

Long-Term Forest Loss and Biodiversity Exposure in Indonesia: A Multi-Scale Assessment of National Trends (2001-2024) and Provincial Hotspots (2001-2020)

Ahmad Rizaldy Fanbudy^{1*}, Diganta Hatiboruah²

¹ STAIN Mandailing Natal, Indonesia

² Majuli College, India

Email: fanbudys@gmail.com¹

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Abstract

Indonesia's forest-loss trajectory is nationally improving but spatially uneven, creating a need to separate aggregate decline from subnational biodiversity exposure. This study integrates annual Global Forest Watch/University of Maryland tree-cover loss (2001-2024), tropical primary-forest loss (2002-2024), and province-level five-year loss aggregates (2001-2020) within a landscape-fragmentation and social-ecological resilience framework. Trend inference used Kendall's tau and Theil-Sen slopes, while provincial concentration was evaluated with regional aggregation, concentration shares, trajectory ratios, and a Gini coefficient. Indonesia lost 31.96 million ha of tree cover during 2001-2024, with a 2016 peak of 2.42 million ha. For 2015-2024, tree-cover loss declined significantly ($\tau=-0.511$, $p=0.047$; Sen slope=-97,216 ha/year), while primary-forest loss also declined ($\tau=-0.689$, $p=0.0047$; Sen slope=-34,399 ha/year). Provincial exposure remained concentrated: Riau lost 49.7% of its 2000 tree-cover baseline by 2020, followed by Bangka Belitung (41.7%), South Sumatra (40.6%), and Jambi (37.3%); the five largest-loss provinces accounted for 62.3% of provincial loss and the Gini coefficient was 0.649. The results show that national improvement does not remove localized fragmentation risk, especially across peat-dominated Sumatran and Kalimantan landscapes. Conservation monitoring should therefore combine national trend metrics with province-level pressure trajectories, functional connectivity, hydrological condition, fire recurrence, and species-level validation.

Keywords : forest loss, biodiversity exposure, fragmentation, peatland, Indonesia, Global Forest Watch.



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INTRODUCTION

Indonesia contains globally significant lowland, montane, and peat-swamp forest systems, but the ecological value of these systems depends not only on the hectares that remain but also on the spatial continuity, interior conditions, and disturbance regimes of those hectares. Global fragmentation research demonstrates that subdivision of forest landscapes increases edge exposure, reduces interior habitat, constrains dispersal, and can generate extinction debts that remain hidden for years after clearing occurs (Haddad et al., 2015; Betts et al., 2017; Pfeifer et al., 2017; Crooks et al., 2017). Indonesian evidence is consistent with this mechanism: forest loss alters habitat configuration and interacts with roads, plantations, settlement expansion, and repeated disturbance, while Southeast Asian syntheses show a marked biodiversity penalty in deforested relative to intact forests (Gunawan et al., 2024; Botterill-James et al., 2024). The analytical implication is that a national decline in annual forest loss should not automatically be interpreted as an equivalent reduction in biodiversity exposure because spatial concentration can preserve intense local pressure even while the aggregate curve improves.

Landscape-fragmentation theory provides the first theoretical foundation for this distinction. Taubert et al. (2018) show that tropical fragmentation is structured by patch size, edge density, and isolation rather than by forest amount alone, while Newbold et al. (2015) demonstrate that land-use intensification changes local biodiversity across terrestrial systems and Potapov et al. (2017) document the continuing erosion of intact forest landscapes. These findings imply a multi-scale exposure pathway: national forest-loss totals measure the magnitude of disturbance, province-level trajectories indicate where that disturbance is concentrated, and ecological studies explain why equivalent areas of loss can

generate different consequences when they occur in already fragmented or edge-dominated landscapes. The present study therefore treats forest loss as a measurable pressure variable and biodiversity exposure as a theoretically grounded risk condition rather than claiming that satellite-observed loss directly measures species decline.

Peat-swamp forests require an additional process-based interpretation because fragmentation is coupled to hydrology and fire. Regional land-cover evidence documents extensive long-term transformation of peatlands across Sumatra and Borneo (Miettinen et al., 2016), while integrated reviews emphasize that drainage lowers water tables, accelerates oxidation, increases fire susceptibility, and alters the matrix between surviving forest remnants (Mishra et al., 2021; Page & Hooijer, 2016). Indonesian conservation research similarly shows that peatland outcomes are shaped by the interaction of ecological condition, restoration design, and land-use institutions (Harrison et al., 2020; Puspitaloka et al., 2020). Consequently, high forest-loss percentages in peat-rich provinces cannot be read only as a reduction in area; they also signal landscapes in which hydrological degradation may reduce corridor quality and amplify edge and fire effects across boundaries.

Restoration evidence further supports a resilience perspective in which spatial reconnection must be ecologically functional. Large-scale rewetting can reduce subsidence and support forest regrowth when hydrological conditions are restored (Hooijer et al., 2024), yet restoration costs, institutional coordination, and long recovery horizons constrain what can be achieved after severe degradation (Puspitaloka et al., 2021). Paludiculture and low-drainage production systems have been proposed as alternatives that reduce pressure to maintain deeply drained peatland economies, but their effectiveness depends on technical feasibility and institutional fit (Uda et al., 2020a; Uda et al., 2020b). These mechanisms make temporal and spatial forest-loss patterns especially relevant for prioritization: landscapes with historically high cumulative loss require different interventions from landscapes where recent loss is accelerating despite a relatively intact baseline.

The governance dimension is also inseparable from ecological durability. Local institutions affect fire prevention, restoration maintenance, access regulation, tenure security, and the distribution of benefits from conservation programs (Januar et al., 2021; Medrilzam et al., 2017; Sanders et al., 2019). Participatory research in Indonesian peat landscapes indicates that community knowledge systems and community-based fire prevention can strengthen project performance when local incentives are aligned with ecological objectives (Robins et al., 2022; Purnomo et al., 2024). Equitable restoration principles and community-led approaches likewise emphasize legitimacy, livelihood compatibility, and long-term stewardship rather than short project cycles (Terzano et al., 2022; Toumbourou et al., 2024). A data-rich forest-pressure assessment therefore has practical value only when it is interpreted alongside the institutional conditions that determine whether declining loss rates can be maintained.

Monitoring design remains a major methodological challenge because easily mapped structural variables are not equivalent to ecological function. Peat thickness and carbon stocks can be mapped using spatial methods that improve landscape targeting (Rudiyanto et al., 2018), while livelihood-oriented restoration research shows that households can respond to degraded peatland conditions in ways that either reinforce or reduce pressure (Sakuntaladewi et al., 2022). Natural regeneration itself depends on distance to forest and animal-mediated dispersal, demonstrating that biological recovery is constrained by connectivity processes not visible in a national loss total (Wijedasa et al., 2020). Long-term forest-cover monitoring therefore needs to be paired with field, movement, genetic, hydrological, and governance indicators if it is to distinguish visually greener landscapes from landscapes that actually recover ecological function.

Existing Indonesian fragmentation scholarship is rich in mechanism but comparatively fragmented in scale. Reviews synthesize ecological pathways, peatland studies describe restoration and fire processes, and national monitoring platforms provide annual satellite-based loss data, yet fewer analyses connect a long national time series with comparable province-level trajectories in a framework explicitly designed to identify spatial concentration and persistence of biodiversity exposure. Vancutsem et al. (2021) demonstrate the value of long-term humid-tropical forest monitoring, while the Global Forest Watch record derived from Landsat enables consistent annual comparison of stand-replacement tree-cover loss over multiple decades (Hansen et al., 2013; Global Forest Watch, 2025). The research gap is therefore not the absence of data but the need to integrate temporal trend, subnational concentration, and ecological interpretation without conflating forest-cover change with direct biodiversity measurement.

This study addresses that gap through a multi-scale longitudinal assessment of Indonesia. It asks three questions: (1) how did national tree-cover and tropical primary-forest loss change from the early 2000s through 2024; (2) how concentrated was cumulative tree-cover loss across provinces and major island regions during 2001-2020; and (3) what do the combined temporal and spatial patterns imply for biodiversity exposure, particularly in peat-dominated landscapes? The study contributes a reproducible analytical architecture that combines nonparametric time-series trend tests, five-year provincial trajectories, regional aggregation, and concentration statistics, while interpreting results through fragmentation theory and social-ecological resilience rather than through area-loss totals alone.

RESEARCH METHODS

The study used a quantitative longitudinal secondary-data design with three nested analytical scales. National annual tree-cover loss for 2001-2024 was taken from the Global Forest Watch/University of Maryland record as processed by Our World in Data, using a 30% canopy threshold and the annual stand-replacement loss definition developed from Landsat observations (Hansen et al., 2013; Global Forest Watch, 2025; Our World in Data, 2025). Tropical primary-forest loss was compiled for 2002-2024 from the same UMD/GFW monitoring framework and WRI annual forest-loss reporting, while province-level tree-cover extent and five-year loss aggregates for 2001-2005, 2006-2010, 2011-2015, and 2016-2020 were taken from the GFW-derived Indonesia archive distributed by Mongabay (Mongabay, 2022; World Resources Institute, 2025). The provincial table uses the administrative units and forest baseline represented in the source archive; later province splits were not back-cast because doing so would create non-comparable denominators. Tree-cover loss is a biophysical disturbance metric rather than a legal deforestation category, and the analysis therefore does not substitute GFW values for Indonesia's official forest-class accounting.

National series were summarized with cumulative loss, annual means, period means, three-year centered moving averages, and peak-year diagnostics. Trend direction was tested using Kendall's tau because annual loss is non-normal, serially irregular, and strongly influenced by extreme fire years; magnitude was estimated with the Theil-Sen median slope and 95% confidence interval. Because improvements in Landsat inputs and loss-detection methods complicate direct comparison across the early and late record, formal inference emphasized 2015-2024 while the full 2001-2024 series was retained for long-term description, consistent with WRI's caution regarding pre/post-2015 comparability. The relationship between total tree-cover loss and primary-forest loss over 2002-2024 was evaluated using Pearson correlation as a descriptive correspondence measure, not as a causal model.

Subnational analysis calculated cumulative loss as a percentage of the 2000 tree-cover baseline, the share of each province's cumulative loss occurring in 2016-2020, and an acceleration ratio defined as 2016-2020 loss divided by 2001-2005 loss. Provinces were then aggregated into Sumatra, Kalimantan, Java-Bali, Sulawesi, Maluku, Papua, and Nusa Tenggara to compare regional exposure. Spatial concentration was assessed using the cumulative share of total provincial loss captured by the five and ten largest-loss provinces and a Gini coefficient across provincial loss totals; values closer to one indicate stronger concentration. Interpretation followed a two-layer theoretical framework: landscape-fragmentation theory was used to explain why concentrated cover loss can magnify edge and connectivity effects, while social-ecological resilience theory was used to interpret peatland hydrology, fire, restoration, livelihood, and governance constraints. No species abundance data were modeled, so all biodiversity conclusions are framed as exposure and conservation-priority implications rather than direct estimates of population decline.

Table 1. Data Architecture, Temporal Coverage, and Analytical Role

Dataset / indicator		Coverage	Unit / resolution	Analytical role
Tree-cover (GFW/UMD)	loss	2001-2024, annual	ha; 30% canopy threshold	National magnitude, moving average, trend
Tropical forest (GFW/WRI)	primary-forest loss	2002-2024, annual	ha; humid tropical primary forest	High-value forest pressure trend

Provincial tree-cover baseline and loss	2000 baseline; 2001-2020 in four 5-year blocks	ha, province	Hotspots, concentration	acceleration,
Regional aggregation	2001-2020	7 island-region groups	Cross-region comparison	exposure
Ecological and governance literature	2015-2024 emphasis; retained foundational studies	Peer-reviewed evidence	Fragmentation and interpretation	resilience

Source: Global Forest Watch (2025), Hansen et al. (2013), Mongabay (2022), Our World in Data (2025), World Resources Institute (2025), and retained peer-reviewed literature.

Table 1 separates what is measured from how it is interpreted. The satellite series measures stand-replacement tree-cover loss and primary-forest loss, while fragmentation, hydrological vulnerability, species sensitivity, restoration durability, and governance are interpreted from the retained literature; this distinction prevents an area-based indicator from being overstated as a direct biodiversity outcome.

RESULTS AND DISCUSSION

National Forest-Loss Trajectory: Long-Term Volatility Followed By A Lower Recent Regime

Indonesia's annual tree-cover loss remained highly volatile across the 24-year series, but the distribution of loss changed markedly after the mid-2010s. Cumulative loss reached 31.96 million ha during 2001-2024, equivalent to an annual mean of 1.33 million ha, and the maximum occurred in 2016 at 2.42 million ha. The six-year period means reveal a rise from 1.01 million ha/year in 2001-2006 to 1.64 million ha/year in 2007-2012 and 1.62 million ha/year in 2013-2018, followed by a decline to 1.06 million ha/year in 2019-2024. This shift is ecologically important because the recent national average is materially lower than the two preceding six-year blocks, yet it still represents more than one million hectares of annual stand-replacement disturbance and therefore substantial continuing pressure on landscape continuity.

The nonparametric results confirm that the recent decline is not visible when the entire record is treated as a single linear trend. For 2001-2024, Kendall's tau was 0.014 ($p=0.941$) and the Theil-Sen slope was approximately +1,199 ha/year, indicating no monotonic long-run direction because early increases, extreme mid-series peaks, and later declines offset one another. In contrast, the 2015-2024 window produced $\tau=-0.511$ ($p=0.047$) and a Sen slope of -97,216 ha/year (95% CI: -162,725 to -11,324), showing a statistically detectable downward trajectory after the mid-decade peak. This temporal structure is consistent with Vancutsem et al. (2021), who emphasize the importance of long monitoring windows, and with the caution that forest-change series should not be summarized by a single endpoint comparison when disturbance is episodic.

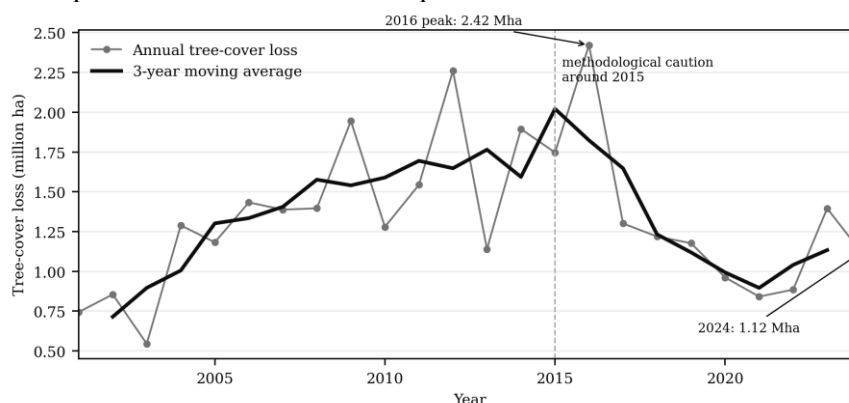


Figure 1. Annual Tree-Cover Loss in Indonesia, 2001-2024, with Three-Year Moving Average

Source: Author calculation from Global Forest Watch/UMD data processed by Our World in Data (2025).

Primary-forest loss shows an even clearer recent decline. The reconstructed 2002-2024 series totals 10.73 million ha, with the highest annual value again in 2016 (928,660 ha); for 2015-2024, Kendall's $\tau = -0.689$ ($p = 0.0047$) and the Sen slope $= -34,399$ ha/year (95% CI: $-79,317$ to $-13,480$). Total tree-cover loss and primary-forest loss are strongly correlated across overlapping years ($r = 0.930$, $p < 0.001$), showing that years of broad stand-replacement disturbance usually coincide with elevated pressure on humid tropical primary forests. The correlation does not imply identical processes because tree-cover loss includes plantations and temporary disturbances, but it demonstrates that the two indicators share a strong national temporal signal.

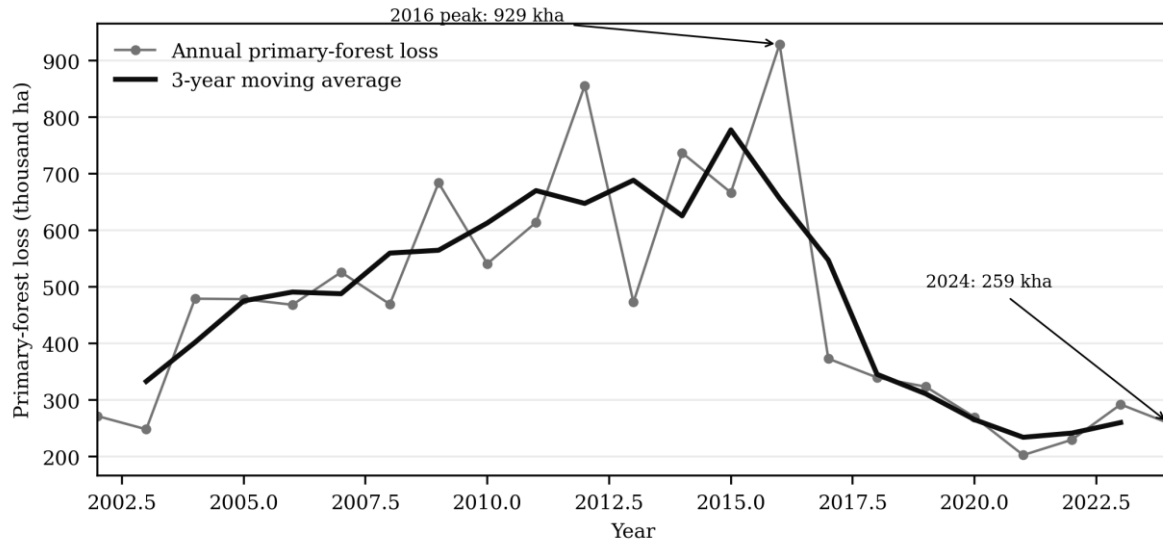


Figure 2. Tropical Primary-Forest Loss in Indonesia, 2002-2024, with Three-Year Moving Average

Source: Author calculation from Global Forest Watch/WRI annual primary-forest-loss series. UMD primary forest is a biophysical classification and differs from Indonesia's legal primary-forest class.

From a fragmentation perspective, the decline after 2016 is encouraging but incomplete. Haddad et al. (2015) and Betts et al. (2017) show that ecological consequences persist after the initial clearing event, while Pfeifer et al. (2017) demonstrate that new edges can alter vertebrate assemblages even where substantial forest cover remains. A lower annual loss rate therefore reduces the rate at which new disturbance is added but does not automatically reverse the edge exposure, isolation, road access, hunting pressure, or demographic disconnection created by previous loss. This distinction is critical for interpreting the 2019-2024 low-loss regime: it signals reduced incremental pressure, not restoration of the historical landscape structure.

The same distinction applies to intactness and functional connectivity. Potapov et al. (2017) documented loss of intact forest landscapes globally, and Taubert et al. (2018) showed that tropical fragmentation can persist and reorganize networks even when total forest remains extensive. Indonesian conservation planning should therefore read Figure 1 as a rate-of-pressure signal rather than a complete status indicator. A province that experienced heavy loss in the 2000s can remain biodiversity-vulnerable during a later period of reduced annual clearing because the surviving habitat network may already have high edge-to-interior ratios and weak connections among source populations (Crooks et al., 2017; Gunawan et al., 2024).

Table 2. Six-Year Summary of National Tree-Cover Loss

Period	Mean annual loss (ha)	Cumulative loss (ha)	Minimum (ha)	Maximum (ha)	CV (%)
2001-2006	1,008,130	6,048,783	544,811	1,433,147	34.3
2007-2012	1,635,340	9,812,038	1,279,328	2,260,258	23.5
2013-2018	1,620,273	9,721,640	1,139,300	2,422,065	30.6

2019-2024	1,063,441	6,380,645	841,390	1,395,285	19.6
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Source: Author calculation from the annual Global Forest Watch/UMD tree-cover-loss series.

Table 2 shows that the 2019-2024 block combined the lowest mean loss since 2001-2006 with the lowest coefficient of variation, suggesting a lower and more stable recent disturbance regime than the high-loss 2007-2018 interval. That improvement should nevertheless be interpreted with the known methodology changes in the underlying satellite record and with the ecological lag between reduced clearing and recovery of interior habitat or connected populations.

Table 3. Nonparametric Trend Tests for National Forest-Loss Indicators

Indicator / window	n	Kendall tau	p-value	Sen slope (ha/year)	95% CI (ha/year)
Tree-cover loss, 2001-2024	24	0.014	0.9413	1,199	[-25,779, 39,505]
Tree-cover loss, 2015-2024	10	-0.511	0.0466	-97,216	[-162,725, -11,324]
Primary-forest loss, 2002-2024	23	-0.202	0.1888	-10,367	[-19,733, 6,767]
Primary-forest loss, 2015-2024	10	-0.689	0.0047	-34,399	[-79,317, -13,480]

Source: Author calculation. Statistical inference is emphasized for 2015-2024 because WRI cautions against treating the full pre/post-2015 series as methodologically uniform.

The contrasting full-series and post-2015 results in Table 3 are substantively important: Indonesia's recent decline is real within the contemporary segment of the record, but the 24-year series is not a simple monotonic success story. Conservation evaluation should therefore report both the current direction and the accumulated historical pressure that continues to structure fragmented landscapes.

Spatial Concentration and Provincial Trajectories: National Improvement Masks Persistent Hotspots

Provincial aggregation reveals a much sharper concentration of forest pressure than the national series alone. Across the 33 provincial units represented in the 2001-2020 archive, the Gini coefficient for cumulative tree-cover loss is 0.649, the five provinces with the largest absolute losses account for 62.3% of all provincial loss, and the ten largest account for 81.5%. Riau recorded the highest proportional loss relative to its 2000 baseline (49.7%), followed by Bangka Belitung (41.7%), South Sumatra (40.6%), Jambi (37.3%), and South Kalimantan (28.9%). In absolute terms, Riau, West Kalimantan, Central Kalimantan, East Kalimantan, and South Sumatra dominate the loss distribution, demonstrating that biodiversity exposure is spatially clustered within a limited number of high-pressure landscapes.

Regional aggregation reinforces this pattern. Sumatra lost 31.6% of its aggregated 2000 tree-cover baseline by 2020 and Kalimantan lost 23.0%, compared with 12.8% in Sulawesi, 6.8% in Maluku, 5.6% in Nusa Tenggara, 4.2% in Java-Bali, and 2.4% in Papua. The interpretation should not be that low-percentage regions are ecologically secure: Papua, for example, retains a very large baseline area, so even a smaller proportional loss can represent substantial absolute habitat change and can be consequential where new roads and development fronts create future fragmentation. Instead, the regional percentages identify accumulated exposure relative to starting forest extent and highlight the exceptional historical pressure in Sumatra and Kalimantan.

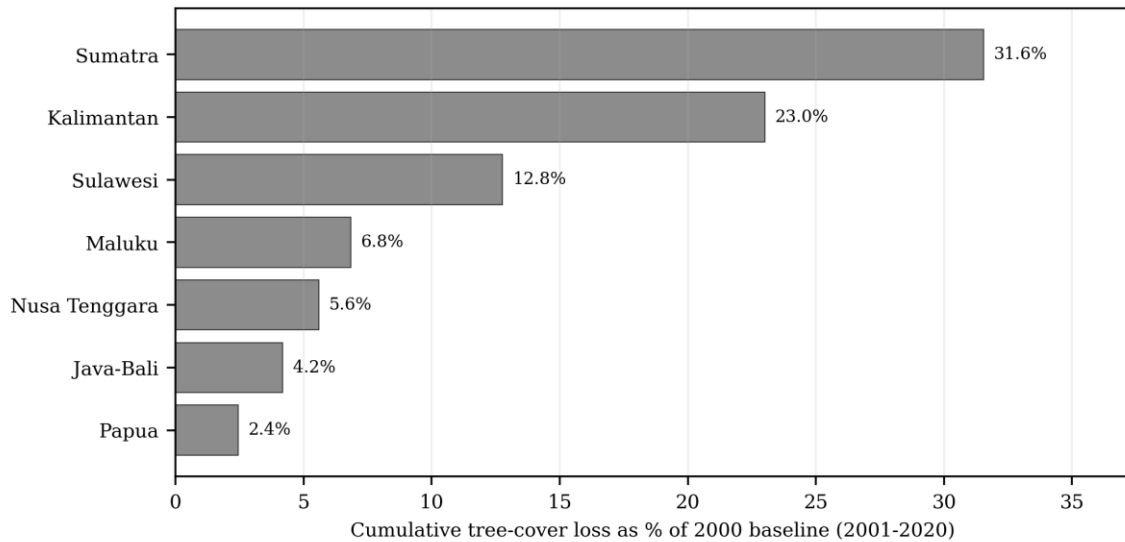


Figure 3. Cumulative Tree-Cover Loss by Major Indonesian Region, 2001-2020

Source: Author aggregation of province-level Global Forest Watch-derived data reported by Mongabay (2022).

The five-year trajectories also show that pressure does not evolve uniformly. Riau's loss fell markedly in 2016-2020 relative to 2001-2005, but East Kalimantan, West Kalimantan, South Sumatra, Aceh, Bangka Belitung, Jambi, Central Kalimantan, and several Sulawesi provinces still recorded higher 2016-2020 loss than in 2001-2005. This divergence explains why national improvement can coexist with local persistence or acceleration. Landscape management should therefore distinguish legacy hotspots, where cumulative loss is already extremely high but recent loss is falling, from active-frontier hotspots, where the recent five-year block remains elevated relative to the early baseline.

Table 4. Twelve Highest Provincial Tree-Cover-Loss Percentages and Temporal Pressure Indicators

Province	Baseline 2000 (ha)	Loss 2001-2020 (ha)	Loss (%)	2016-20 share (%)	Accelerati on ratio
Riau	7,848,796	3,903,861	49.7	14.6	0.57
Bangka Belitung	1,332,851	555,630	41.7	28.1	2.11
Sumatera Selatan	7,037,573	2,860,391	40.6	25.8	2.13
Jambi	4,484,195	1,672,045	37.3	27.5	1.63
Kalimantan Selatan	2,818,022	814,813	28.9	25.3	1.60
Kalimantan Barat	13,640,415	3,581,940	26.3	24.9	1.99
Kalimantan Tengah	14,220,872	3,470,846	24.4	26.5	1.47
Sumatera Utara	5,784,860	1,381,511	23.9	23.3	1.16
Bengkulu	1,795,195	387,880	21.6	28.6	1.54
Kepulauan Riau	689,817	139,668	20.2	32.2	2.08
Kalimantan Timur	18,555,914	3,460,911	18.7	28.4	2.42
Sumatera Barat	3,810,768	602,009	15.8	31.5	1.97

Source: Author calculation from Global Forest Watch-derived provincial aggregates. Acceleration ratio = loss in 2016-2020 / loss in 2001-2005; values above 1 indicate a higher recent five-year loss than the early five-year block.

This spatial heterogeneity has direct fragmentation implications. Crooks et al. (2017) show that fragmentation is associated with mammal extinction risk, and Botterill-James et al. (2024) synthesize evidence of lower Southeast Asian biodiversity in deforested landscapes. In provinces with high

cumulative loss, each additional clearing event can have disproportionate effects when it widens an existing edge, severs a narrow connection, or isolates a remnant that had functioned as a stepping stone. Conversely, maintaining large source forests in lower-loss regions can preserve future options for connectivity that become difficult or expensive to recreate after fragmentation proceeds.

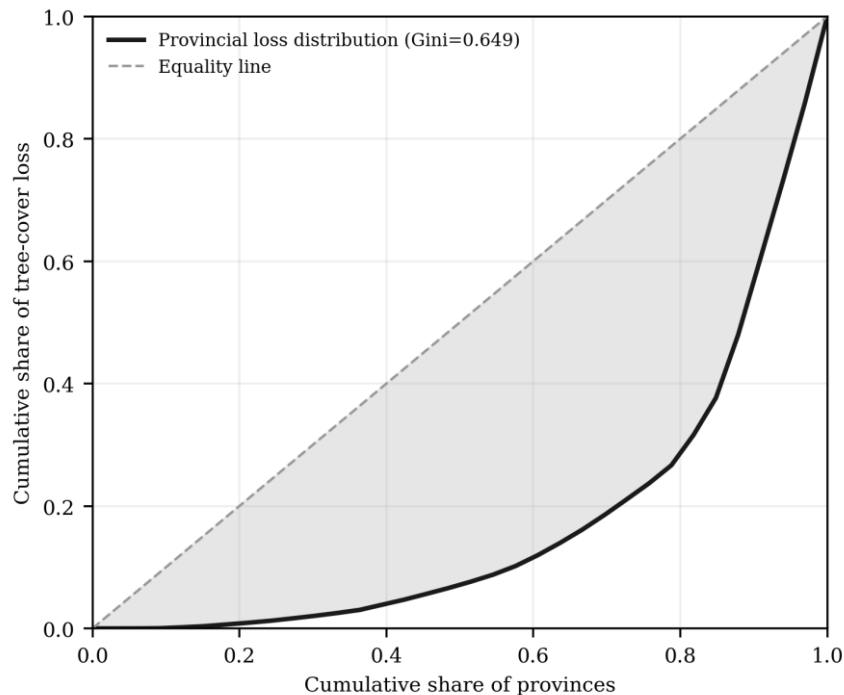


Figure 4. Lorenz Curve of Provincial Tree-Cover Loss, 2001-2020

Source: Author calculation from 33 provincial units in the source archive; Gini coefficient = 0.649.

The Lorenz curve in Figure 4 makes the concentration problem explicit: most provincial units account for a relatively small share of total loss, while a small number of high-loss provinces account for the majority. This is not simply a statistical property; it implies that national conservation gains may be increased by geographically targeted interventions, provided that targeting does not neglect emerging frontiers. A dual strategy is therefore warranted: intensive restoration and reconnection in legacy hotspots, combined with avoidance of new fragmentation in comparatively intact provinces where prevention has greater ecological leverage.

Table 5. Regional Aggregation of Provincial Forest-Loss Exposure

Region	2000 baseline (ha)	Loss 2001-2020 (ha)	Loss / baseline (%)	Share occurring 2016-20 (%)
Sumatra	39,551,920	12,479,557	31.6	22.8
Kalimantan	49,235,223	11,328,510	23.0	26.5
Sulawesi	15,683,294	2,001,338	12.8	30.6
Maluku	7,220,691	494,244	6.8	28.4
Nusa Tenggara	3,432,779	191,878	5.6	36.9
Java-Bali	6,493,042	270,880	4.2	28.8
Papua	39,024,275	954,588	2.4	34.4

Source: Author calculation from province-level Global Forest Watch-derived data reported by Mongabay (2022).

Table 5 provides a scale bridge between province and nation. Sumatra and Kalimantan combine high proportional loss with very large forest baselines, making them central to both restoration and connectivity policy; by contrast, Papua's low proportional loss indicates a stronger prevention

opportunity, where maintaining large intact systems can avoid the nonlinear ecological costs that appear after landscapes become heavily subdivided.

Peatland vulnerability, functional connectivity, and conservation prioritization

The spatial results align closely with the geography of Indonesia's peatland conservation challenge. Riau, Jambi, South Sumatra, and Central and West Kalimantan are prominent in the high-loss distribution and also contain extensive peat and lowland forest landscapes where drainage, fire, plantations, and settlement interact. Miettinen et al. (2016) documented major peatland land-cover change across Sumatra and Borneo, while Page and Hooijer (2016) and Mishra et al. (2021) explain why drainage creates a landscape-scale fire mechanism rather than a patch-specific disturbance. The conservation implication is that a remaining forest strip in a high-loss peat landscape cannot be assumed to function as a corridor if its hydrological regime has been disrupted or if recurrent fire keeps the matrix hostile.

Restoration should therefore be evaluated through process indicators, not hectares planted alone. Puspitaloka et al. (2020) argue for ecologically explicit peatland restoration definitions, and Hooijer et al. (2024) provide large-scale evidence that rewetting can reduce subsidence and support forest regrowth. Puspitaloka et al. (2021) further show that costs and governance alternatives shape restoration feasibility, while Ward et al. (2020) demonstrate that national stakeholders attach multiple meanings and expectations to peatland restoration. In the high-pressure provinces identified here, prioritization should favor sites where hydrological repair can be connected to large source forests, where corridor width can reduce edge dominance, and where land-use arrangements can protect the investment from renewed drainage or burning.

Livelihood design is equally important because the matrix surrounding fragments is often economically active. Uda et al. (2020a) show that paludiculture and low-drainage food crops can reduce dependence on drainage-intensive peat use, while Uda et al. (2020b) emphasize the need for institutional arrangements that fit the ecological scale of peat systems. Medrilzam et al. (2017) demonstrate how smallholder dynamics can contribute to peat degradation, and Sakuntaladewi et al. (2022) show that livelihood-oriented innovations can be integrated with restoration goals. These findings suggest that the provinces with the highest cumulative loss require landscape programs that manage production, hydrology, habitat, and access together rather than treating forest remnants as isolated protected islands.

Community and governance evidence further modifies the interpretation of the numerical hotspots. Robins et al. (2022) show that knowledge systems influence community fire-management performance, Purnomo et al. (2024) demonstrate the value of participatory action research for fire prevention and restoration, and Terzano et al. (2022) frame community-led restoration through a multidimensional 5Rs approach. Toumbourou et al. (2024) add that equitable and resilient restoration requires attention to local rights, benefits, and social differentiation. These studies imply that a province's loss percentage should guide where to look, not prescribe a single intervention: ecological urgency must be matched with locally legitimate institutions capable of maintaining hydrological and connectivity gains over time.

Connectivity monitoring also needs a biological validation layer. Wijedasa et al. (2020) found that distance to forest and mammal and bird dispersal influence natural regeneration on degraded tropical peatland, demonstrating that source habitat and dispersal agents jointly shape recovery. Pfeifer et al. (2017) and Crooks et al. (2017) likewise show that edge and fragmentation effects are taxon-dependent, while Gunawan et al. (2024) identify multiple drivers and response pathways relevant to Indonesian biodiversity conservation. Restoration success should therefore be assessed with repeated wildlife observations, occupancy, movement, genetic indicators, and regeneration data in addition to remote-sensing measures of area and structural continuity.

A practical prioritization sequence follows from the combined evidence. First, avoid new fragmentation of large remaining forest systems, particularly in lower-loss regions where prevention protects future connectivity options (Potapov et al., 2017; Betts et al., 2017). Second, in legacy hotspots such as Riau, South Sumatra, Jambi, and the Kalimantan provinces, reconnect remnants only where corridor width, matrix permeability, hydrology, and fire management can support functional movement rather than merely visual continuity (Harrison et al., 2020; Mishra et al., 2021). Third, monitor whether restoration changes biological processes and not only mapped cover, using field and genetic validation where feasible (Wijedasa et al., 2020; Rudiyanto et al., 2018). Fourth, embed those ecological measures

in institutions and livelihood systems capable of maintaining the intervention after project finance ends (Januar et al., 2021; Sanders et al., 2019; Robins et al., 2022).

The study's novelty lies in making the scale mismatch visible. National annual loss has declined significantly in the post-2015 period, yet accumulated provincial pressure remains highly unequal and several provinces still show recent five-year losses above their early-2000s levels. This combination explains why aggregate improvement and local biodiversity vulnerability can coexist. The results strengthen the case for a monitoring architecture in which national trend statistics are used to assess broad direction, provincial trajectories are used to detect concentration and persistence, and ecological field indicators determine whether landscapes remain functionally connected and resilient.

CONCLUSION

Indonesia's forest-loss trajectory has entered a lower recent regime, but the ecological meaning of that improvement depends on where historical and continuing pressure is concentrated. The 2001-2024 record contains 31.96 million ha of tree-cover loss and a 2016 peak of 2.42 million ha, while the post-2015 trend declines significantly at approximately 97,216 ha per year; tropical primary-forest loss shows an even clearer post-2015 decline of approximately 34,399 ha per year. At the same time, the 2001-2020 provincial distribution is highly concentrated (Gini=0.649), with the five largest-loss provinces accounting for 62.3% of total provincial loss and extremely high baseline-relative losses in Riau, Bangka Belitung, South Sumatra, and Jambi. National progress therefore does not eliminate the fragmentation legacy embedded in high-pressure landscapes.

Conservation should use this scale-sensitive evidence to differentiate prevention, reconnection, and repair. Comparatively intact regions require strong avoidance of new fragmentation, while heavily transformed Sumatran and Kalimantan landscapes require restoration that integrates corridor design with peat rewetting, fire prevention, compatible livelihoods, and durable governance. Future monitoring should combine annual forest-cover change with edge density, patch configuration, hydrological condition, fire recurrence, species occupancy and movement, regeneration, and genetic connectivity. Such integration would convert forest-loss monitoring from a descriptive accounting system into a biologically defensible framework for tracking whether Indonesia's improving national trend is also producing more resilient local landscapes.

REFERENCES

- Betts, M. G., Wolf, C., Ripple, W. J., Phalan, B., Millers, K. A., Duarte, A., Butchart, S. H. M., & Levi, T. (2017). Global forest loss disproportionately erodes biodiversity in intact landscapes. *Nature*, 547, 441-444. <https://doi.org/10.1038/nature23285>
- Botterill-James, T., Yates, L. A., Buettel, J. C., Aandahl, Z., & Brook, B. W. (2024). Southeast Asian biodiversity is a fifth lower in deforested versus intact forests. *Environmental Research Letters*, 19, 113007. <https://doi.org/10.1088/1748-9326/ad86ce>
- Crooks, K. R., Burdett, C. L., Theobald, D. M., King, S. R. B., Di Marco, M., Rondinini, C., & Boitani, L. (2017). Quantification of habitat fragmentation reveals extinction risk in terrestrial mammals. *Proceedings of the National Academy of Sciences*, 114(29), 7635-7640. <https://doi.org/10.1073/pnas.1705769114>
- Global Forest Watch. (2025). Tree cover loss by dominant driver [Dataset]. World Resources Institute. <https://www.globalforestwatch.org/>
- Gunawan, H., Setyawati, T., Atmoko, T., et al. (2024). A review of forest fragmentation in Indonesia under the DPSIR framework for biodiversity conservation strategies. *Global Ecology and Conservation*, 51, e02918. <https://doi.org/10.1016/j.gecco.2024.e02918>
- Haddad, N. M., Brudvig, L. A., Clobert, J., et al. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances*, 1(2), e1500052. <https://doi.org/10.1126/sciadv.1500052>
- Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, S. V., Goetz, S. J., Loveland, T. R., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O., & Townshend, J. R. G. (2013). High-resolution global maps of 21st-century forest cover change. *Science*, 342(6160), 850-853. <https://doi.org/10.1126/science.1244693>

- Harrison, M. E., Ottay, J. B., D'Arcy, L. J., et al. (2020). Tropical forest and peatland conservation in Indonesia: Challenges and directions. *People and Nature*, 2, 4-28. <https://doi.org/10.1002/pan3.10060>
- Hooijer, A., Vernimmen, R., Mulyadi, D., Triantomo, V., Hamdani, Lampela, M., et al. (2024). Benefits of tropical peatland rewetting for subsidence reduction and forest regrowth: Results from a large-scale restoration trial. *Scientific Reports*, 14, 10721. <https://doi.org/10.1038/s41598-024-60462-3>
- Januar, R., Sari, E. N. N., & Putra, S. (2021). Dynamics of local governance: The case of peatland restoration in Central Kalimantan, Indonesia. *Land Use Policy*, 102, 105270. <https://doi.org/10.1016/j.landusepol.2020.105270>
- Medrilzam, M., Smith, C., Aziz, A. A., Herbohn, J., & Dargusch, P. (2017). Smallholder farmers and the dynamics of degradation of peatland ecosystems in Central Kalimantan, Indonesia. *Ecological Economics*, 136, 101-113. <https://doi.org/10.1016/j.ecolecon.2017.02.017>
- Miettinen, J., Shi, C., & Liew, S. C. (2016). Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. *Global Ecology and Conservation*, 6, 67-78. <https://doi.org/10.1016/j.gecco.2016.02.004>
- Mishra, S., Page, S. E., Cobb, A. R., Lee, J. S. H., Jovani-Sancho, A. J., Sjogersten, S., Jaya, A., Aswandi, & Wardle, D. A. (2021). Degradation of Southeast Asian tropical peatlands and integrated strategies for their better management and restoration. *Journal of Applied Ecology*, 58, 1370-1387. <https://doi.org/10.1111/1365-2664.13905>
- Mongabay. (2022). Deforestation statistics for Indonesia: Annual and subnational tree-cover data [Data archive]. <https://worldrainforests.com/deforestation/archive/Indonesia.htm>
- Newbold, T., Hudson, L. N., Hill, S. L. L., et al. (2015). Global effects of land use on local terrestrial biodiversity. *Nature*, 520, 45-50. <https://doi.org/10.1038/nature14324>
- Our World in Data. (2025). Tree cover loss [Dataset; based on Global Forest Watch]. <https://ourworldindata.org/grapher/tree-cover-loss>
- Page, S. E., & Hooijer, A. (2016). In the line of fire: The peatlands of Southeast Asia. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371, 20150176. <https://doi.org/10.1098/rstb.2015.0176>
- Pfeifer, M., Lefebvre, V., Peres, C. A., et al. (2017). Creation of forest edges has a global impact on forest vertebrates. *Nature*, 551, 187-191. <https://doi.org/10.1038/nature24457>
- Potapov, P., Hansen, M. C., Laestadius, L., Turubanova, S., Yaroshenko, A., Thies, C., Smith, W., Zhuravleva, I., Komarova, A., Minnemeyer, S., & Esipova, E. (2017). The last frontiers of wilderness: Tracking loss of intact forest landscapes from 2000 to 2013. *Science Advances*, 3(1), e1600821. <https://doi.org/10.1126/sciadv.1600821>
- Purnomo, H., Puspitaloka, D., Okarda, B., Andrianto, A., Qomar, N., Sutikno, S., et al. (2024). Community-based fire prevention and peatland restoration in Indonesia: A participatory action research approach. *Environmental Development*, 50, 100971. <https://doi.org/10.1016/j.envdev.2024.100971>
- Puspitaloka, D., Kim, Y. S., Purnomo, H., & Fule, P. Z. (2020). Defining ecological restoration of peatlands in Central Kalimantan, Indonesia. *Restoration Ecology*, 28, 435-446. <https://doi.org/10.1111/rec.13097>
- Puspitaloka, D., Kim, Y. S., Purnomo, H., & Fule, P. Z. (2021). Analysis of challenges, costs, and governance alternative for peatland restoration in Central Kalimantan, Indonesia. *Trees, Forests and People*, 6, 100131. <https://doi.org/10.1016/j.tfp.2021.100131>
- Robins, L., van Kerkhoff, L., Rochmayanto, Y., Sakuntaladewi, N., & Agrawal, S. (2022). Knowledge systems approaches for enhancing project impacts in complex settings: Community fire management and peatland restoration in Indonesia. *Regional Environmental Change*, 22, 100. <https://doi.org/10.1007/s10113-022-01960-w>
- Rudiyanto, R., Minasny, B., Setiawan, B. I., Saptomo, S. K., & McBratney, A. B. (2018). Open digital mapping as a cost-effective method for mapping peat thickness and assessing the carbon stock of tropical peatlands. *Geoderma*, 313, 25-40. <https://doi.org/10.1016/j.geoderma.2017.10.018>
- Sakuntaladewi, N., Rachmanadi, D., Mendham, D., Yuwati, T. W., Winarno, B., Premono, B. T., et al. (2022). Can we simultaneously restore peatlands and improve livelihoods? Exploring community

- home yard innovations in utilizing degraded peatland. *Land*, 11, 150. <https://doi.org/10.3390/land11020150>
- Sanders, A. J. P., Ford, R. M., Mulyani, L., Prasti, H. R. D., Larson, A. M., Jagau, Y., & Keenan, R. J. (2019). Unrelenting games: Multiple negotiations and landscape transformations in the tropical peatlands of Central Kalimantan, Indonesia. *World Development*, 117, 196-210. <https://doi.org/10.1016/j.worlddev.2019.01.008>
- Taubert, F., Fischer, R., Groeneveld, J., Lehmann, S., Muller, M. S., Rodig, E., Wiegand, T., & Huth, A. (2018). Global patterns of tropical forest fragmentation. *Nature*, 554, 519-522. <https://doi.org/10.1038/nature25508>
- Terzano, D., Attorre, F., Parish, F., Moss, P., Bresciani, F., Cooke, R., & Dargusch, P. (2022). Community-led peatland restoration in Southeast Asia: 5Rs approach. *Restoration Ecology*, 30, e13642. <https://doi.org/10.1111/rec.13642>
- Toumbourou, T. D., Lestari, S., Yuwati, T. W., Treby, S., Winarno, B., Rachmanadi, D., Idrus, N. I., Sakuntaladewi, N., Budiningsih, K., Grover, S. P. P., & Rawluk, A. (2024). Principles for equitable and resilient tropical peatland restoration in Central Kalimantan, Indonesia. *Restoration Ecology*, 32, e14221. <https://doi.org/10.1111/rec.14221>
- Uda, S. K., Hein, L., & Adventa, A. (2020a). Towards better use of Indonesian peatlands with paludiculture and low-drainage food crops. *Wetlands Ecology and Management*, 28, 509-526. <https://doi.org/10.1007/s11273-020-09728-x>
- Uda, S. K., Schouten, G., & Hein, L. (2020b). The institutional fit of peatland governance in Indonesia. *Land Use Policy*, 99, 103300. <https://doi.org/10.1016/j.landusepol.2018.03.031>
- Vancutsem, C., Achard, F., Pekel, J.-F., Vieilledent, G., Carboni, S., Simonetti, D., Gallego, J., Aragao, L. E. O. C., & Nasi, R. (2021). Long-term (1990-2019) monitoring of forest cover changes in the humid tropics. *Science Advances*, 7(10), eabe1603. <https://doi.org/10.1126/sciadv.abe1603>
- Ward, C., Stringer, L. C., Warren-Thomas, E., Agus, F., Hamer, K., Pettorelli, N., et al. (2020). Wading through the swamp: What does tropical peatland restoration mean to national-level stakeholders in Indonesia? *Restoration Ecology*, 28, 817-827. <https://doi.org/10.1111/rec.13133>
- Wijedasa, L. S., Vernimmen, R., Page, S. E., Mulyadi, D., Bahri, S., Randi, A., et al. (2020). Distance to forest, mammal and bird dispersal drive natural regeneration on degraded tropical peatland. *Forest Ecology and Management*, 461, 117868. <https://doi.org/10.1016/j.foreco.2020.117868>
- World Resources Institute. (2025). How much forest was lost in 2024? *Global Forest Review: Forest Pulse*. <https://gfr.wri.org/global-tree-cover-loss-data-2024>