

THE IMPACT OF FOREST FIRES ON CARBON EMISSIONS, BIODIVERSITY LOSS, AND ECOSYSTEM RECOVERY: A LONGITUDINAL STUDY IN TROPICAL FORESTS**DAMPAK KEBAKARAN HUTAN TERHADAP EMISI KARBON, KEHILANGAN KEANEKARAGAMAN HAYATI, DAN PEMULIHAN EKOSISTEM: STUDI LONGITUDINAL DI HUTAN TROPIS****John F. Sahusilawane¹, Wilma N Imlabla²**Forestry Study Program, Department of Forestry, Faculty of Agriculture, Pattimura University^{1,2}

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Corresponding Author*ABSTRACT**

Forest fires are among the most consequential disturbances affecting tropical forest ecosystems, with cascading effects on the global carbon cycle, biodiversity, and long-term ecosystem functioning. This study employs a longitudinal research design to examine how recurrent fire events influence carbon emission trajectories, species diversity, and post-fire ecosystem recovery across tropical forest landscapes in Southeast Asia and the Amazon Basin. Secondary time-series data spanning multiple decades were synthesized from peer-reviewed remote sensing, biomass, and biodiversity monitoring studies. The results indicate that fire-affected tropical forests lose between 19.9 and 46.0 MgC ha⁻¹ of aboveground carbon depending on disturbance type, with full carbon-balance recovery estimated to take more than 150 years under repeated burning regimes. Biodiversity indicators, including tree density, canopy cover, and vertebrate abundance, declined by 58 to 98 percent in burned relative to unburned plots, with the most severe and sustained losses observed among fire-sensitive forest specialist species. Although vegetation structure and carbon stocks showed measurable recovery within twelve to twenty years post-fire, species composition remained persistently altered, with forest-edge richness declining by 20 to 46 percent even after two decades. These findings suggest that while tropical forests exhibit meaningful structural resilience, recurrent fire disturbance drives a durable process of biotic homogenization that undermines long-term ecological integrity. The study underscores the urgency of integrated fire prevention, peatland rewetting, and long-term, context-specific restoration policy to safeguard tropical forest carbon stocks and biodiversity under intensifying climate change.

Keywords: forest fire; carbon emissions; biodiversity loss; ecosystem recovery; tropical forest; longitudinal study

ABSTRAK

Kebakaran hutan merupakan salah satu gangguan paling berdampak yang memengaruhi ekosistem hutan tropis, dengan efek berantai terhadap siklus karbon global, keanekaragaman hayati, dan fungsi ekosistem dalam jangka panjang. Penelitian ini menggunakan desain penelitian longitudinal untuk mengkaji bagaimana kejadian kebakaran yang berulang mempengaruhi lintasan emisi karbon, keanekaragaman spesies, dan pemulihan ekosistem pasca kebakaran di bentang alam hutan tropis di Asia Tenggara dan Cekungan Amazon. Data sekunder berbentuk deret waktu yang mencakup beberapa dekade disintesis dari berbagai penelitian peer-reviewed mengenai penginderaan jauh, biomassa, dan pemantauan keanekaragaman hayati. Hasil penelitian menunjukkan bahwa hutan tropis yang terdampak kebakaran kehilangan karbon di atas permukaan tanah sebesar 19,9 hingga 46,0 MgC ha⁻¹, bergantung pada jenis gangguan yang terjadi, dengan pemulihan penuh keseimbangan karbon diperkirakan memerlukan waktu lebih dari 150 tahun pada kondisi kebakaran yang berulang. Indikator keanekaragaman hayati, termasuk kepadatan pohon, tutupan tajuk, dan kelimpahan vertebrata, mengalami penurunan sebesar 58 hingga 98 persen pada plot yang terbakar dibandingkan dengan plot yang tidak terbakar, dengan kehilangan paling parah dan berkepanjangan terjadi pada spesies spesialis hutan yang sensitif terhadap api. Meskipun struktur vegetasi dan cadangan karbon menunjukkan pemulihan yang terukur dalam kurun waktu dua belas hingga dua puluh tahun setelah kebakaran, komposisi spesies tetap mengalami perubahan yang persisten, dengan kekayaan spesies di kawasan tepi

hutan menurun sebesar 20 hingga 46 persen bahkan setelah dua dekade . Temuan ini menunjukkan bahwa meskipun hutan tropis memiliki resiliensi struktural yang signifikan, gangguan kebakaran yang berulang mendorong proses homogenisasi biotik yang bersifat jangka panjang sehingga melemahkan integritas ekologis ekosistem. Penelitian ini menegaskan urgensi penerapan strategi terpadu yang mencakup pencegahan kebakaran, pembasahan kembali lahan gambut, serta kebijakan restorasi jangka panjang yang kontekstual untuk melindungi cadangan karbon dan keanekaragaman hayati hutan tropis di tengah semakin intensifnya perubahan iklim.

Kata Kunci: *kebakaran hutan; emisi karbon; kehilangan keanekaragaman hayati; pemulihan ekosistem; hutan tropis; studi longitudinal*

1. INTRODUCTION

Tropical forests store an estimated one-quarter of the world's terrestrial carbon and harbor more than half of global terrestrial biodiversity, making their stability central to both climate regulation and conservation objectives (de Andrade et al., 2017). Over the past two decades, however, tropical forest regions in Southeast Asia, the Amazon Basin, and Central Africa have experienced a marked intensification of fire activity, driven by the interaction of land-use change, agricultural expansion, peatland drainage, and increasingly fire-prone climatic conditions (Zheng et al., 2024). Unlike fire-adapted biomes such as savannas, tropical forests are largely maladapted to combustion, meaning that even single burn events can trigger long-lasting structural, functional, and compositional changes (Harrison et al., 2024).

Forest fires contribute substantially to the global carbon budget. Globally, forest fire carbon emissions have risen sharply in recent decades, with extratropical and tropical forest ecoregions together contributing an estimated sixty percent increase in fire-related carbon emissions linked to a warming and drying climate (Zheng et al., 2024). In tropical Asia specifically, differences in fuel structure and vegetation type strongly mediate emission intensity, with mixed and degraded forest types emitting substantially more particulate and gaseous carbon than intact evergreen broadleaf forest (Chen et al., 2025). At the ecosystem scale, modelling of a tropical sub-montane forest at Mount Kilimanjaro demonstrated that it can take more than one hundred and fifty years for the cumulative carbon balance of a burned forest to converge with that of an undisturbed stand, illustrating the extraordinarily long recovery horizon associated with tropical forest fire (Ruecker et al., 2021).

Beyond carbon, fire is a powerful ecological filter that reshapes species composition and community structure. A sixteen-year multi-taxon study of a tropical peat-swamp forest in Indonesian Borneo found that burned forest had between fifty-eight and ninety-eight percent less habitat structure, tree density, and canopy cover than unburned forest, with the steepest declines in species diversity recorded for trees, invertebrates, and threatened vertebrates (Harrison et al., 2024). Similarly, understorey regeneration studies in the southern Amazon show that increasing fire frequency progressively erodes floristic richness and family-level diversity, with frequently burned plots consistently ranking lowest in species diversity among all disturbance classes examined (Alvarado et al., 2020). These findings raise the question of whether tropical forests are capable of genuine ecological recovery following fire, or whether repeated disturbance instead drives a long-term trajectory of biotic homogenization.

Recent two-decade monitoring in the southeastern Brazilian Amazon offers an important, nuanced answer to this question. Although degraded forests subjected to repeated fire, drought, and windstorm disturbance showed a surprising capacity for structural and carbon recovery with no evidence of transition toward savanna, species richness at forest edges nonetheless declined by twenty to forty-six percent between 2004 and 2024, and even after fourteen years the original, fire-sensitive specialist species composition had not returned (Maracahipes et al., 2026). Complementary landscape-scale research confirms that biodiversity resilience in tropical rainforest is conditional and taxon-specific, rather than uniform across ecological communities (Metz et al., 2026). Collectively, this body of evidence suggests that carbon and structural recovery metrics alone are insufficient proxies for full ecological recovery,

and that biodiversity-specific, long-term monitoring is essential to accurately characterize the trajectory of fire-affected tropical forests.

Despite the growing volume of individual case studies, there remains a scarcity of longitudinal research that jointly tracks carbon emission dynamics, biodiversity trajectories, and structural recovery within a single, integrated analytical framework across multiple tropical forest regions (Harrison et al., 2024). Most existing assessments compare burned and unburned areas at a single time point, rather than examining how ecosystem properties evolve over years to decades following disturbance (Harrison et al., 2024). This study therefore aims to (1) synthesize longitudinal evidence on carbon emission trajectories following tropical forest fires, (2) evaluate the magnitude and persistence of fire-induced biodiversity loss across taxonomic groups, and (3) characterize the pace, extent, and limits of post-fire ecosystem recovery in tropical forest systems. By integrating findings from long-term monitoring programs in Indonesia, the Amazon Basin, and Central Africa, this research aims to provide a more comprehensive evidence base to inform tropical forest fire prevention and restoration policy.

2. METHODS

2.1. Research Design

This study adopts a longitudinal, literature-based synthesis design, integrating multi-year and multi-decade empirical datasets drawn from peer-reviewed studies of tropical forest fire impacts. A longitudinal approach was selected because cross-sectional comparisons of burned and unburned plots cannot adequately capture the temporal dynamics of carbon flux, biodiversity change, and ecosystem recovery following disturbance (Harrison et al., 2024).

2.2. Study Sites and Data Sources

Data were synthesized from four principal longitudinal monitoring programs situated in tropical forest biomes: (1) a sixteen-year, 320-km² tropical peat-swamp forest research area in Sebangau National Park, Indonesian Borneo, encompassing seventeen ecosystem-property variables and twenty-one biodiversity variables across 236 sampling locations (Harrison et al., 2024); (2) a twenty-year field monitoring program in degraded forests of the southeastern Brazilian Amazon tracking recovery pathways after fire, drought, and windstorm disturbance (Maracahipes et al., 2026); (3) a process-based modelling study of carbon stock and biomass trajectories in a tropical sub-montane forest on Mount Kilimanjaro, Tanzania, simulating single and recurrent fire scenarios over a 150-year horizon (Ruecker et al., 2021); and (4) a pan-tropical synthesis of short-term emission factors and recovery trajectories following logging and fire degradation compiled from multiple tropical forest regions in support of REDD+ carbon accounting (de Andrade et al., 2017).

Complementary satellite-derived carbon emission datasets, including the Global Fire Emissions Database (GFED), the Fire Energetics and Emissions Research (FEER) product, and the Global Fire Assimilation System (GFAS), were referenced to contextualize regional and global forest fire carbon emission trends (Guo et al., 2023). Biodiversity trend data were further supplemented with acoustic ecosystem-monitoring evidence demonstrating that soundscape indices can reliably track faunal biodiversity recovery following tropical forest disturbance (Müller et al., 2023).

2.3. Variables and Measurement

Three categories of outcome variables were extracted and analyzed across studies. Carbon-related variables included aboveground biomass loss (MgC ha⁻¹), net ecosystem exchange, and cumulative carbon balance relative to undisturbed reference forest. Biodiversity-related variables included species richness, abundance, and diversity indices for trees, invertebrates, and vertebrates, alongside compositional shifts toward fire-tolerant

generalist species. Recovery-related variables included canopy cover, tree density, habitat structural complexity, and time-to-convergence with unburned reference conditions.

2.4. Data Synthesis and Analysis

Quantitative findings reported in the source studies were extracted, tabulated by biome and disturbance type, and compared across the temporal scales examined by each study (ranging from three months to twenty years post-fire). Because the constituent studies employed heterogeneous designs, including satellite-based emissions modelling, field biomass inventories, and multi-taxon biodiversity surveys, a narrative and comparative synthesis approach was used rather than formal meta-analytic pooling, consistent with established practice for integrating structurally distinct longitudinal ecological datasets (de Andrade et al., 2017).

3. RESULTS

3.1. Carbon Emission Dynamics

Across the reviewed longitudinal studies, tropical forest fires generated substantial and disturbance-specific carbon losses. Pan-tropical synthesis of degradation events found average aboveground carbon losses of 19.9 MgC ha⁻¹ for logging disturbance and 46.0 MgC ha⁻¹ for fire disturbance, based on average post-disturbance monitoring periods of 3.22 and 2.15 years, respectively (de Andrade et al., 2017). At the landscape scale, the 2015–2016 El Niño-driven understory wildfires in central-eastern Amazonia burned nearly one million hectares and released immediate carbon emissions substantially higher than estimates derived from standard global fire-emissions databases, reflecting the high necromass fuel loads characteristic of human-modified tropical forest (Silva Junior et al., 2018).

Process-based modelling of a tropical sub-montane forest at Mount Kilimanjaro indicated that, under a single large-scale fire event, more than 150 years were required for the cumulative carbon balance of the regenerating forest to compensate fully for fire-related emissions, while under a regime of recurring fires the standard deviation of annual carbon flux increased roughly tenfold relative to an undisturbed forest, despite the long-term mean flux remaining close to zero (Ruecker et al., 2021). At the global scale, forest fire carbon emissions increased by approximately sixty percent across forest ecoregions in recent decades, an increase attributed primarily to intensifying fire-weather conditions under climate change rather than to expansion of burned area alone (Zheng et al., 2024). Regional analysis of tropical Asian forests further showed that vegetation type strongly mediates emission intensity, with average gas and particulate emissions in mixed forest exceeding those in evergreen broadleaf forest by 172 percent and 151 percent, respectively (Chen et al., 2025).

3.2. Biodiversity Loss

Biodiversity indicators showed marked and, in several taxa, sustained declines following fire disturbance. In the sixteen-year Indonesian peat-swamp forest study, burned forest exhibited fifty-eight to ninety-eight percent reductions in habitat structure, tree density, and canopy cover relative to unburned forest, with the sharpest diversity and abundance declines recorded among trees, damselflies, and threatened vertebrates (Harrison et al., 2024). Megafire events were found to compromise water quality and tree reproductive phenology almost immediately, contributing to the collapse of commercially valuable fish populations within three months and a gradual decline in threatened vertebrate populations over nine months following the burn (Harrison et al., 2024).

In the Amazon, understory fire-frequency experiments demonstrated that species composition, abundance, richness, and family-level diversity were consistently highest in unburned forest and lowest in frequently burned plots, indicating a clear dose-dependent relationship between fire recurrence and biodiversity erosion (Alvarado et al., 2020). At a landscape scale, the twenty-year Amazonian monitoring program found that species richness

at forest edges declined by twenty to forty-six percent between 2004 and 2024, with vulnerable, fire-sensitive forest-specialist species progressively replaced by fast-growing, drought-tolerant generalist species (Maracahipes et al., 2026). Even after fourteen years of post-disturbance regrowth, the original forest-specialist species composition had not returned, indicating that biodiversity recovery substantially lags behind structural and carbon recovery (Maracahipes et al., 2026).

3.3. Ecosystem Recovery Trajectories

Despite pronounced initial losses, the reviewed longitudinal evidence indicates that tropical forests possess meaningful, though incomplete, capacity for post-fire recovery. In the Indonesian peat-swamp forest study, some recovery of ecosystem properties was evident in burned areas within twelve years, although the authors caution that repeated fire events risk reversing these recovery gains entirely (Harrison et al., 2024). In the Amazon, degraded forest plots exposed to repeated fire, drought, and windstorm disturbance demonstrated high ecological resilience at the level of vegetation structure and carbon and water flux recovery, with no evidence of a transition toward savanna-like vegetation states, even under repeated compounding disturbance (Maracahipes et al., 2026).

However, recovery pathways were found to diverge sharply between structural and compositional dimensions of the ecosystem. While carbon stocks and canopy structure recovered relatively quickly, the underlying species composition shifted permanently toward generalist, disturbance-tolerant assemblages, a pattern the authors describe as a process of biotic homogenization rather than genuine ecological restoration (Maracahipes et al., 2026; Metz et al., 2026). Complementary acoustic-monitoring evidence supports this pattern, showing that soundscape diversity indices can effectively track the pace of faunal community reassembly following tropical forest disturbance, but that full recovery of the vocalizing faunal community typically lags well behind vegetation recovery (Müller et al., 2023).

4. DISCUSSION

The findings of this longitudinal synthesis reinforce that tropical forest fires generate consequences that extend far beyond the immediate combustion event, with carbon and biodiversity impacts propagating across years to decades (Zheng et al., 2024; Harrison et al., 2024). The observation that full carbon-balance recovery may require more than 150 years under a recurrent fire regime (Ruecker et al., 2021) suggests that tropical forests functioning as long-term carbon sinks are especially vulnerable to any increase in fire return interval, since successive burns can prevent forests from ever reaching a pre-disturbance carbon equilibrium (Zheng et al., 2024).

The persistent divergence between structural recovery and biodiversity recovery documented across the reviewed studies carries significant implications for conservation and climate policy. Carbon-focused conservation instruments, such as REDD+, primarily track aboveground biomass and carbon stock trajectories, which the present synthesis shows can recover measurably within one to two decades (Maracahipes et al., 2026). However, this recovery signal may obscure a slower, less visible process of biodiversity erosion and compositional homogenization that carbon-centric monitoring frameworks are not designed to detect (Sethi et al., 2021; Metz et al., 2026). This finding echoes long-standing concerns that carbon-focused conservation may not translate into commensurate gains for tropical forest biodiversity (Sethi et al., 2021).

The comparatively rapid and severe collapse of aquatic and vertebrate populations following megafire events, occurring within months rather than years (Harrison et al., 2024), further indicates that fire impacts propagate through tropical forest food webs and hydrological systems more quickly than they propagate through vegetation structure. This has direct implications for local communities dependent on fisheries and forest resources, and

underscores that fire impact assessments limited to vegetation and carbon metrics likely underestimate the true socioecological cost of tropical forest fire (Harrison et al., 2024).

These findings also highlight the disproportionate vulnerability of forest edges and human-modified landscapes to fire-related biodiversity loss. Edge-associated richness declines of twenty to forty-six percent over two decades (Maracahipes et al., 2026), combined with evidence that forest degradation from fire and logging can double biodiversity loss relative to deforestation alone (Sethi et al., 2021), suggest that fire prevention efforts should be spatially prioritized toward fragmented and edge-exposed tropical forest landscapes, where both fire risk and ecological vulnerability are highest.

From a management perspective, the evidence assembled here supports a dual policy emphasis on fire prevention and long-term, context-specific restoration, rather than reliance on structural recovery as a sufficient indicator of ecological recovery (Harrison et al., 2024). In fire-prone tropical peatlands specifically, rewetting and hydrological restoration are likely to be essential complements to fire suppression, given that peatland drainage is a primary driver of fire susceptibility in this biome (Harrison et al., 2024). More broadly, the persistence of altered species composition even after fourteen years of regrowth (Maracahipes et al., 2026) suggests that biodiversity-inclusive restoration targets, potentially supported by scalable acoustic and remote-sensing monitoring tools (Müller et al., 2023), should be incorporated alongside carbon-stock targets in tropical forest restoration and climate mitigation frameworks.

This study is subject to several limitations inherent to a literature-synthesis design. The constituent longitudinal studies vary in geographic scope, forest type, fire regime, and monitoring methodology, which constrains direct quantitative comparison across regions and limits the generalizability of specific numerical estimates beyond the biomes in which they were generated (de Andrade et al., 2017). Future research employing standardized, multi-region longitudinal monitoring protocols that jointly track carbon, structural, and taxon-specific biodiversity indicators would substantially strengthen the evidence base needed to inform integrated tropical forest fire management policy.

5. CONCLUSION

This longitudinal synthesis demonstrates that tropical forest fires impose substantial and long-lasting costs on carbon storage and biodiversity, with recovery trajectories that differ markedly across ecosystem dimensions. Carbon losses from fire disturbance can reach 46.0 MgC ha⁻¹ per event, with full carbon-balance recovery potentially requiring over 150 years under recurrent fire regimes, while biodiversity indicators such as tree density, canopy cover, and vertebrate abundance can decline by up to 98 percent in burned relative to unburned forest. Although tropical forests display meaningful structural and carbon resilience, with measurable recovery within twelve to twenty years, species composition remains persistently altered toward disturbance-tolerant generalists even after fourteen years, reflecting a durable process of biotic homogenization rather than complete ecological restoration. These findings indicate that carbon-stock recovery alone is an insufficient proxy for ecological recovery, and that fire prevention, peatland rewetting, and biodiversity-inclusive, long-term restoration strategies are essential to safeguard the dual climate and conservation value of tropical forests under continuing climate change.

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