary forest monitoring protocols. Where invasive species cover exceeds threshold levels or where critical growth stages are absent, active management interventions—including invasive removal and native seedling enrichment planting—are warranted to prevent successional arrest.

Future research priorities include longitudinal monitoring studies that track vegetation structure and diversity trajectories over decadal time scales, comparative

studies that disentangle biotic from abiotic determinants of secondary forest recovery across contrasting ecological zones in Indonesia, and methodological studies that evaluate the performance of remote sensing indicators as proxies for ground-based structure and diversity metrics at landscape scales. As Indonesia's secondary forests continue to expand in area while varying dramatically in ecological quality, evidence-based frameworks for assessing and managing their stability represent a scientific and policy priority of considerable importance.

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