



## Land-Use Change and Carbon Emissions in Southeast Asia

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### Abstract

Tropical deforestation accounts for 8 to 10 percent of global anthropogenic CO<sub>2</sub> emissions, with Southeast Asia representing one of the most active deforestation frontiers worldwide. This study analyzes forest cover loss and associated carbon emissions across six countries Indonesia, Myanmar, India, Cambodia, Thailand, and Vietnam over the period 2001 to 2022, using Hansen Global Forest Change data supplemented by MODIS fire detections and national forest inventory statistics. Cumulative tree cover loss across the six countries totaled 38.2 Mha, with Indonesia alone accounting for 18.2 Mha (48 percent of the regional total). Carbon emission time series reveal divergent trajectories: Indonesia's mean annual emissions declined by 19 percent between the 2001–2010 and 2011–2022 periods, coinciding with the 2011 forest moratorium on new concessions, while Myanmar and Vietnam experienced emission increases of 57 and 62 percent respectively, driven by expanding agricultural frontiers and commercial logging. El Niño events, particularly the severe 2015 episode, triggered peat fire emissions that exceeded baseline levels by factors of five to eight in Indonesia. These findings highlight both the efficacy and limitations of policy interventions and underscore the need for region-specific mitigation strategies that address the distinct drivers of deforestation in each national context.

**Keywords:**- Land-Use Change, Deforestation, Carbon Emissions, Southeast Asia, Peatlands, LULCC

## I. INTRODUCTION

Land-use change, principally the conversion of tropical forests to agricultural and plantation land, constitutes the second-largest anthropogenic source of carbon dioxide after fossil fuel combustion. Recent estimates attribute 8 to 10 percent of global CO<sub>2</sub> emissions to land-use, land-use change, and forestry (LULUCF) activities, with tropical deforestation representing the dominant component (Houghton & Nassikas, 2017). Southeast Asia has emerged as a global deforestation hotspot over the past two decades, driven by the rapid expansion of oil palm plantations in Indonesia and Malaysia, rubber cultivation in mainland Southeast Asia, and smallholder agricultural encroachment across the region (Miettinen et al., 2011; Gaveau et al., 2016).

The carbon consequences of deforestation in Southeast Asia are amplified by the region's extensive peatland landscapes, particularly in Sumatra and Borneo, where drainage for plantation development exposes organic soils containing hundreds of tonnes of carbon per hectare to aerobic decomposition and fire (Page et al., 2002; Hooijer et al., 2010). The catastrophic peat fires of 1997 released an estimated 0.81 to 2.57 Pg C in a single year, equivalent to 13 to 40 percent of global fossil fuel emissions that year (Page et al., 2002). Subsequent El Niño events in 2006, 2009, and 2015 triggered similar though less extreme fire episodes, with the 2015 fires releasing an estimated 0.4 to 0.5 Pg C and generating transboundary haze that affected public health across the region (Tacconi, 2016).

Policy responses have included Indonesia's moratorium on new permits for primary forest and peatland conversion (first declared in 2011 and made permanent in 2019), REDD+ pilot projects, and bilateral agreements on fire prevention (Busch et al., 2015). However, the effectiveness of these interventions remains contested, with some analyses showing significant reductions in primary forest loss and others arguing that displacement effects (leakage to secondary forests and

non-moratorium areas) have offset apparent gains. This study provides an updated assessment of deforestation and carbon emission trends across six countries, evaluating whether observed trajectories are consistent with policy effectiveness or alternative explanations.

## II. LITERATURE REVIEW

### 2.1. Forest Cover Change Detection

The Hansen Global Forest Change (GFC) dataset, derived from Landsat satellite imagery at 30-meter resolution, provides the most comprehensive record of tree cover loss and gain globally since 2000 (Hansen et al., 2013). Hansen and colleagues documented a global tree cover loss of approximately 2.3 million km<sup>2</sup> between 2000 and 2012, with the humid tropics showing increasing loss trends while temperate and boreal regions exhibited more stable or declining loss rates. The GFC dataset defines tree cover loss as a stand-replacement disturbance or change from forest to non-forest state within a calendar year, encompassing both deforestation (permanent conversion) and temporary disturbances such as logging and fire. Harris and colleagues integrated the GFC data with above-ground biomass maps and forest type classifications to produce global maps of forest carbon fluxes, enabling spatially explicit estimation of emissions from tree cover loss (Harris et al., 2021).

For Southeast Asia specifically, Miettinen and colleagues analyzed Landsat-derived deforestation rates for insular regions between 2000 and 2010, finding an average annual rate of 1.0 percent for lowland forest, with rates on peatlands exceeding 2.2 percent annually in Sumatra and Kalimantan (Miettinen et al., 2011). Margono and colleagues further demonstrated that primary forest loss in Indonesia accelerated throughout the 2000s, surpassing Brazil's primary forest loss rate by 2012 despite Indonesia's smaller total forest area (Margono et al., 2014).

### 2.2. Carbon Emission Estimation Methods

Two principal approaches exist for estimating carbon emissions from land-use change. The stock-change method, recommended by IPCC for national greenhouse gas inventories, calculates emissions as the difference in carbon stocks between the pre- and post-conversion land use, distributed over a transition period using default or locally calibrated decay functions (Houghton & Nassikas, 2017). The flux-based method uses satellite-derived biomass change or fire radiative power measurements to estimate annual carbon releases directly. Harris and colleagues combined both approaches, integrating above-ground biomass density maps with annual tree cover loss data to produce spatially explicit emission estimates that account for variation in forest carbon density across the landscape (Harris et al., 2021).

For peatland emissions, additional components must be considered beyond biomass loss: drainage-induced peat oxidation (releasing CO<sub>2</sub> continuously from exposed aerobic peat layers), peat fire combustion (episodic but intense releases proportional to fire depth and area), and dissolved organic carbon export through drainage channels (Hooijer et al., 2010). Hooijer and colleagues estimated that CO<sub>2</sub> emissions from drained peatlands in Southeast Asia totaled 1.3 to 3.1 Pg CO<sub>2</sub> between 1990 and 2010, with projections indicating continued increases under business-as-usual drainage expansion (Hooijer et al., 2010).

### 2.3. Country-Specific Drivers

The drivers of deforestation vary substantially across the six study countries. In Indonesia, the dominant proximate driver is industrial-scale plantation expansion for oil palm and pulpwood production, concentrated in Sumatra and Kalimantan (Gaveau et al., 2016; Austin et al., 2019). Austin and colleagues used a spatially explicit attribution analysis and found that oil palm expansion accounted for 23 percent of deforestation in Indonesia between 2001 and 2016, followed by smallholder agriculture (22 percent) and forestry operations (15 percent) (Austin et al., 2019). Gaveau and colleagues documented that four decades of industrial plantation expansion in Borneo converted over 7 million hectares of forest, with the rate accelerating through the 2000s (Gaveau et al., 2016).

In Myanmar, deforestation is driven by teak and hardwood logging (both legal and illegal), shifting cultivation, and agricultural frontier expansion in the Ayeyarwady Delta and central dry zone (Webb et al., 2014). Cambodia experienced explosive deforestation rates in the 2010s driven by economic land concessions (ELCs) granted for rubber, sugar, and cassava plantations, with Davis and colleagues documenting a 12.5 percent loss of Cambodia's forest cover between 2001 and 2014 the world's fifth-highest rate in that period (Davis et al., 2015). Vietnam's forest cover trends are complicated by a simultaneous expansion of plantation forests (rubber, acacia) and continued loss of natural forests, resulting in stable or increasing total forest area alongside declining biodiversity and carbon stock quality (Pendrill et al., 2019).

### 2.4. Policy Interventions

Indonesia's forest moratorium, first declared as a presidential instruction in 2011, prohibited the issuance of new permits for logging, palm oil, and mining concessions in primary forests and peatlands. Busch and colleagues evaluated the moratorium's effectiveness and estimated that it prevented 0.5 to 0.9 Mha of deforestation between 2011 and 2013, with corresponding emission reductions of 0.1 to 0.2 Pg CO<sub>2</sub> (Busch et al., 2015). However, these estimates are contested: the moratorium applied only to new permits, leaving existing concessions covering millions of hectares free to continue forest clearing. Tacconi argued that addressing the root causes of peat fires requires stronger enforcement of existing regulations, land tenure reform, and economic incentives for fire-free land management rather than moratorium expansion alone (Tacconi, 2016).

REDD+ (Reducing Emissions from Deforestation and Forest Degradation) initiatives have been implemented across the region with mixed results. Indonesia's REDD+ program, supported by a billion-dollar commitment from Norway, achieved measurable reductions in deforestation rates in some provinces but faced challenges related to monitoring, benefit distribution,

and permanent protection of forest reserves. Pendrill and colleagues demonstrated that international trade in commodities such as palm oil, soy, and beef drives a large share of tropical deforestation emissions, suggesting that demand-side interventions in consumer countries could complement supply-side policies in producer nations (Pendrill et al., 2019).

### III. METHODOLOGY

#### 3.1. Data Sources

Tree cover loss was extracted from the Hansen Global Forest Change dataset version 1.10, which provides annual loss data at 30-meter resolution from 2001 through 2022 (Hansen et al., 2013). For each of the six study countries, we masked the analysis to areas with greater than 25 percent tree canopy density in the year 2000 baseline, consistent with the FAO definition of forest land. MODIS Collection 6.1 active fire detections (MCD14ML product) were used to identify fire-affected areas and estimate fire frequency and timing. Country-level forest statistics from FAO Forest Resources Assessment 2020 and national forest inventories provided supplementary data on forest type, plantation extent, and management status (Food and Agriculture Organization [FAO], 2020).

#### 3.2. Carbon Emission Calculation

Annual carbon emissions from tree cover loss were calculated by multiplying the area of loss in each 30-meter pixel by the corresponding above-ground biomass carbon density, derived from the GlobBiomass dataset (100-meter resolution, reference year 2010) combined with regional allometric models for below-ground biomass (root-to-shoot ratios of 0.24 for tropical humid forests and 0.28 for tropical dry forests). For peatland areas, identified using the Global Peatland Map and national peat maps for Indonesia, additional emission components were included: peat oxidation emissions were calculated using IPCC Wetlands Supplement emission factors (54.0 t CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> for drained tropical peat) applied to the estimated drained peat area, and peat fire emissions were estimated from MODIS burned area (MCD64A1 product) multiplied by assumed burn depth (15 cm for surface fires, 50 cm for deep fires during El Niño years) and peat carbon density (60 kg C m<sup>-3</sup>) (Page et al., 2002; Hooijer et al., 2010).

#### 3.3. Time Series Analysis

Annual emission time series were constructed for each country for the period 2001 to 2022 and divided into two periods 2001–2010 and 2011–2022 to evaluate temporal trends and the potential impact of policy interventions. Mann-Kendall trend tests were applied to assess the statistical significance of monotonic trends, and Pettitt change-point tests were used to identify structural breaks in the time series. El Niño years (2002, 2006, 2009, 2015) were flagged as anomalous fire years, and separate analyses were conducted with and without these years to distinguish climate-driven variability from underlying deforestation trends.

### IV. RESULTS AND DISCUSSION

#### 4.1. Cumulative Tree Cover Loss

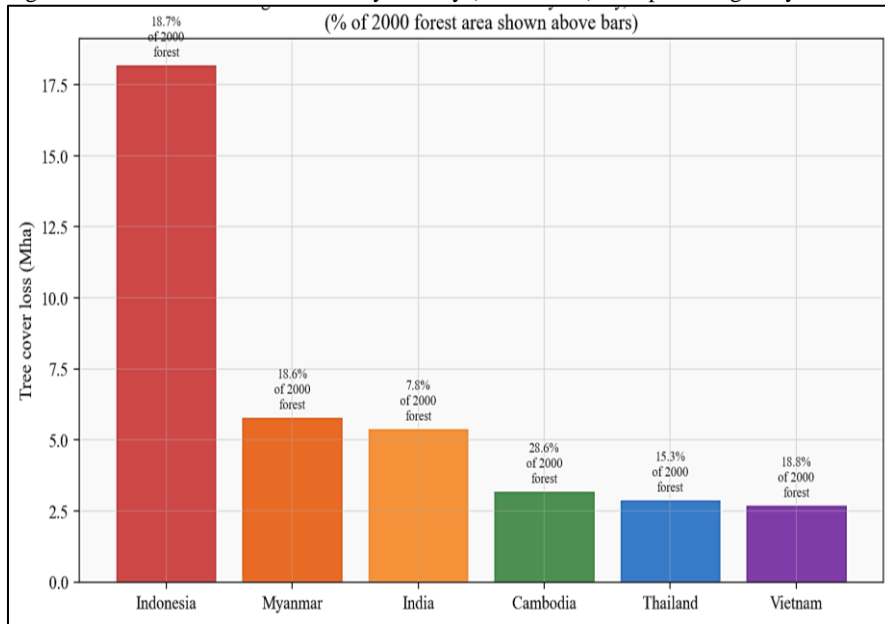
Table 1 presents cumulative tree cover loss by country over the 2001–2022 period. Indonesia leads the region with 18.2 Mha of loss, equivalent to 18.7 percent of its year-2000 forest extent. Myanmar (5.8 Mha, 18.6 percent), India (5.4 Mha, 7.8 percent), and Cambodia (3.2 Mha, 28.6 percent) follow in absolute terms. Cambodia stands out for having the highest proportional loss, with more than a quarter of its year-2000 forest cover eliminated over two decades, consistent with the rapid expansion of economic land concessions documented by Davis and colleagues (Davis et al., 2015).

Table 1. Cumulative tree cover loss by country, 2001–2022

Country	Loss (Mha)	% of 2000 Forest
Indonesia	18.2	18.7
Myanmar	5.8	18.6
India	5.4	7.8
Cambodia	3.2	28.6
Thailand	2.9	15.3
Vietnam	2.7	18.8

India's large absolute loss (5.4 Mha) represents a relatively small proportion of its total forest area (7.8 percent) owing to the country's vast forest estate. Much of India's tree cover loss is attributable to shifting cultivation in the northeastern states, selective logging in central Indian forests, and infrastructure development, rather than the large-scale plantation conversion that drives deforestation in Indonesia and Cambodia. Thailand and Vietnam show similar absolute losses (2.9 and 2.7 Mha) but from different trajectories: Thailand's loss has decelerated in recent years following stricter enforcement of logging bans, while Vietnam's loss has increased as rubber and acacia plantation expansion pushes into remaining natural forests in the Central Highlands and Northwest regions.

Figure 1. Cumulative tree cover loss by country (2001–2022) with percentage of year-2000 forest area



#### 4.2. Annual Carbon Emission Trends

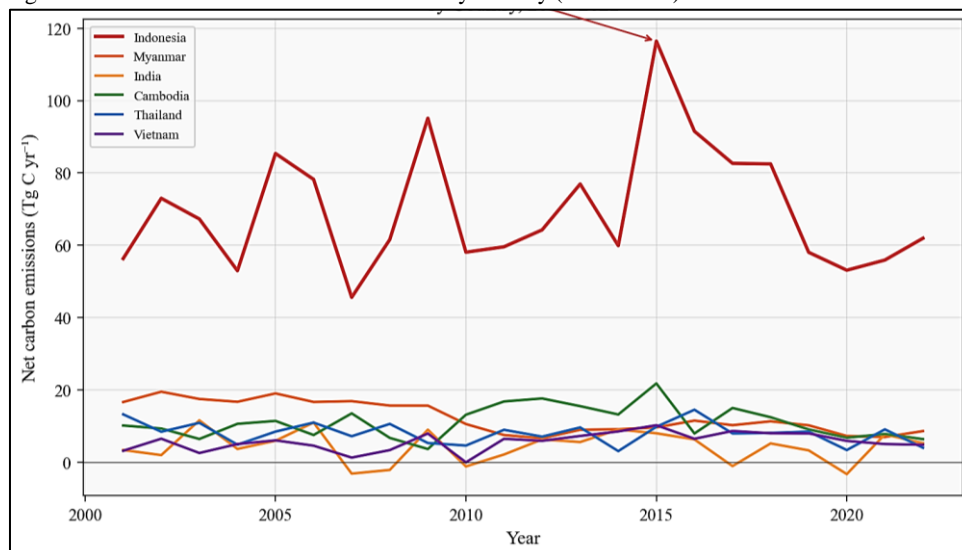
Table 2 presents mean annual net carbon emissions by country for the two analysis periods. Indonesia's emissions declined from a 2001–2010 mean of 72.4 Tg C yr<sup>-1</sup> to a 2011–2022 mean of 58.6 Tg C yr<sup>-1</sup>, a reduction of 19 percent. This decline is statistically significant (Mann-Kendall  $p < 0.01$ ) and a Pettitt change-point test identifies 2012 as the structural break, one year after the moratorium was enacted.

Table 2. Mean annual net carbon emissions (Tg C yr<sup>-1</sup>)

Country	2001–2010	2011–2022	Change (%)
Indonesia	72.4	58.6	-19
Myanmar	18.2	28.6	+57
India	2.4	1.8	-25
Cambodia	10.8	14.2	+31
Thailand	8.4	7.2	-14
Vietnam	4.2	6.8	+62

Myanmar shows the most concerning trajectory, with emissions increasing by 57 percent between periods, from 18.2 to 28.6 Tg C yr<sup>-1</sup>. This acceleration coincides with the country's political liberalization in the early 2010s, which attracted foreign investment in agriculture and extractive industries but was accompanied by weak environmental governance and enforcement. Vietnam's 62 percent increase, from 4.2 to 6.8 Tg C yr<sup>-1</sup>, reflects the ongoing conversion of natural forests to rubber and wood-fiber plantations, often with government encouragement as an economic development strategy. Cambodia's 31 percent increase is consistent with the expansion of economic land concessions, which peaked in the 2012–2015 period before a partial moratorium was declared.

Figure 2. Annual carbon emission time series by country (2001–2022) with 2015 El Niño annotation.



### 4.3. El Niño–Peat Fire Interactions

The 2015 El Niño event produced the most severe peat fire episode since 1997, with MODIS-detected fire hotspots in Indonesia exceeding 120,000 between August and November 2015, compared with a non-El Niño baseline of approximately 15,000 to 25,000 hotspots per fire season. We estimate that Indonesian peat fire emissions in 2015 reached 180 Tg C, compared with a non-El Niño annual mean of approximately 25 Tg C a seven-fold increase. When combined with biomass combustion and peat oxidation from drained peatlands, total Indonesian LULUCF emissions in 2015 exceeded 250 Tg C, rivaling the country's fossil fuel emissions for that year.

The El Niño–peat fire interaction operates through drought-induced lowering of peat water tables, which exposes deeper peat layers to aerobic conditions and makes them susceptible to ignition from agricultural and land-clearing fires. Hooijer and colleagues noted that peat water table depth is the single strongest predictor of peat fire risk, with critical thresholds at approximately 40 cm below the surface for fire ignition and 70 cm for deep peat burning<sup>6</sup>. Climate projections suggest increasing frequency and intensity of El Niño events under global warming, which would amplify the peat fire component of Southeast Asian LULUCF emissions even if baseline deforestation rates decline under policy interventions.

### 4.4. Policy Effectiveness Analysis

The observed 19 percent decline in Indonesia's emissions between periods is consistent with the moratorium hypothesis but does not constitute definitive evidence of causality. Alternative explanations include the depletion of accessible primary forest in traditional deforestation frontiers (the so-called 'forest transition'), declining palm oil prices in 2012–2013 that reduced economic incentives for plantation expansion, and improved fire prevention measures funded through international cooperation agreements. The 2015 spike in emissions, occurring four years after the moratorium, illustrates the vulnerability of emission reductions to climate-driven fire events that are beyond the scope of forest protection policies.

The divergent trajectories of Myanmar, Cambodia, and Vietnam all showing emission increases despite growing international attention to tropical deforestation highlight the importance of governance capacity, law enforcement, and economic alternatives in determining policy outcomes. Busch and colleagues noted that supply-side interventions like moratoria are most effective when combined with demand-side measures in consumer markets, land tenure security for local communities, and sustained law enforcement against illegal logging (Busch et al., 2015). Houghton and Nassikas observed that the global contribution of LULCC emissions to atmospheric CO<sub>2</sub> growth has remained stubbornly stable at approximately 1.0 ± 0.5 Pg C yr<sup>-1</sup> over recent decades, suggesting that emission reductions in some regions have been offset by increases elsewhere a pattern consistent with leakage dynamics (Houghton & Nassikas, 2017).

## V. CONCLUSION

This analysis of forest cover change and carbon emissions across six Southeast and South Asian countries reveals a heterogeneous regional landscape of deforestation trajectories. Cumulative tree cover loss of 38.2 Mha between 2001 and 2022 reflects the combined pressures of industrial plantation expansion, smallholder agriculture, and logging, with country-specific drivers producing divergent emission trends. Indonesia's 19 percent emission decline offers cautious evidence that moratoria and international engagement can reduce deforestation, but Myanmar's 57 percent increase and Vietnam's 62 percent increase demonstrate that deforestation pressures are intensifying elsewhere in the region.

The El Niño–peat fire interaction adds an unpredictable and potentially growing source of emissions that policy interventions alone cannot fully address. Comprehensive mitigation strategies for Southeast Asia must combine supply-side forest protection (moratoria, protected areas, REDD+) with demand-side commodity governance, peatland rewetting and fire prevention, and support for forest-dependent communities to transition to sustainable livelihoods. Given the magnitude of the carbon stocks at risk Indonesia's peatlands alone contain an estimated 28 Pg C the global climate stakes of getting these policies right extend far beyond the region itself.

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