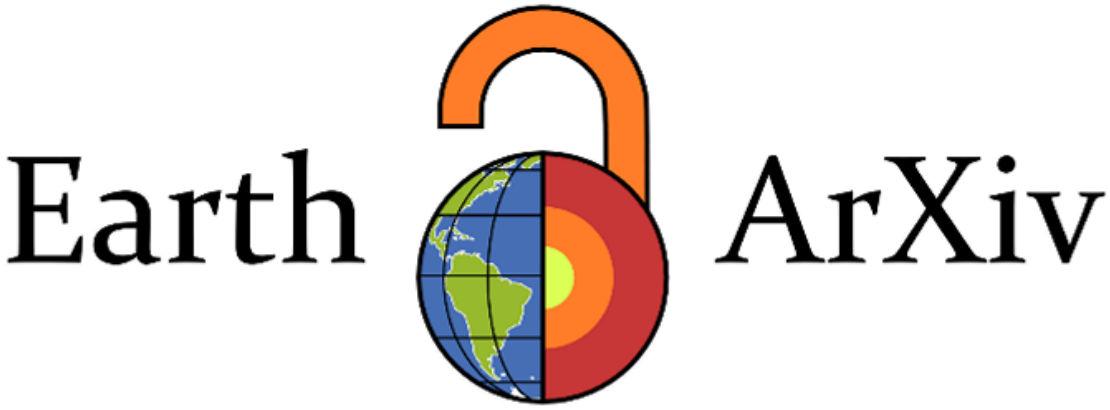


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One island, three countries: aquaculture ponds explain the cross-border gap in mangrove loss on Borneo

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One island, three countries: aquaculture ponds explain the cross-border gap in mangrove loss on Borneo

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Abstract

Borneo's mangroves share one coastline, climate and sediment regime, yet they are governed by three countries. Using the annual Global Mangrove Watch v4.1 series and open data, this study asks why mangrove in Indonesian Kalimantan is lost faster than in Malaysian Borneo and Brunei, and tests three explanations: protected-area performance, conversion pathways and El Niño sea-level fall. Between 2010 and 2020, Kalimantan lost 1.23% of its mangrove a year, against 0.43 to 0.74% in Malaysian Borneo and 0.50% in Brunei; it held 59% of the island's mangrove and 77% of its gross loss. Matched comparisons show long-standing strict protected areas reduced loss in Malaysian Borneo by about 2 percentage points but had no detectable effect in Kalimantan. Protection nonetheless explains little of the gap: 84% of it arises outside protected areas, and Sabah's 2015 upgrades of low-loss production reserves to full protection added nothing measurable. Classifying what replaced mangrove lost from 2000 to 2024 shows that conversion to aquaculture ponds, concentrated in the early 2000s, accounts for all of Kalimantan's 15.9-point excess loss, while loss away from ponds was similar in total on both sides of the border (clearing in Kalimantan and Sarawak, mostly edge change in Sabah) and oil palm replaced little mangrove overall. Annual loss outside conversion was lowest in El Niño years and highest in high-sea-level years, consistent with humid mangroves buffered against El Niño sea-level fall. Reducing Borneo's mangrove loss therefore depends on governing pond expansion outside protected areas more than on adding protected areas.

Keywords: Mangrove loss; aquaculture; protected areas; Borneo; El Niño; Global Mangrove Watch

1. Introduction

1.1 Background

Mangroves store large amounts of carbon, support coastal fisheries and protect shorelines, yet they have been lost faster than most tropical forests (Friess et al. 2019). Southeast Asia holds about a third of the world's mangroves and accounted for most of the global net loss between the 1980s and 2010 (Zhang et al. 2026). The main proximate causes in the region are well established: conversion to aquaculture ponds, rice and oil palm, and to a lesser extent coastal development (Richards and Friess 2016; Goldberg et al. 2020; Hagger et al. 2022). Global rates of human-driven loss have slowed since the early 2000s (Goldberg et al. 2020), and recent satellite records show the region moving from net loss to net gain after 2010 (Zhang et al. 2026). These regional and global syntheses, however, describe where and how mangroves were lost; they are less able to say why loss was faster in one place than in a neighbouring one with similar physical conditions.

Borneo offers an unusually clean comparison. The island's mangroves share tides, sediment supply, species pools and climate, but they are governed by three countries: Indonesia (Kalimantan), Malaysia (the states of Sabah and Sarawak, and the federal territory of Labuan) and Brunei. Each has its own forest law, protected-area system, land tenure and aquaculture policy. For terrestrial forest, this contrast is known to matter: Bryan et al. (2013) found extreme differences in logging and clearing between the Malaysian states and Brunei between 1990 and 2009. No equivalent comparison exists for mangroves. Regional assessments name Kalimantan as a hotspot of mangrove loss (Richards and Friess 2016; Wei et al. 2026; Zhang et al. 2026), and a recent hotspot analysis identifies enduring loss in Sarawak and dynamic loss along the coasts of Kalimantan and Sabah (Wei et al. 2026), but none asks how much faster one side of the border loses mangrove, or why.

Three explanations are plausible. First, protected areas may perform differently under different governments. Matched evaluations show that marine protected areas reduced mangrove loss in Indonesia between 2000 and 2010, while species-management areas did not (Miteva et al. 2015); globally, loss inside protected areas is driven by commodities and is highest in areas managed by national governments and in the strictest categories (Heck et al. 2024), and conversion to aquaculture and agriculture often occurs inside protected areas (Hagger et al. 2022). No matched evaluation exists for Malaysian Borneo or Brunei, so whether protection explains a cross-border gap is untested. Second, the gap may reflect different conversion pathways: aquaculture in one jurisdiction, oil palm in another, which earlier work flagged as an under-recognised threat in Malaysia and

Indonesia (Richards and Friess 2016). Third, climate may play a part. Sea-level fall during El Niño events has been linked to mangrove dieback in northern Australia and to reduced leaf area across the western Pacific (Zhang et al. 2025); whether it also removes mangrove extent in humid Borneo, where rainfall and river discharge may buffer the trees, is unknown.

1.2 Aim and contribution

This study explains the cross-border gap in mangrove loss on Borneo. Using only open data, it (i) measures loss by jurisdiction in the annual Global Mangrove Watch (GMW) v4.1 series and establishes which parts of that series can be used for change; (ii) gives the first matched evaluation of protected-area effectiveness for mangroves on both sides of the border, and tests whether Sabah's 2015 upgrades of production mangrove reserves to full protection reduced loss; (iii) classifies what replaced the mangrove lost between 2000 and 2024 and decomposes the gap by pathway; and (iv) tests whether loss not explained by conversion responds to El Niño sea-level fall. The results show that protection differs by jurisdiction but explains little of the gap, which is instead the product of aquaculture pond expansion outside protected areas in Kalimantan.

2. Study area

Borneo (about 743,000 km²) lies on the equator between the South China Sea, the Sulu and Celebes Seas, the Makassar Strait and the Java Sea (Fig. 1). Its climate is humid tropical throughout, with no month reliably dry, and its large rivers deliver sediment to extensive deltas, notably the Mahakam, Kayan and Berau on the east coast of Kalimantan, the Kapuas in the west, the Rajang in Sarawak and the Kinabatangan in Sabah. In 2020, GMW v4.1 mapped about 1.14 million ha of mangrove on the island: 664,000 ha in Kalimantan, 323,000 ha in Sabah, 141,000 ha in Sarawak and 13,000 ha in Brunei.

The four jurisdictions differ in how mangroves are held. In Sabah, most mangrove lies in state forest reserves, divided into production reserves (Class V, mangrove forest reserves) and fully protected classes (Class I, protection forest; Class VI, virgin jungle reserve; Class VII, wildlife reserve); in Sarawak, mangroves lie partly in the Permanent Forest Estate and partly in national parks; in Brunei, most mangrove lies in two forest reserves at Labu and Selirong. In Kalimantan, mangroves are state forest land under national law, with nature reserves (Cagar Alam), national parks (Taman Nasional) and wildlife reserves (Suaka Margasatwa) as the strict

categories. In 2015, Sabah upgraded portions of three production mangrove reserves (Tawau, Trusan Kinabatangan, and Pulau Banggi and Pulau Balambangan) to Class I protection forests, creating an additional natural experiment.

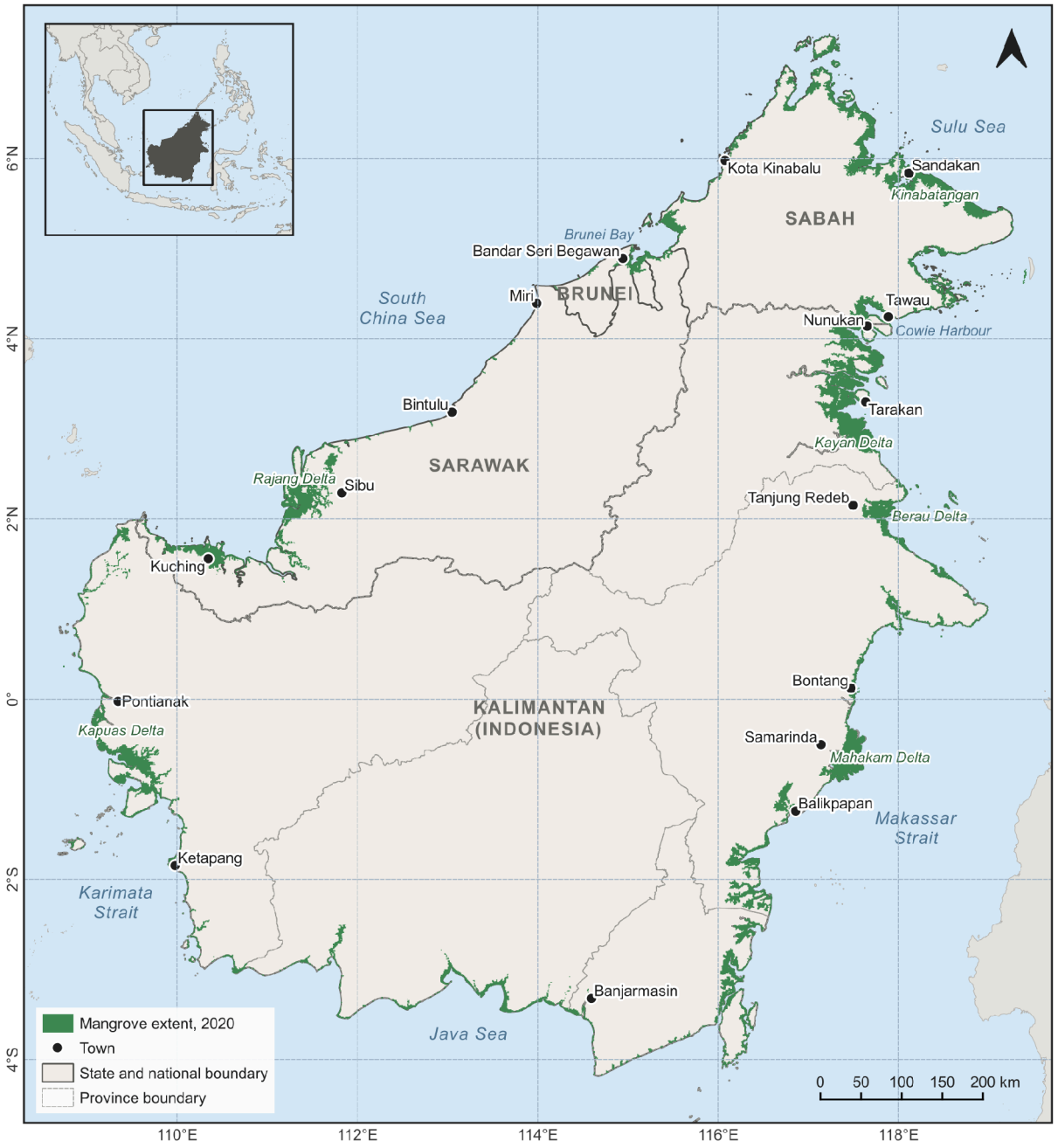


Figure 1. *Study area: the four jurisdictions of Borneo (Sabah and Sarawak, Malaysia; Brunei; Kalimantan, Indonesia) and mangrove extent in 2020 (GMW v4.1). Mangrove is shown as 1 km cells containing any mangrove, so its extent is enlarged for visibility. Inset: location of Borneo in Southeast Asia.*

3. Data and methods

3.1 Data

All data are openly available (Supplementary Table S1). Mangrove extent comes from GMW v4.1.12, which provides annual maps from 1985 to 2025 at 25 m (Bunting et al. 2026). Protected areas come from the World Database on Protected Areas (October 2026) (UNEP-WCMC and IUCN 2026), administrative boundaries from GADM v4.1 (GADM 2022), and roads and settlements from OpenStreetMap extracts of October 2026 (OpenStreetMap contributors 2026). Replacement land uses come from three global or regional maps: oil palm extent and planting year, 1990 to 2021 (Descals et al. 2024); coastal aquaculture pond outlines for 2020 (Jiang et al. 2024); and dissolved regions of land-based aquaculture ponds (Wang et al. 2022). Forest loss years and the water mask come from Hansen Global Forest Change v1.13 (Hansen et al. 2013). Sea-level anomalies come from the Copernicus Marine daily gridded product (Copernicus Marine Service 2026), rainfall from CHIRPS (Funk et al. 2015), the El Niño–Southern Oscillation from the Relative Oceanic Niño Index (RONI) (L'Heureux et al. 2024) and the Indian Ocean Dipole from the Dipole Mode Index (Saji et al. 1999). The analysis was run in Python; the code is available (see Data availability). An earlier study of East Malaysia used GMW v3.0 (Tai 2026a). GMW v4.1 maps 10 to 20% more mangrove than v3.0 and records more change at the mangrove fringe, so rates in this study differ from those reported there and are not directly comparable; GMW v3.0 is used here only as a robustness check. The additional fringe area also makes v4.1 more sensitive to change in the mapped mangrove edge, which is why edge, water and Hansen checks accompany the analyses of loss outside conversion (Sections 3.6 and 5.4; Supplementary Sections S4 and S5).

3.2 Mangrove extent, loss and the reliability of the annual series

Each GMW polygon was assigned to the nearest land unit (Kalimantan, Sabah, Sarawak, Labuan or Brunei) from GADM, and areas were computed in UTM zone 50N (EPSG:32650). The main measure of loss is gross loss: mangrove present at the start of a period and absent at its end, as a share of the start-year extent. Rates per year are that share divided by the period length. The headline comparison uses 2010 and 2020, both baseline years of the series.

Before using the annual series for change, its year-to-year behaviour was examined for each jurisdiction (Supplementary Section S1). Two abrupt drops appear in Kalimantan, of 8% between 1998 and 1999 and 10% between 2003 and 2004, with little change either side (Fig. 2; Supplementary Fig. S1). Both fall in the 1999 to

2006 gap in L-band radar coverage on which the series is anchored. Lost patches in these steps are large (80 to 83% of the area in blocks of 5 ha or more), lie on the pond frontiers of the east coast, and are partly confirmed by GMW v3.0, so they record real conversion whose timing is compressed rather than mapping error. The series was therefore used as follows: 1985 to 1997 not for change; 1995 to 2005 only between the 1995, 2000 and 2005 baseline maps; 2005 to 2014 as interval change, because clearing in 2011 to 2013 is recorded mostly in 2014; and 2014 to 2024 annually, with dates uncertain by about a year. The 2025 map is provisional and was used only to check whether 2024 losses returned.

3.3 Protected-area effectiveness

Protection was evaluated separately in Kalimantan and Malaysian Borneo with a two-tier design: strictly protected mangrove against mangrove outside protected areas. Brunei, whose mangrove lies almost entirely in production reserves, was not tested. The units are 500 m cells (blocks of 10 × 10 pixels of 50 m) with at least 20% mangrove in the start year. A cell is treated if its centre lies inside a strict protected area designated before the period begins; it is a control if it lies outside every protected area and more than 2 km from a strict site. In Kalimantan, the strict categories are national parks, nature reserves and wildlife reserves (15 sites hold treated cells); in Malaysian Borneo, every WDPA site is a strict category, including Sabah's Class I, VI and VII reserves (25 sites designated by 2010). Production reserves (Sabah Class V, Sarawak's Permanent Forest Estate) are not openly mapped, so they lie among the controls; this biases the Malaysian estimate towards zero. The Kuala Segama and Kuala Maruap reserves, upgraded in 2016 but absent from the WDPA, were masked from the controls (Supplementary Section S2).

For each cell, the covariates are mangrove cover in the start year, distance to the coast, distance to the nearest road and settlement (log of one plus the distance in kilometres), and province or state. The outcome is the share of start-year mangrove lost by the end of the period. Six estimators were used: nearest-neighbour matching within province or state on standardised covariates and location, with a caliper, with and without the accessibility covariates; regression adjustment, with and without location; and entropy balancing (Hainmueller 2012), alone and with a location regression. In Kalimantan, the matching specification was also varied in caliper, cell size (250 m and 1 km) and GMW version (v3.0), giving twelve estimates in all. Confidence intervals are 95% intervals from 1,000 bootstrap draws that resample protected sites and 25 km blocks of control

cells. Matched designs of this kind are standard for protected-area evaluation, because protected areas are rarely placed at random (Andam et al. 2008; Joppa and Pfaff 2009).

The main period is 2010 to 2020. For Malaysian Borneo a second period, 2015 to 2024, uses the reliable annual window and distinguishes sites designated by 2010 from those designated in 2011 to 2014, which include Sabah's upgrades. To quantify the proportion of the cross-border gap attributable to protection, the loss differential between Kalimantan and Malaysian Borneo was decomposed into components from protected cells and from cells outside protected areas. A counterfactual was then computed assuming Kalimantan's protected cells performed at the level of Malaysia's; pairing each of the twelve Kalimantan estimates with the Malaysian regression estimate yields a range.

3.4 Sabah's 2015 upgrades

Sabah's Forest Enactment amendments brought parts of the Tawau, Trusan Kinabatangan, and Pulau Banggi and Pulau Balambangan mangrove reserves from production (Class V) into Class I protection from 1 January 2015, as confirmed in the published reserve schedules. Three further mangrove protection forests carry the same WDPA year (Sungai Maruap, Sungai Lasun and Pulau Evans, and Trusan Sugut), but their origin could not be traced; they form a wider treated group. Controls are Sabah mangrove outside all protected areas, more than 5 km from the upgraded reserves, more than 2 km from other strict sites and outside the Kuala Segama and Kuala Maruap reserves. Annual gross loss rates were computed at 50 m for the intervals 2000 to 2005, 2005 to 2010 and 2010 to 2014, and for each year from 2015 to 2024. The effect of the upgrade is a difference in differences: the mean post-upgrade difference between upgraded reserves and controls, minus the mean pre-upgrade difference, with 95% intervals from a bootstrap over 25 km blocks. Leakage was tested in rings 0 to 2 km and 2 to 5 km around the upgraded reserves, which hold much of the reserves' unmapped Class V remainder.

3.5 Conversion pathways

Mangrove present in 2000 and absent in 2024 was rasterised at 30 m and classed by what occupies it now, in this order of precedence: oil palm (2021), mapped aquaculture ponds (2020), and OpenStreetMap residential, industrial, commercial or retail land. Loss under none of these was split into loss near or among ponds (within about 250 m of a mapped pond, or inside a mapped pond region), which most likely records ponds the maps miss, and other loss away from ponds. Each lost pixel was dated to the interval in which it first dropped out of

the series. The gap between Kalimantan and Malaysian Borneo, as a share of 2000 extent, was decomposed by pathway. For oil palm, the clearing-to-planting lag was the planting year minus the Hansen loss year. In Sarawak, where loss away from ponds was concentrated, its character was checked in two steps (Supplementary Section S5): every lost pixel was compared with Hansen loss, the mangrove edge and permanent water, and 40 patches of 5 ha or more, drawn at random with probability proportional to area, were inspected against recent satellite imagery and compared with ESA WorldCover 2021 (Zanaga et al. 2022) and a map of the drivers of forest loss (Sims et al. 2025).

3.6 El Niño and loss outside conversion

For each year from 2015 to 2024, annual gross loss of mangrove outside conversion (excluding oil palm, ponds and their 250 m zone, pond regions and built-up land) was computed for 25 km coastal cells at 50 m. Loss in year t is the change between the maps of $t-1$ and t, matched to climate from July of $t-1$ to June of t. Sea level and rainfall are anomalies from each cell's monthly climatology after removing its 1993 to 2024 linear trend. Because ten years cannot separate El Niño from the 18.61-year lunar nodal cycle, whose minimum fell in mid-2015 (Haigh et al. 2011), the main tests compare cells within each El Niño event (2015 to 2016 and 2023 to 2024): did cells with larger sea-level falls lose more mangrove than in their own normal years? A panel regression with cell and year fixed effects over all ten years complements them.

Two independent checks describe the nature of this loss (Supplementary Section S4): whether Hansen Global Forest Change records loss at the same pixels within a year either side, and whether lost pixels lie at the mangrove edge (within 100 m of non-mangrove) or beside permanent water (within 100 m, from the Hansen water mask).

4. Results

4.1 Loss by jurisdiction

Between 2010 and 2020, Kalimantan lost 86,163 ha of mangrove, 12.3% of its 2010 extent or 1.23% a year (Table 1). Gross loss in Malaysian Borneo and Brunei was 0.43% a year in Sabah, 0.74% in Sarawak and 0.50% in Brunei, so Kalimantan lost mangrove 1.7 (against Sarawak) to 2.9 times (against Sabah) as fast. Kalimantan held 59% of the island's mangrove in 2010 but accounted for 77% of its gross loss. The difference is older than

the decade: between the 1995 and 2005 baseline maps, Kalimantan lost 19.3% of its mangrove, against 2.3% in Sabah and 4.8% in Sarawak (Fig. 2).

Table 1. *Mangrove extent and gross loss by jurisdiction, 2010–2020 (GMW v4.1).*

Jurisdiction	Mangrove 2010 (ha)	Gross loss 2010–2020 (ha)	Loss (% a year)	Share of Borneo's mangrove (%)	Share of gross loss (%)
Kalimantan	700,818	86,163	1.23	59.0	77.0
Sabah	329,818	14,256	0.43	27.7	12.7
Sarawak	143,594	10,691	0.74	12.1	9.6
Brunei	14,010	697	0.50	1.2	0.6
Labuan	426	45	1.04	<0.1	<0.1
Borneo	1,188,666	111,852	0.94	100	100

Gross loss is 2010 mangrove absent in 2020. Brunei's mangrove in GMW v4.1 is about three quarters of the national figure of 18,418 ha (FAO 2007); see Section 5.4.

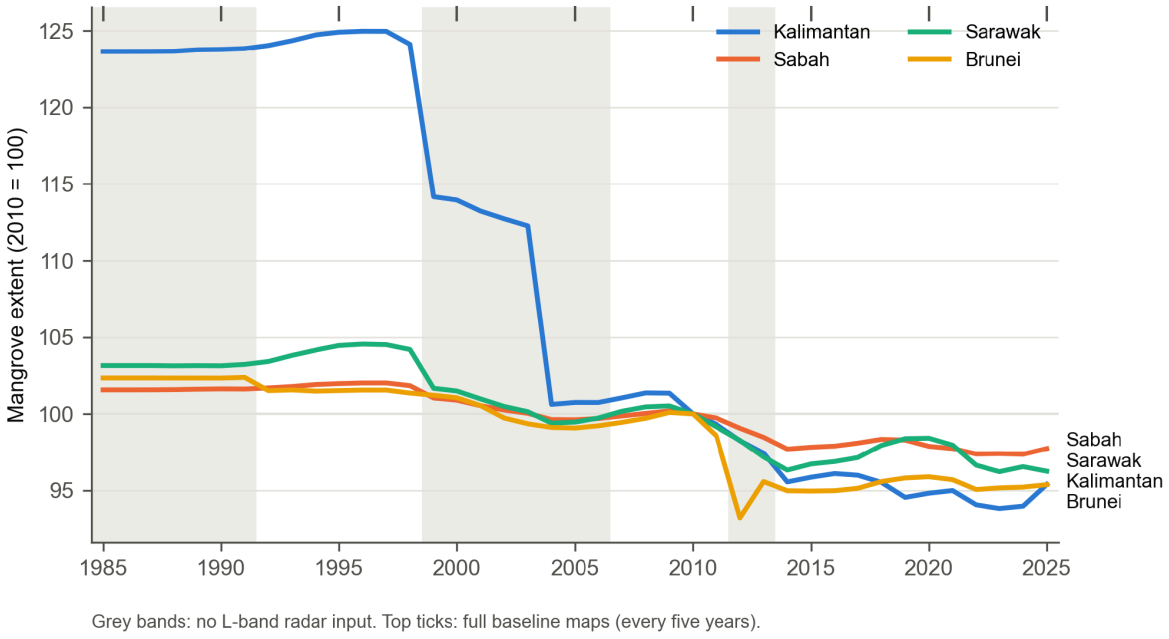


Figure 2. *Annual mangrove extent by jurisdiction in GMW v4.1, 1985–2025. The steps in Kalimantan between 1998 and 1999 and between 2003 and 2004 fall in the 1999–2006 gap in L-band radar coverage; they record real conversion with compressed timing (Supplementary Fig. S1). The 2025 map is provisional.*

4.2 Protected-area effectiveness

In Malaysian Borneo, strictly protected mangrove designated by 2010 lost 2.2% of its extent between 2010 and 2020, against 5.6% outside protected areas. After adjustment, protection reduced loss by about 2 percentage points (regression adjustment −2.1, 95% interval −3.2 to −0.7), and all six estimators exclude zero (−1.5 to −3.1;

Table 2). The effect is robust to dropping any of the three largest protected sites (−2.0 to −2.1) and is clearer in Sabah (−2.6, −4.4 to +0.1) than in Sarawak (−0.8, −3.5 to +2.0). Relative to the controls' loss, protection reduced loss by about 40%.

In Kalimantan, the 15 strict sites holding treated cells lie closer to roads (mean 2.8 km against 5.1 km) and settlements (5.0 against 6.7 km) than mangrove outside protected areas, so omitting accessibility biases the comparison against protection. The first specification, without accessibility, gives +3.4 points (−4.3 to +8.4); adding road and settlement distance reduces this to +0.6 (−3.7 to +4.1), with good balance after matching (all standardised mean differences 0.03 or less). Across twelve specifications varying the covariates, caliper, cell size, estimator and GMW version, the estimate runs from −3.2 to +9.9 points, and every interval includes zero (Table 2). Strict protection had no detectable effect on mangrove loss in Kalimantan.

Table 2. *Effect of strict protection on mangrove loss, 2010–2020: difference in the share of 2010 mangrove lost by 2020 between treated and matched or adjusted control cells (percentage points; negative values mean less loss under protection), with 95% bootstrap intervals.*

Estimator	Kalimantan	Malaysian Borneo
Matching: cover, coast, location	+3.4 (−4.3 to +8.4)	−3.1 (−5.1 to −0.5)
Matching: + road and settlement distance	+0.6 (−3.7 to +4.1)	−1.5 (−2.3 to −0.9)
Regression adjustment	+9.9 (−3.0 to +15.5)	−2.1 (−3.2 to −0.7)
Regression adjustment + location	+4.8 (−4.2 to +10.0)	−1.7 (−3.4 to −0.02)
Entropy balancing	+3.1 (−6.9 to +14.2)	−1.9 (−5.8 to −0.8)
Entropy balancing + location regression	−1.0 (−9.0 to +6.0)	−1.8 (−5.9 to −0.4)
Range over all specifications	−3.2 to +9.9 (12)	−3.1 to −1.5 (6)
Treated cells (sites)	4,511 (15)	1,269 (25)

All estimators include accessibility (log distance to road and settlement) except the first matching row. Kalimantan's further specifications (caliper 0.10 and 0.50, 250 m and 1 km cells, GMW v3.0) are listed in Supplementary Table S3.

Protection nonetheless explains little of the cross-border gap. In the 500 m cells of both tests, Kalimantan lost 11.8% of its 2010 mangrove by 2020 and Malaysian Borneo 4.8%, a gap of 6.9 points; 84% of it arises outside protected areas, where mangrove lost 11.5% in Kalimantan against 5.0% in Malaysian Borneo. Strict protection covers only 10.8% of Kalimantan's mangrove (5.4% in Malaysian Borneo). If Kalimantan's protected mangrove had performed as Malaysia's does, the gap would have closed by between −2% and 19% (median 7%) across the twelve Kalimantan estimates.

In 2015 to 2024, sites designated by 2010 still lost less than the controls (−1.4, −2.9 to +0.9), while sites designated in 2011 to 2014, mostly Sabah's upgrades, did not (+1.4, −0.8 to +4.7). The treated and control cells of both tests are mapped in Fig. 3.

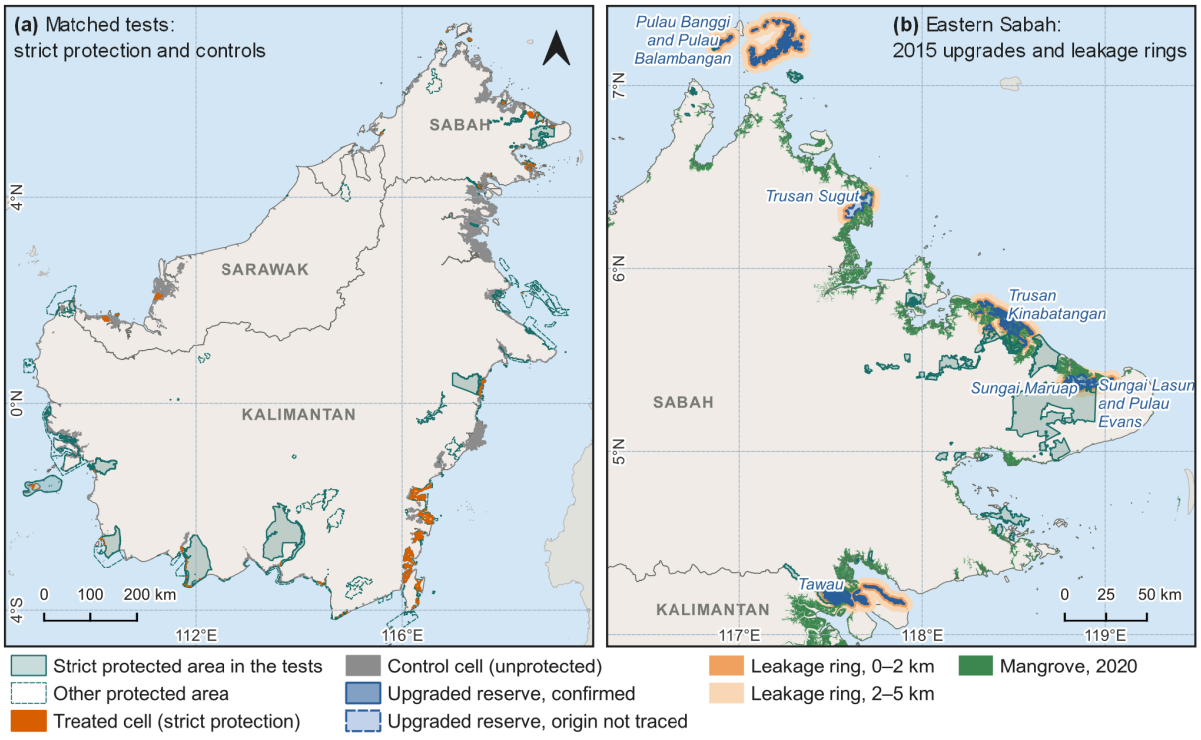


Figure 3. *Design of the protection tests. (a) 500 m cells of the two matched tests, 2010–2020: treated cells lie inside strictly protected areas (WDPA, October 2026; only sites holding treated cells are shown); control cells lie outside all protected areas and more than 2 km from a strict site. (b) North and east Sabah: the six mangrove protection forests in force from 1 January 2015, three of them confirmed upgrades from production (Class V) reserves, with the 0–2 km and 2–5 km leakage rings and mangrove in 2020 (GMW v4.1).*

4.3 Sabah's 2015 upgrades

The three confirmed upgraded reserves lost less mangrove than the controls in every interval, both before and after 1 January 2015 (Fig. 4): they were low-loss production reserves before they were protected. Relative to the controls, their loss did not fall after the upgrade. The difference in differences against all pre-upgrade intervals is +0.10 percentage points a year (−0.05 to +0.23); against 2010 to 2014 alone it is +0.41 (0.17 to 0.63), but that interval holds the clearing of 2011 to 2013, recorded mostly in 2014, and the controls' highest loss rate, so it is the least reliable baseline. In the 0 to 2 km ring, loss rose slightly relative to the controls after the upgrade (+0.17, −0.02 to +0.31); in the 2 to 5 km ring it did not (+0.06, −0.08 to +0.18). The upgrades added no measurable protection, and leakage was weak at most.

Including the three protection forests of untraced origin raises the estimate to +0.19 (−0.04 to +0.40). Two of them, Sungai Maruap and Sungai Lasun and Pulau Evans, lost 426 ha (8.5%) and 184 ha (6.2%) between 2019 and 2022, mostly in 2020. This loss is scattered over hundreds of small patches, lies 67 to 72% within 60 m of the mangrove edge, has not returned by 2025, touches no ponds or built-up land, and is not recorded by Hansen at all (Supplementary Section S3). It is more likely a shift of the mapped mangrove boundary than clearing, so the confirmed upgrades are the main result.

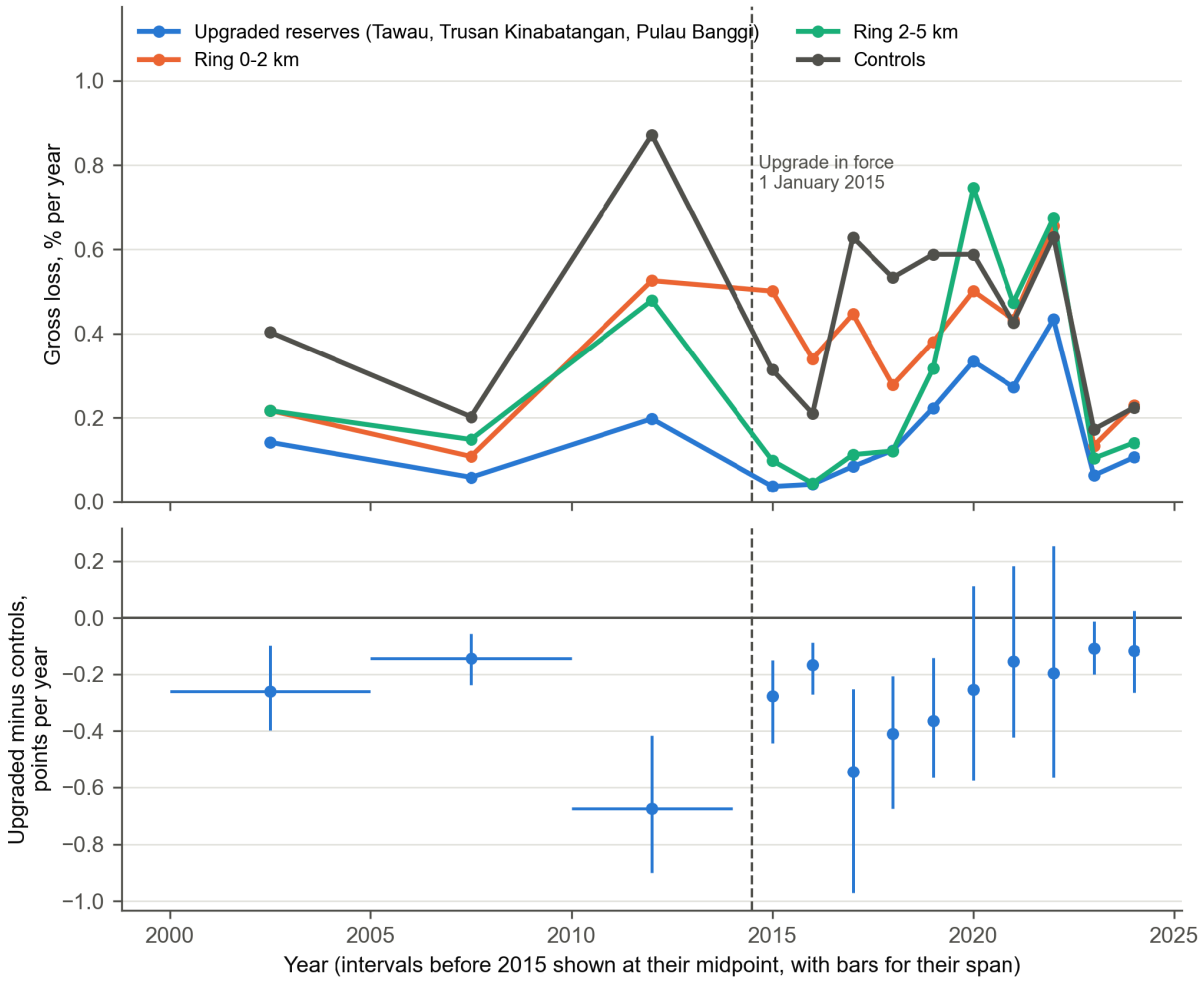


Figure 4. *Mangrove loss before and after Sabah's 2015 upgrades of production reserves to Class I protection forest. Top: annual gross loss rate in the three confirmed upgraded reserves, the 0–2 km and 2–5 km rings around them and the controls. Bottom: upgraded reserves minus controls, with 95% block-bootstrap intervals. Points before 2015 are multi-year intervals plotted at their midpoint, with bars for their span.*

4.4 What replaced the lost mangrove

Between 2000 and 2024, Kalimantan lost 195,531 ha of mangrove, 24.5% of its 2000 extent, against 8.6% in Malaysian Borneo and 7.0% in Brunei (Table 3). Mapped aquaculture ponds occupy 9.4% of Kalimantan's 2000

extent, and unmapped loss near or among ponds a further 7.2%; together, pond-related loss accounts for all of Kalimantan's 15.9-point excess over Malaysian Borneo. Loss away from ponds is similar in total on both sides of the border (7.6% in Kalimantan, 7.8% in Malaysian Borneo, 6.5% in Brunei). Oil palm replaced little mangrove: 3,480 ha across Kalimantan, Sabah and Sarawak, proportionally more in Malaysian Borneo (0.45% of the 2000 extent) than in Kalimantan (0.17%). Where oil palm did replace mangrove, it was usually planted within a year of clearing in Kalimantan and Sarawak (median lag 1 year), and later in Sabah (median 3 years, with 23% planted six or more years after clearing).

Table 3. *Mangrove lost between 2000 and 2024 (still not mangrove in 2024) by what occupies the land now, as a share of the 2000 extent (%; GMW v4.1).*

Pathway	Kalimantan	Malaysian Borneo	Brunei	Kalimantan minus Malaysian Borneo
Mapped aquaculture ponds	9.41	0.05	0.10	+9.36
Near or among ponds (unmapped)	7.24	0.15	0.46	+7.08
Oil palm	0.17	0.45	0.00	−0.28
Settlement or industry	0.03	0.08	0.00	−0.05
Other loss away from ponds	7.64	7.81	6.49	−0.18
Total	24.48	8.55	7.05	+15.93
Mangrove in 2000 (ha)	798,638	478,934	14,171	+319,704

Malaysian Borneo is Sabah, Sarawak and Labuan. Ponds: Jiang et al. (2024), 2020; pond regions: Wang et al. (2022); oil palm: Descals et al. (2024), 2021; settlement: OpenStreetMap land use, October 2026.

Pond-related loss is concentrated on Kalimantan's east coast, from the Kayan and Tarakan coast to the Mahakam Delta and the south-east (Fig. 5a); loss not related to ponds is spread around the whole island, on both sides of the border (Fig. 5b). Within two frames of the same size, the Mahakam Delta lost 22,247 ha of mangrove to or among ponds and 1,619 ha to other causes, while the lower Kinabatangan and Sandakan Bay in Sabah lost none to ponds and 3,126 ha to other causes (Fig. 6). The Mahakam Delta also regained 11,660 ha of mangrove between 2000 and 2024, three fifths of it inside or beside mapped ponds and half on land that was mangrove in 1990, consistent with regrowth on abandoned or partly cleared ponds; this is an area equal to about half of its pond-related loss.

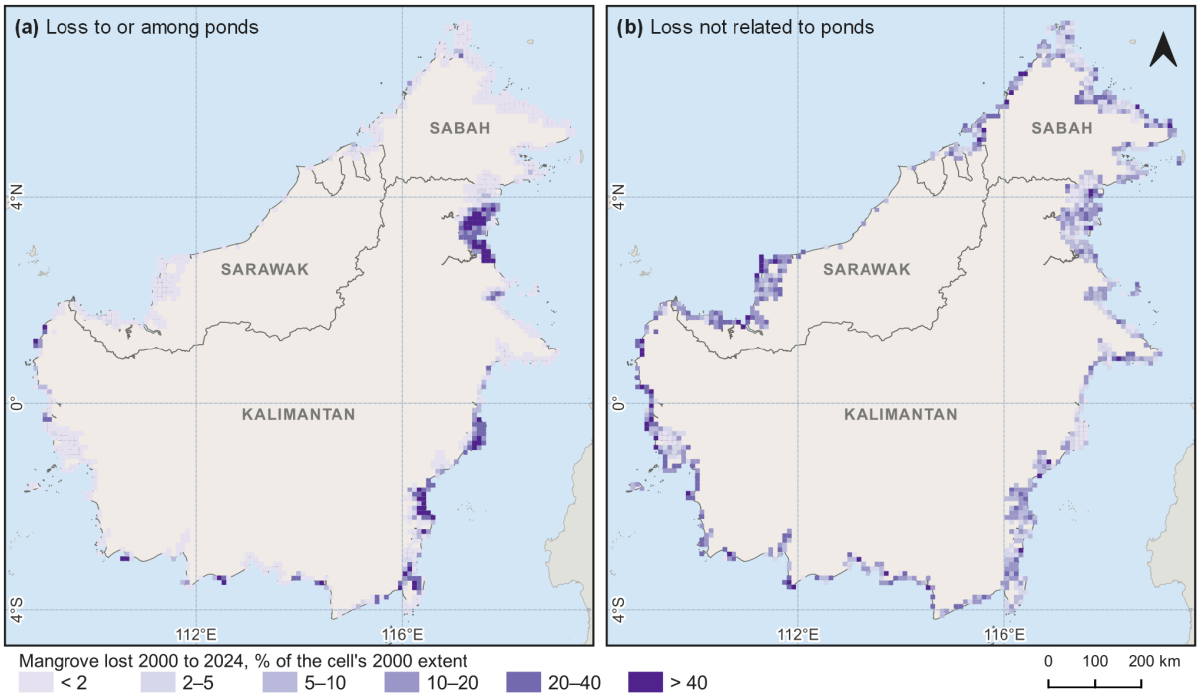


Figure 5. *Mangrove lost between 2000 and 2024 and still not mangrove in 2024, as a share of each 10 km cell's 2000 extent (GMW v4.1): (a) loss to mapped aquaculture ponds or among them (within about 250 m of a mapped pond or inside a mapped pond region); (b) loss not related to ponds (oil palm, settlement and all other loss). Cells with less than 50 ha of mangrove in 2000 are omitted.*

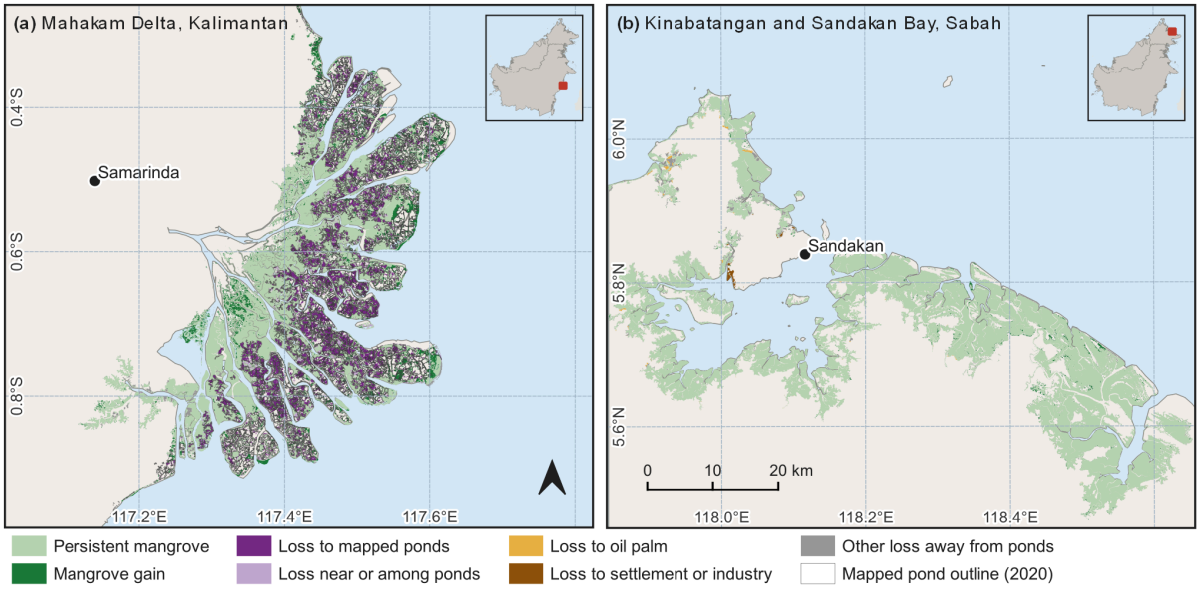


Figure 6. *Mangrove change between 2000 and 2024 in two frames of 90 × 80 km at the same scale (GMW v4.1, 30 m): (a) Mahakam Delta, East Kalimantan; (b) lower Kinabatangan and Sandakan Bay, Sabah. Loss is classed by what occupies the land now; pond outlines are from Jiang et al. (2024), mapped in 2020.*

Pond conversion was concentrated early. In Kalimantan, mapped ponds alone took 5.7% of the 2000 mangrove extent in 2000 to 2005, about 1.1% a year, falling to 1.7% in 2005 to 2010, 1.1% in 2010 to 2014 and 0.15% in 2020 to 2024. The two steps in the annual series fall in this early period (Section 3.2). In contrast, non-pond loss

increased over the same period on both sides of the border. Because Hansen loss years overlap with the Global Mangrove Watch (GMW) period for only 12% to 28% of Kalimantan's loss, they offer an unreliable proxy for mangrove clearing dates and were excluded from dating pond conversions.

In Malaysian Borneo, loss away from ponds is concentrated in Sarawak, in the Rajang Delta (63% of Sarawak's) and south-west Sarawak (32%), where it reached 12 to 13% of the 2000 extent, against 5.8% in Sabah. Unlike in Sabah, it carries the signature of clearing: half of it was also recorded by Hansen and most lay in patches of 5 ha or more (Supplementary Section S5). In the 40 sampled patches, about half of it had become other land uses (oil palm in 9 patches, cleared land in 8, including logged mangrove in the Rajang Delta, and built-up land in 4), 5 had become open water through coastal retreat, and 14 still looked like mangrove or young regrowth (Supplementary Table S9). Consequently, the oil palm dataset undercounts plantations established on former mangrove land. If the sample is representative, oil palm replaced approximately 2,200 to 3,800 ha across the two study areas, compared to only about 960 ha mapped statewide in Sarawak. Furthermore, a portion of the recorded loss stems from dataset disagreement rather than physical conversion, particularly in the Rajang Delta, where ESA WorldCover still classifies 43% of the lost area as mangrove (compared to 21% in south-west Sarawak).

4.5 El Niño and loss outside conversion

Annual loss of mangrove outside conversion was lowest in the El Niño years, about 0.2% a year in 2015, 2016 and 2024, and highest in the wet La Niña years of high sea level, 1.0 to 1.5% in 2021 and 2022 (Fig. 7). Only 1 to 7% of each year's loss was mangrove again within two years, so the pattern is not year-to-year flicker in the maps. Within each El Niño event, cells with larger sea-level falls did not lose more mangrove: per centimetre of sea level, +0.00 percentage points (−0.33 to +0.47) in 2015 to 2016 and −0.26 (−0.62 to +0.03) in 2023 to 2024. In the panel with cell and year fixed effects, the sea-level coefficient is +0.005 per centimetre (−0.06 to +0.08). Rainfall and its interaction with sea level had no detectable effect in any model.

Non-conversion loss is inherently edge-dominated. Each year, 80% to 98% of this loss occurs within 100 m of the mangrove edge on both sides of the border, compared to only 40% of total mangrove coverage, with 15% to 37% coinciding within one year of loss recorded by Hansen. The high-sea-level losses of 2020 to 2022 are not a waterline artefact: only 9 to 10% lie beside permanent water, fewer than expected from the 12 to 13% of all

mangrove that does, whereas in the El Niño years the little loss there is lies more often beside water (17 to 33%). Hansen-confirmed loss alone also rises with sea level across the ten years (correlation +0.41 in Kalimantan, +0.70 in Malaysian Borneo) and is lowest in the El Niño years.

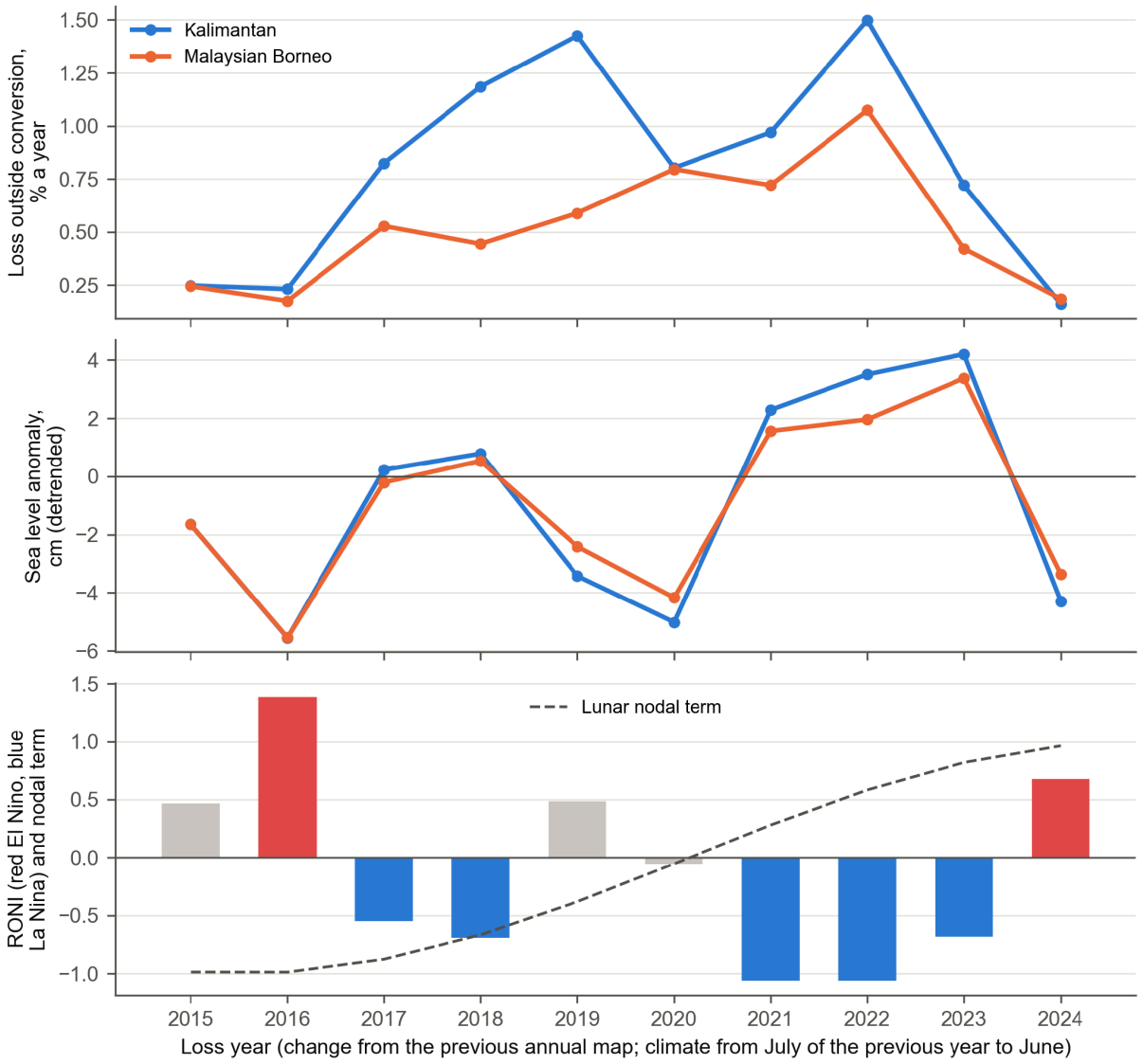


Figure 7. *Annual loss of mangrove outside conversion, 2015–2024, for Kalimantan and Malaysian Borneo (top), with the mean de-trended sea-level anomaly of the same cells (middle) and the Relative Oceanic Niño Index and the lunar nodal term (bottom). Loss in year t is the change between the maps of t−1 and t; climate is averaged from July of t−1 to June of t.*

5. Discussion

5.1 The gap is ponds

On one island with shared tides, sediment and climate, Kalimantan lost mangrove two to three times faster than Malaysian Borneo and Brunei, and the excess is aquaculture. Pond-related loss accounts for all of the 15.9-point excess between 2000 and 2024, while loss away from ponds proceeded at almost exactly the same rate on both sides of the border. That similarity hides a contrast within Malaysian Borneo. In Sarawak, loss away from ponds is concentrated in two areas and is mostly conversion that the replacement maps miss, to oil palm, cleared or logged land and settlement (Section 4.4), consistent with the enduring loss that Wei et al. (2026) identify in Sarawak; in Sabah it is mostly change in the mapped boundary. Loss away from ponds is therefore not one process on both sides of the border, but this does not weaken the pond result: in Kalimantan, some of it may be ponds more than 250 m from the mapped ones, which would enlarge the pond-related share of the gap, and in Sarawak it is conversion to uses other than ponds. The result sharpens regional syntheses that list aquaculture, rice and oil palm together as drivers (Richards and Friess 2016; Hagger et al. 2022): on Borneo, the driver that differs across the border is ponds, and oil palm, despite its prominence in the island's terrestrial deforestation (Gaveau et al. 2016), replaced little mangrove on either side, even allowing for the plantations the oil palm map misses in Sarawak. The timing agrees with independent evidence. Pond conversion peaked in 2000 to 2005 and has declined since, and Zhang et al. (2026) find that loss in Southeast Asia peaked between 1990 and 2005 and that Indonesia's loss stabilised after 2005; the Mahakam Delta's regrowth on abandoned ponds fits their observation that mangroves regenerate in abandoned aquaculture ponds.

The divergence in pond expansion between Kalimantan and Malaysian Borneo stems from historical policy differences rather than this study's empirical dataset; it is therefore summarised here based on existing literature. Indonesia's shrimp pond expansion in the 1980s and 1990s, and its acceleration around the 1997 to 1998 economic crisis, have been documented as major causes of mangrove loss (Ilman et al. 2016). In the Mahakam Delta, ponds were dug by hand from about 1970, spread after trawling was banned in the early 1980s and when excavators arrived around 1990, and by about 2001 had replaced roughly three quarters of the delta's mangrove (Bosma et al. 2012). The collapse of the rupiah in 1997 and 1998 made shrimp, sold for dollars, far more profitable in local currency, and clearing accelerated (Bosma et al. 2012; Persoon and Simarmata 2014). Regional autonomy after 1998 then allowed land in the delta, officially state forest, to be claimed through letters issued by village and sub-district heads, with little involvement of the Ministry of Forestry (Persoon and

Simarmata 2014). From the early 2000s, disease, low yields and falling prices ended the boom and left many ponds unproductive or abandoned (Bosma et al. 2012; Persoon and Simarmata 2014), in line with the decline of pond conversion after 2005 and the regrowth on ponds found here. In Sabah, by contrast, about 93% of the mangrove has been gazetted as permanent forest reserve, almost all of it as mangrove forest reserve (Class V) for timber and other produce (Mojiol et al. 2017); the low loss in production reserves before Sabah's 2015 upgrades (Section 4.3) suggests that this status has limited conversion. This study makes no causal claim about these factors; it shows only where and when the cross-border difference arose.

5.2 Protection works where it is enforced, but is not the main lever

Long-standing strict protected areas reduced mangrove loss in Malaysian Borneo by about 2 percentage points over a decade, roughly 40% of the controls' loss, and the estimate is conservative because unmapped production reserves sit among the controls. In Sabah these reserves are most of the controls: about 93% of the state's mangrove is gazetted forest reserve, almost all of it Class V production reserve (Mojiol et al. 2017), while strict sites hold about 5% of Malaysian Borneo's mangrove in the matched cells; Sarawak's share in its Permanent Forest Estate is not openly reported. The Malaysian estimate therefore compares strict protection mainly with production reserves rather than with unprotected mangrove, and against unprotected mangrove the effect would be larger, by an amount the open data cannot measure. In Kalimantan, strict protection had no detectable effect, even after accounting for the fact that strict sites there are more accessible than mangrove outside protected areas. The contrast is consistent with global evidence that protected-area performance depends on governance (Heck et al. 2024) and that conversion often proceeds inside protected areas (Hagger et al. 2022), and it updates the earlier Indonesian evaluation (Miteva et al. 2015) for Kalimantan with a decade of later data. The Kalimantan result rests on 15 sites, however, so it rules out large protective effects rather than small ones.

The more important finding for policy is that protection explains little of the gap. Most of Kalimantan's excess loss arose outside protected areas, and even if Kalimantan's protected areas had performed as Malaysia's, the gap would have narrowed by a median of 7%. Sabah's experience points the same way from the other side: upgrading low-loss production reserves to full protection added no measurable protection, because those reserves were already well protected as production forest. For mangrove conservation on Borneo, how mangrove outside strict protected areas is governed, whether as state forest in Kalimantan or as production

reserve in Sabah, and in particular how pond expansion is controlled, matters more than the extent of the strict protected-area network.

5.3 Borneo's humid mangroves and El Niño

Zhang et al. (2025) found that sea-level fall during El Niño reduces mangrove leaf area across the western Pacific but that humid Southeast Asia appeared buffered. This study finds the same at the level of extent: loss outside conversion was lowest in El Niño years, cells with larger sea-level falls did not lose more, and loss was highest when sea level was high. Two cautions apply. First, extent loss in the annual series is marginal by nature, mostly within 100 m of the mangrove edge and only partly recorded as canopy loss, so it describes change in the mapped margin rather than dieback of closed stands; it is not, however, an artefact of high water at image dates. Second, ten years cannot separate El Niño from the lunar nodal cycle, whose minimum fell during the 2015 to 2016 event (Haigh et al. 2011), and the strong 1997 to 1998 El Niño lies outside the reliable part of the series, whose annual maps before about 2000 are filled from sparse imagery (Supplementary Section S1). The finding is that Borneo's humid mangroves showed no loss of extent from El Niño sea-level fall in 2015 to 2024, not that they are immune.

5.4 Data and the GMW v4.1 series

The annual GMW v4.1 series makes this analysis possible, but it has to be used with care. Its two Kalimantan steps compress real conversion into single years; 2011 to 2013 clearing appears mostly in 2014; and annual loss outside conversion is predominantly marginal and only partly confirmed by an independent product. The study therefore uses baseline maps for early change, intervals for 2005 to 2014, and annual change only from 2014, and it reports edge and Hansen checks alongside the ENSO results. Three practical points follow for other users of the series. Change across 1998 to 2004 should be measured between the 1995, 2000 and 2005 baseline maps rather than year by year; change across the 2011 to 2013 radar gap should be measured as one interval ending in 2014; and annual loss that lies at the mangrove edge in patches smaller than 5 ha should be read as change in the mapped margin unless an independent product such as Hansen records it. Checks of this kind (Supplementary Sections S1, S4 and S5) need only open data and separate conversion from change in the mapped boundary. The same care applies to small jurisdictions and sites. Brunei's 713 ha of loss in 2010 to 2014 is not a single project but diffuse edge change, partly reversed by 2020, so its 2010 to 2020 rate is the better measure. Brunei's mangrove in GMW v4.1 (about 14,000 ha) is about three quarters of the national figure of 18,418 ha, which

dates from aerial photographs of about 1979 (FAO 2007); the difference is not due to the boundary with Sarawak in Brunei Bay and is probably partly definitional.

5.5 Limitations

Five limitations qualify the results. First, the protection tests are two-tier, strict against everything else, because production reserves in Sabah and Sarawak and forest-estate classes in Kalimantan are not openly mapped; the Malaysian effect is probably understated, since most Sabah controls lie in Class V production reserves (Section 5.2). Second, WDPA designation years are approximate, and the Kalimantan result rests on 15 sites. Third, the replacement maps are snapshots (ponds in 2020, oil palm in 2021), so recent loss may not yet show its replacement, and loss near or among ponds is a proxy for ponds the maps miss; loss away from ponds in Kalimantan and Sarawak has the signature of clearing, and in Sarawak the visual check shows much of it to be oil palm, cleared land or settlement that these maps do not record, while part is disagreement between mangrove maps. Fourth, OpenStreetMap roads and settlements are mapped as of 2026, not 2010, so accessibility covariates may be affected by roads built after clearing. Fifth, the ENSO analysis covers ten years, with the caveats above. All data and code are open, so each of these can be revisited as better maps become available.

6. Conclusion

Kalimantan lost mangrove two to three times faster than Malaysian Borneo and Brunei between 2010 and 2020, and the difference is old: it was largest in the early 2000s. Strict protected areas reduced loss in Malaysian Borneo but not in Kalimantan, yet this explains little of the gap, which lies outside protected areas and is accounted for entirely by conversion to aquaculture ponds; loss away from ponds is similar in total on both sides of the border, though in Kalimantan and Sarawak it is mostly clearing, in Sarawak for oil palm, cleared land and settlement that the maps miss, and oil palm replaced little mangrove. Borneo's humid mangroves showed no loss of extent from El Niño sea-level fall over the past decade. Reducing mangrove loss on Borneo is therefore mainly a matter of governing pond expansion and supporting the regrowth of abandoned ponds outside protected areas, rather than of adding protected areas. With El Niño forecast to become one of the strongest on record in 2026 to 2027, continued annual monitoring will show whether that buffering holds.

Statements and Declarations

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Competing interests

The author has no relevant financial or non-financial interests to disclose.

Author contributions

Lik Ren Tai conceived and designed the study, carried out the analysis and wrote the manuscript.

Data availability

All input data are open (Supplementary Table S1). The notebooks, scripts, derived data and figures used in this study are openly available in Zenodo (Tai 2026b; https://doi.org/10.5281/zenodo.23671057).

Ethics approval

Not applicable. This study used only openly available secondary data and involved no human participants or animals.

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Supplementary Information

One island, three countries: aquaculture ponds explain the cross-border gap in mangrove loss on Borneo

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Contents: Table S1, open data; Section S1, the GMW v4.1 annual series in Kalimantan (Table S2, Figs S1 and S2); Section S2, protection tests (Tables S3 to S5); Section S3, small-site and Brunei checks (Table S6); Section S4, the signature of loss outside conversion (Table S7); Section S5, Sarawak's loss away from ponds (Tables S8 and S9). Analyses are in notebooks 01 to 12, openly available in Zenodo (https://doi.org/10.5281/zenodo.23671057).

Open data

Table S1. *Open data used in the study. All were downloaded without registration fees or data requests.*

Dataset	Version or date	Resolution	Use	Reference
Global Mangrove Watch	v4.1.12; annual, 1985–2025	25 m (vector)	Mangrove extent and change	Bunting et al. (2026)
Global Mangrove Watch	v3.0; 1996–2020	25 m (vector)	Robustness check	Bunting et al. (2022)
World Database on Protected Areas	October 2026	Polygons	Protected areas and designation years	UNEP-WCMC and IUCN (2026)
GADM	v4.1	Polygons	Jurisdictions, provinces and states	GADM (2022)
OpenStreetMap	Geofabrik extracts, 23 October 2026	Vector	Roads, settlements, built-up land	OpenStreetMap contributors (2026)
Oil palm extent and planting year	2016–2021; planting year 1990–2021	10 m	Conversion to oil palm; planting lag	Descals et al. (2024)
Coastal aquaculture ponds	2020	30 m (polygons)	Conversion to ponds	Jiang et al. (2024)
Landside clustering aquaculture ponds	2020	10 m (regions)	Pond regions	Wang et al. (2022)
Global Forest Change	v1.13; loss year 2001–2025, data mask	30 m	Independent loss dates; permanent water	Hansen et al. (2013)
Sea-level anomaly	SEALEVEL_GLO_PHY_L4_MY_008_047, daily	0.125°	Sea-level anomalies	Copernicus Marine Service (2026)
CHIRPS	v2.0, monthly	0.05°	Rainfall anomalies	Funk et al. (2015)
Relative Oceanic Niño Index	NOAA Climate Prediction Center	Three-month seasons	El Niño–Southern Oscillation	L'Heureux et al. (2024)

Dipole Mode Index	HadISST, NOAA Physical Sciences Laboratory	Monthly	Indian Ocean Dipole	Saji et al. (1999)
ESA WorldCover	v200, 2021	10 m	Land cover on lost mangrove (Sarawak check)	Zanaga et al. (2022)
Drivers of forest loss	v1.2, 2001–2024	1 km	Dominant driver of loss (Sarawak check)	Sims et al. (2025)
Natural Earth	Admin 0 countries, 1:10 m	Vector	Map context	naturalearthdata.com

Section S1. The GMW v4.1 annual series in Kalimantan

Before the annual series was used for change, the loss between every pair of consecutive annual maps in Kalimantan was examined (notebook 03). Lost pixels (50 m) were grouped into 8-connected clusters, and the share of the loss in clusters of 5 ha or more (blocks, as clearing for ponds or plantations leaves) and in clusters of one to three pixels (speckle, as classification noise leaves) was counted, together with the share on the edge of a mangrove patch. Two pairs stand apart (Table S2): 1998 to 1999 and 2003 to 2004 lost 71,778 ha (8.3%) and 84,954 ha (10.8%), with 80 and 83% of the loss in blocks, against 0 to 3% in most other years before 2008. Both fall in the 1999 to 2006 gap in L-band radar input, and the lost blocks lie on the pond frontiers of the east coast (Fig. S1). They therefore record real conversion whose timing is compressed into single years, rather than mapping error. The 2013 to 2014 pair also holds blocks (31% of its loss), consistent with clearing in 2011 to 2013 being recorded mostly in 2014 after the 2011 to 2013 radar gap (Fig. S2). From 2014, block shares are moderate in every year (0 to 34%), so annual change was used from 2014 with dates uncertain by about a year.

Table S2. *Gross loss between consecutive GMW v4.1 annual maps in Kalimantan, 1996–2025: area, share of the start-year extent, and the share of the loss in blocks of 5 ha or more, in specks of one to three pixels and on patch edges, against the edge share of all mangrove.*

Pair	Loss (ha)	Loss (%)	Blocks (% of loss)	Specks (% of loss)	Edge (% of loss)	Edge (% of mangrove)
1995–1996	877	0.1	0	92	94	28
1996–1997	1,125	0.1	2	89	90	28
1997–1998	6,610	0.8	40	39	64	28
1998–1999	71,778	8.3	80	9	34	28
1999–2000	2,550	0.3	2	86	95	33
2000–2001	5,722	0.7	0	90	97	33
2001–2002	4,250	0.5	2	91	90	33
2002–2003	4,143	0.5	0	95	90	33

2003–2004	84,954	10.8	83	6	39	33
2004–2005	1,753	0.2	0	98	99	37
2005–2006	3,037	0.4	2	85	98	37
2006–2007	2,183	0.3	0	90	98	37
2007–2008	2,114	0.3	0	88	96	37
2008–2009	10,234	1.4	22	50	78	37
2009–2010	15,554	2.2	49	26	69	37
2010–2011	7,379	1.1	0	90	97	37
2011–2012	9,792	1.4	0	87	94	37
2012–2013	8,016	1.2	1	84	92	37
2013–2014	20,607	3.0	31	38	77	38
2014–2015	5,550	0.8	13	61	94	38
2015–2016	3,858	0.6	4	77	94	38
2016–2017	11,239	1.7	18	51	82	38
2017–2018	13,309	2.0	27	45	80	38
2018–2019	13,378	2.0	34	44	79	38
2019–2020	6,574	1.0	10	66	84	39
2020–2021	8,433	1.3	14	63	85	39
2021–2022	12,296	1.8	18	59	84	39
2022–2023	6,169	0.9	23	52	79	39
2023–2024	1,904	0.3	0	93	97	40
2024–2025	8,385	1.3	32	42	74	40

50 m pixels; 8-connected clusters. Blocks are clusters of 20 pixels (5 ha) or more.

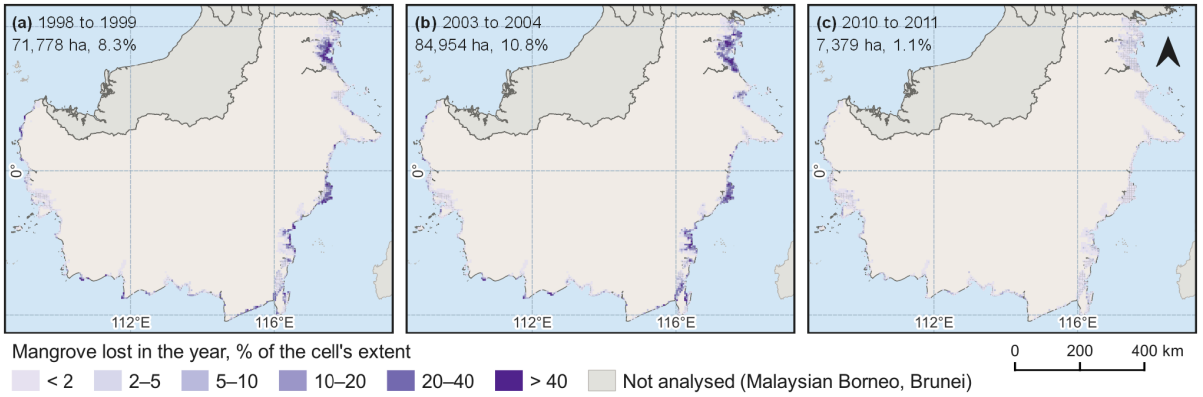


Figure S1. *Mangrove lost in single years in Kalimantan, as a share of each 5 km cell's extent in the first year (GMW v4.1): (a) 1998 to 1999, (b) 2003 to 2004 and (c) 2010 to 2011, a normal year, for comparison. Malaysian Borneo and Brunei were not analysed.*

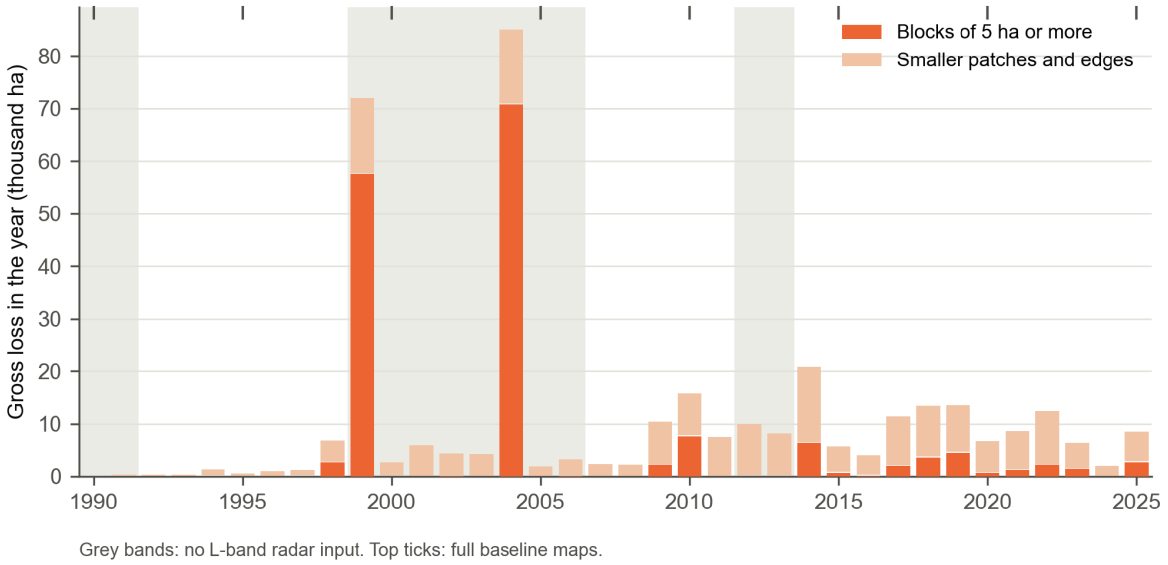


Figure S2. *Annual gross loss of mangrove in Kalimantan in GMW v4.1, 1990–2025, split into blocks of 5 ha or more and smaller patches and edges. Grey bands mark years without L-band radar input; ticks on the top axis mark the full baseline maps.*

Section S2. Protection tests

The units are 500 m cells with at least 20% mangrove in the start year. Treated cells have their centre inside a strict protected area designated before the period; controls lie outside every protected area and more than 2 km from a strict site. In Sabah, the Kuala Segama and Kuala Maruap reserves, upgraded to protection forest on 31 December 2016 but absent from the WDPA, were masked from the controls with a box of 118.45 to 118.85° E and 5.25 to 5.65° N. Matching is nearest-neighbour within province (Kalimantan) or state (Malaysian Borneo) on standardised covariates, with a caliper of 0.25 standard deviations unless stated; entropy balancing follows Hainmueller (2012). Intervals are 95% intervals from 1,000 bootstrap draws that resample protected sites and 25 km blocks of control cells.

In Kalimantan, the strict sites lie closer to the coast, roads and settlements than unprotected mangrove; after matching on these covariates, every standardised mean difference is 0.03 or less (Table S4). The twelve Kalimantan specifications all have intervals that include zero (Table S3). In Malaysian Borneo, sites designated by 2010 reduced loss in 2010 to 2020 under all six estimators and in every subset that drops one of the three largest sites; in 2015 to 2024, those long-standing sites still lost less than the controls (−1.4), while sites designated in 2011 to 2014, mostly Sabah's upgrades, did not (+1.4; Table S5).

Table S3. *Effect of strict protection on mangrove loss in Kalimantan, 2010–2020, in all twelve specifications (percentage points; negative values mean less loss under protection).*

Specification	Cells	Caliper	Treated cells (sites)	Effect	95% interval
Pilot: cover, coast, location	v4 500 m	0.25	4,511 (15)	+3.4	−4.3 to +8.4
+ road and settlement distance	v4 500 m	0.25	4,511 (12)	+0.6	−3.7 to +4.1
+ access, caliper 0.10	v4 500 m	0.10	4,511 (5)	−3.2	−8.8 to +0.1
+ access, caliper 0.50	v4 500 m	0.50	4,511 (14)	+4.3	−2.4 to +10.6
+ access, 250 m cells	v4 250 m	0.25	16,876 (14)	−1.8	−4.5 to +2.5
+ access, 1 km cells	v4 1 km	0.25	1,206 (9)	−1.3	−8.9 to +2.0
+ access, GMW v3	v3 500 m	0.25	4,483 (9)	+1.1	−2.1 to +3.4
Matching, no location term	v4 500 m	–	4,511	+8.8	−0.7 to +15.4
Regression adjustment	v4 500 m	–	4,511	+9.9	−3.0 to +15.5
Regression adjustment + location	v4 500 m	–	4,511	+4.8	−4.2 to +10.0
Entropy balancing	v4 500 m	–	4,511	+3.1	−6.9 to +14.2
Entropy balancing + location regression	v4 500 m	–	4,511	−1.0	−9.0 to +6.0

Rows 2 to 7 add log distance to road and settlement to the pilot specification and vary it; the last five rows are matching without the location term and the regression and entropy-balancing estimators of Table 2 in the main text.

Table S4. *Covariate balance in Kalimantan before and after matching (500 m cells, with access covariates).*

Covariate	Treated mean	Control mean	Standardised difference before	Standardised difference after
Mangrove cover (fraction)	0.64	0.64	−0.03	0.001
Distance to coast (km)	1.48	2.94	−0.35	0.029
Distance to road (km)	2.79	5.05	−0.61	0.014
Distance to main road (km)	14.12	19.37	−0.32	0.020
Distance to settlement (km)	5.03	6.66	−0.44	0.009

Table S5. *Effect of strict protection on mangrove loss in Malaysian Borneo by period, estimator and subset (percentage points).*

Period	Estimator or subset	Treated cells (sites)	Effect	95% interval
2010–2020	Matching: cover, coast, location	1,269 (25)	−3.1	−5.1 to −0.5
2010–2020	Matching: + road and settlement	1,269 (16)	−1.5	−2.3 to −0.9
2010–2020	Regression adjustment	1,269 (25)	−2.1	−3.2 to −0.7
2010–2020	Regression adjustment + location	1,269 (25)	−1.7	−3.4 to −0.0
2010–2020	Entropy balancing	1,269 (25)	−1.9	−5.8 to −0.8
2010–2020	Entropy balancing + location regression	1,269 (25)	−1.8	−5.9 to −0.4

2015–2024	Matching: cover, coast, location	3,488 (39)	−1.2	−3.2 to +0.8
2015–2024	Matching: + road and settlement	3,488 (27)	−1.9	−4.3 to +0.4
2015–2024	Regression adjustment	3,488 (39)	+0.2	−1.4 to +2.4
2015–2024	Regression adjustment + location	3,488 (39)	+0.0	−1.8 to +2.6
2015–2024	Entropy balancing	3,488 (39)	−0.0	−1.7 to +2.1
2015–2024	Entropy balancing + location regression	3,488 (39)	−0.1	−2.0 to +2.1
2010–2020	Regression adjustment, without Rajang Mangrove National Park	24 sites	−2.1	−3.6 to −0.5
2010–2020	Regression adjustment, without Sungai Gologob Virgin Jungle Reserve	24 sites	−2.1	−3.5 to −0.3
2010–2020	Regression adjustment, without Kuching Wetland National Park	24 sites	−2.0	−3.5 to −0.4
2010–2020	Regression adjustment, Sabah only	20 sites	−2.6	−4.4 to +0.1
2010–2020	Regression adjustment, Sarawak only	5 sites	−0.8	−3.5 to +2.0
2015–2024	Regression adjustment, sites designated by 2010	25 sites	−1.4	−2.9 to +0.9
2015–2024	Regression adjustment, sites designated 2011-2014	14 sites	+1.4	−0.8 to +4.7
2015–2024	Regression adjustment, Sabah only	30 sites	+0.5	−1.1 to +3.0
2015–2024	Regression adjustment, Sarawak only	9 sites	−1.4	−3.5 to +7.8

Section S3. Small-site and Brunei checks

Two protection forests of untraced origin, Sungai Maruap and Sungai Lasun and Pulau Evans, lost 426 ha (8.5%) and 184 ha (6.2%) of mangrove between 2019 and 2022, mostly in 2020, and Brunei lost 713 ha in 2010 to 2014 (notebook 09). In all three cases the loss is spread over hundreds of small patches (587, 379 and 1,697), lies mostly within 60 m of the mangrove edge, is rarely or never recorded by Hansen, and does not lie beside open water (Table S6). In the two Sabah sites, less than 1% had returned by 2025 and none touches mapped ponds or built-up land; in Brunei, 20% had returned by 2020. These losses are more likely shifts of the mapped mangrove boundary than clearing, so the main text uses the three confirmed Sabah upgrades and Brunei's 2010 to 2020 rate.

Table S6. *Character of three local losses: area, the share recorded by Hansen in any year, within 60 m of the mangrove edge, more than 150 m inside it and within 100 m of permanent water, against the water share of all mangrove at the site.*

Site and period	Loss (ha)	Hansen (%)	Within 60 m of edge (%)	Over 150 m inside (%)	Beside water (%)	All mangrove beside water (%)
Sungai Maruap, 2019–2022	425.7	0.0	72	7	0.6	2.7

Sungai Lasun and Pulau Evans, 2019–2022	183.7	0.4	67	9	1.0	3.2
Brunei, 2010–2014	716.9	7.3	84	4	5.1	11.7

Section S4. The signature of loss outside conversion

For every 50 m pixel lost outside conversion in each loss year from 2015 to 2024, notebook 10 recorded whether it lay within 100 m of the edge of the start-year mangrove, within 100 m of permanent water (Hansen data mask), whether Hansen recorded loss there in the loss year or the year either side, and whether it was mangrove again within two years. In every year and on both sides of the border, 80 to 98% of the loss lay at the edge, against about 40% of all mangrove (Table S7). The high-sea-level losses of 2020 to 2022 lay less often beside water (9 to 11%) than all mangrove (12 to 13%), so they are not an artefact of high water at the image dates; the share beside water was highest in the El Niño years, when loss was small. Hansen-confirmed loss alone also rose with sea level across the ten years (correlation +0.41 in Kalimantan and +0.70 in Malaysian Borneo).

Table S7. *Annual loss of mangrove outside conversion, 2015–2024: rate, share at the edge and beside water (expected share from all mangrove in brackets), share recorded by Hansen within a year, share back within two years, and the mean de-trended sea-level anomaly.*

Side	Year	Loss (% a year)	Edge (%)	Beside water (%)	Hansen (%)	Back (%)	Sea level (cm)
Kalimantan	2015	0.25	95 (40)	18 (12)	23	3	−1.6
	2016	0.23	94 (40)	17 (12)	18	2	−5.6
	2017	0.82	84 (40)	11 (12)	29	2	+0.2
	2018	1.18	80 (40)	10 (12)	34	4	+0.8
	2019	1.42	80 (40)	9 (12)	37	3	−3.4
	2020	0.80	87 (41)	9 (12)	23	1	−5.0
	2021	0.96	87 (41)	10 (12)	26	2	+2.3
	2022	1.49	87 (41)	9 (12)	22	1	+3.5
	2023	0.72	81 (42)	10 (13)	35	15	+4.2
	2024	0.16	98 (42)	25 (13)	15	54	−4.3
Malaysian Borneo	2015	0.25	94 (40)	19 (13)	20	5	−1.6
	2016	0.18	95 (40)	20 (13)	10	3	−5.5
	2017	0.53	84 (40)	13 (13)	29	4	−0.2
	2018	0.45	90 (41)	15 (13)	25	3	+0.5

2019	0.59	89 (41)	16 (13)	18	4	−2.4
2020	0.81	85 (41)	11 (13)	17	2	−4.2
2021	0.73	89 (42)	10 (13)	18	2	+1.6
2022	1.10	88 (42)	9 (13)	15	1	+2.0
2023	0.42	80 (43)	13 (13)	37	9	+3.4
2024	0.19	96 (43)	33 (13)	13	29	−3.4

Section S5. Sarawak's loss away from ponds

Loss away from ponds (mangrove in 2000 and not in 2024, with no oil palm, mapped pond, pond zone, pond region or built-up land) is about the same share of the 2000 extent in Kalimantan (7.6%) and Malaysian Borneo (7.8%), but within Malaysian Borneo it is concentrated in Sarawak (notebook 11). Of Sarawak's 17,742 ha, 63% lies in the Rajang Delta (111.0 to 112.5° E, 1.5 to 3.0° N) and 32% in south-west Sarawak (109.5 to 111.0° E, 1.0 to 2.0° N), where it reached 12 to 13% of the 2000 extent, against 5.8% in Sabah. For every 30 m pixel of this loss, the same edge and water flags as in Section S4 were recorded against the 2000 extent, together with Hansen loss in any year from 2001 to 2024 and membership of a connected patch of 5 ha or more. In both Sarawak areas, about half of the loss was recorded by Hansen and most lay in patches of 5 ha or more, as in Kalimantan and unlike in Sabah and Brunei; it lay mostly at the edge but not more often beside water than all mangrove (Table S8). It therefore looks like clearing whose replacement the maps do not record, rather than a shift of the mapped boundary.

Table S8. *Mangrove lost between 2000 and 2024 away from ponds, by region: area and share of the 2000 extent, share at the edge and beside water (expected share from all 2000 mangrove in brackets), more than 150 m inside, recorded by Hansen in any year, and in patches of 5 ha or more.*

Region	Mangrove 2000 (ha)	Loss away from ponds (ha)	Loss (% of 2000)	Edge (%)	Interior (%)	Beside water (%)	Hansen (%)	Patches ≥ 5 ha (%)
Rajang Delta	91,481	11,096	12.1	72 (48)	19	10 (13)	51	54
South-west Sarawak	42,269	5,663	13.4	72 (49)	17	12 (12)	57	65
Other Sarawak	11,823	983	8.3	93 (45)	3	20 (17)	18	38
Sabah	333,962	19,477	5.8	81 (41)	11	14 (14)	27	42
Brunei	14,399	1,145	8.0	88 (43)	6	12 (20)	11	33
Kalimantan	797,809	60,938	7.6	67 (45)	23	12 (15)	49	60

30 m pathway raster (notebook 08). Labuan is included with Sabah. Regions by the jurisdiction of each 10 km cell.

To see what the land became, notebook 12 read the ESA WorldCover 2021 class (Zanaga et al. 2022) at every pixel of this loss and the dominant driver of forest loss in its 1 km cell (Sims et al. 2025), and drew 40 patches of 5 ha or more at random from the Rajang Delta (26) and south-west Sarawak (14), with probability proportional to patch area, so that each patch represents about the same area of loss. The author inspected each patch against Google Satellite and ESRI World Imagery basemaps in QGIS and recorded the main land cover now (Table S9). In the Rajang Delta, 12 patches had become other land uses (oil palm 4, cleared land 6, including logged mangrove, built-up 2), 2 open water and 12 still looked like mangrove or young regrowth; in south-west Sarawak, 9 had become other land uses (oil palm 5, cleared 2, built-up 2), 3 open water and 2 mangrove or regrowth. Several patches showed the rows or drains of earlier plantations. With 40 patches, each share is uncertain by about 15 percentage points, and the sample covers only patches of 5 ha or more, which hold 54 to 65% of the loss. WorldCover still classes 43% of the Rajang Delta's loss away from ponds and 21% of south-west Sarawak's as mangrove (50% in Sabah), and the drivers map assigns 45 to 56% of it to permanent agriculture, with logging at 13% in the Rajang Delta against 2 to 3% elsewhere.

Table S9. *Sampled patches of loss away from ponds in Sarawak: area, first year without mangrove in GMW v4.1, Hansen loss year (0, none), ESA WorldCover 2021 class and driver of forest loss at the patch point, and the land cover seen in recent satellite imagery, with the author's confidence.*

Patch	Region	Area (ha)	Loss year	Hansen year	WorldCover 2021	Driver (1 km)	Land cover in imagery	Confidence
S01	Rajang	278.5	2014	0	Permanent water	Permanent agriculture	water	high
S02	Rajang	224.4	2004	0	Grassland	Permanent agriculture	oil palm, farmland	medium
S03	Rajang	58.0	2009	0	Bare or sparse vegetation	Permanent agriculture	water	medium
S04	Rajang	15.2	2012	2024	Mangroves	Wildfire	mangrove	high
S05	Rajang	149.6	2020	2020	Tree cover	Permanent agriculture	mangrove, farmland	unsure
S06	Rajang	68.7	2009	2009	Grassland	Permanent agriculture	cleared	high
S07	Rajang	59.3	2009	2009	Grassland	Permanent agriculture	cleared, built-up	high
S08	Rajang	21.3	2023	0	Mangroves	Permanent agriculture	built-up	high
S09	Rajang	39.5	2004	2003	Grassland	Permanent agriculture	built-up, cleared, regrowth	high
S10	Rajang	35.7	2012	0	Mangroves	Permanent agriculture	mangrove, regrowth	high
S11	Rajang	17.9	2018	2019	Mangroves	Permanent agriculture	cleared, regrowth	high
S12	Rajang	13.0	2011	2016	Mangroves	Logging	mangrove	high

S13	Rajang	38.9	2021	2020	Mangroves	Logging	mangrove, cleared	high
S14	Rajang	20.6	2023	2023	Mangroves	Logging	mangrove, cleared	high
S15	Rajang	230.2	2013	0	Tree cover	Permanent agriculture	oil palm	high
S16	Rajang	11.3	2021	2022	Mangroves	Permanent agriculture	cleared, mangrove	high
S17	Rajang	5.1	2021	2022	Mangroves	Logging	cleared, mangrove	high
S18	Rajang	19.4	2023	2020	Tree cover	Permanent agriculture	cleared, oil palm	medium
S19	Rajang	296.0	2012	0	Tree cover	Other natural disturbances	mangrove, regrowth	high
S20	Rajang	55.3	2014	2015	Tree cover	Permanent agriculture	oil palm, mangrove	high
S21	Rajang	16.1	2018	2016	Tree cover	Permanent agriculture	regrowth	high
S22	Rajang	76.7	2020	2020	Tree cover	Permanent agriculture	oil palm	high
S23	Rajang	29.1	2014	0	Mangroves	Permanent agriculture	mangrove, regrowth	high
S24	Rajang	10.9	2017	2018	Grassland	Permanent agriculture	regrowth	high
S25	Rajang	23.6	2013	0	Mangroves	Permanent agriculture	mangrove, water	high
S26	Rajang	11.2	2012	0	Mangroves	Wildfire	mangrove, regrowth	high
S27	South-west	40.1	2009	2007	Grassland	Permanent agriculture	cleared, built-up	high
S28	South-west	198.9	2018	2013	Tree cover	Permanent agriculture	oil palm	high
S29	South-west	37.2	2013	2010	Tree cover	Permanent agriculture	oil palm, regrowth	high
S30	South-west	5.3	2004	2010	Grassland	Permanent agriculture	oil palm, grassland	high
S31	South-west	197.7	2017	2017	Grassland	Hard commodities	built-up, cleared	high
S32	South-west	53.2	2014	0	Permanent water	Permanent agriculture	water, cleared, pond, mangrove	low
S33	South-west	21.6	2014	0	Bare or sparse vegetation	Other natural disturbances	water, mangrove	high
S34	South-west	19.9	2014	0	Tree cover	Permanent agriculture	oil palm, built-up, mangrove	medium
S35	South-west	16.1	2014	0	Permanent water	Permanent agriculture	water	high
S36	South-west	135.1	2017	2018	Tree cover	Permanent agriculture	oil palm	high
S37	South-west	19.9	2022	2021	Tree cover	Permanent agriculture	cleared, grassland	medium

S38	South-west	81.4	2010	2005	Mangroves	Permanent agriculture	regrowth, grassland	high
S39	South-west	8.5	2021	2022	Tree cover	Settlements and infrastructure	built-up, cleared, mangrove	high
S40	South-west	22.0	2019	0	Tree cover	Permanent agriculture	mangrove, cleared, built-up	high

Land cover in imagery: main cover first. Coding sheet with the author's notes: OUTPUTS/12_sarawak_drivers/sample_coding_sheet.csv in the Zenodo deposit.

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